5^E COLLOQUE DE L'INITIATIVE EN COMBUSTION AVANCÉE

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INCA
INitiative en Combustion Avancée

7 et 8 Avril 2021
SAFRAN Paris-Saclay

SAFRAN

5ème Colloque INCA
7 et 8 Avril 2021

JOUR 1 – Mercredi 7 avril 2021		
08:30-09:00	***Ouverture des salles de visioconférence***	
09:00-09:30	***Ouverture du Colloque par Pierre-Alain Lambert, Directeur du pôle Energie & Propulsion – Safran Tech, et Claude Berat, Chef de Service BE Chambres de Combustion – Safran HE*** Salle de visioconférence 1	
09:30-10:30	***Guest speaker : Nicolas Jeuland (Safran)*** *Quelles trajectoires pour viser la neutralité carbone de l'aviation ?* Salle de visioconférence 1	
10:30-10:50	*Pause*	
10:50-12:10	*Polluants et gaz à effet de serre 1 – Expérimental* Salle de visioconférence 1	*Méthodes numériques innovantes* Salle de visioconférence 2
12:10-14:00	*Déjeuner*	
14:00-15:40	*Allumage* Salle de visioconférence 1	*Diagnostics expérimentaux* Salle de visioconférence 2
15:40-16:00	*Pause*	
16:00-17:40	*Instabilités de combustion 1* Salle de visioconférence 1	*Spray, gouttes et écoulement multiphasique 1* Salle de visioconférence 2
17h40	***Fin de la 1ère journée***	

5ème Colloque INCA
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JOUR 2 – Jeudi 8 avril 2021		
08:30-09:00	***Ouverture des salles de visioconférence***	
09:00-10:00	***Guest speaker : <u>Matthieu Rullaud</u> (Safran Aircraft Engines)*** *Panorama des projets R&T Safran* Salle de visioconférence 1	
10:00-10:20	*Pause*	
10:20-12:00	*Instabilités de combustion 2* Salle de visioconférence 1	*Stabilisation de flamme* Salle de visioconférence 2
12:00-14:00	*Déjeuner*	
14:00-15:20	*Polluants et gaz à effet de serre 2 - Numérique* Salle de visioconférence 1	*Spray, gouttes et écoulement multiphasique 2* Salle de visioconférence 2
15:20-15:40	*Pause*	
15:40-17:00	*Installations expérimentales* Salle de visioconférence 1	*Spray, gouttes et écoulement multiphasique 3* Salle de visioconférence 2
17:00-17:15	***Clôture du Colloque*** Salle de visioconférence 1	

Mercredi 7 avril >> Matin

10:50 >> POLLUANTS ET GAZ A EFFET DE SERRE 1 - EXPERIMENTAL

Lieu: Salle de visioconférence 1

10:50-11:10
1 – Soot size assessments in a swirl stratified premixed C2H4/air flame: Comparison between in- and ex-situ measurements
Aurélien Perrier – CORIA

11:10-11:30
2 – Hydrophilic properties of soot particles exposed to OH radical: a possible new mechanism involved in the contrail formation
Symphorien Grimonprez – PC2A

11:30-11:50
3 – Experimental investigation of soot production in a swirl stratified premixed flame using various optical diagnostics
Maxime Bouvier – CORIA

11:50-12:10
4 – Primary particle diameters in sooting flames: a challenge for LII measurements and for validation of numerical modeling
Agnès Bodor – EM2C

10:50 >> METHODES NUMERIQUES INNOVANTES

Lieu: Salle de visioconférence 2

10:50-11:10
5 – Machine learning for CPU efficient detailed combustion chemistry in computational fluid dynamics
Kaidan Wan – CORIA

11:10-11:30
6 – Fully conservative Lattice-Boltzmann modelling of reactive flows
Pierre Boivin – AIX MARSEILLE UNIVERSITE

11:30-11:50
7 – Machine learning for modeling particulate and soot emissions from aeronautical engines
Andréa Seltz – CORIA

Le nom associé à l'intitulé de la contribution correspond à celui de l'auteur principal de l'article

Mercredi 7 avril >> Après-midi (1/2)

14:00 >> ALLUMAGE

Lieu: Salle de visioconférence 1

14:00-14:20
8 – Light-round simulation of an annular spray-flame combustor with ambient temperature walls
Karl Topperwien – EM2C

14:20-14:40
9 – Comparison of LES and experiments of methane-air ignition in a closed chamber under various turbulent conditions
Javier Crespo-Anadon – CERFACS/PPRIME

14:40-15:00
10 – A reduced-order model to predict the stability of combustion chambers for relight conditions
Haris Musaefendic – SAFRAN AE

15:00-15:20
11 – High-fidelity one-dimensional boundary model of solid propellant combustion for the simulation of the ignition transients of complete solid rocket motors
Laurent François – ONERA / POLYTECHNIQUE

15:20-15:40
12 – Experimental investigation of the deflagration/autoignition/detonation transition mechanisms in a closed vessel with n-decane/O2/Ar mixtures: influence of the temperature gradient in the end-gas
Hugo Quintens – PPRIME

14:00 >> DIAGNOSTICS EXPERIMENTAUX

Lieu: Salle de visioconférence 2

14:00-14:20
13 – Surface temperature measurements in combustors: accuracy improvement of the phosphor thermometry technique
Sylvain Petit – CORIA

14:20-14:40
14 – Insight into the ozone-assisted low-temperature combustion of DME by means of stabilized cool flames
Thomas Panaget – PC2A

14:40-15:00
15 – Optical flow and POD based processing for non-linear dynamic description of a two-phase flow
Marie Truffot – EM2C

15:00-15:20
16 – X-ray computed tomography to measure 3D gas-temperature in multi-phase combustion systems
Emeric Boigné – Stanford

15:20-15:40
17 – Chirped-probe-pulse femtosecond coherent anti-Stokes Raman scattering for gas-phase temperature measurements in high-pressure kerosene/air flames
Sylvain Legros – CORIA

Mercredi 7 avril >> Après-midi (2/2)

16:00 >> INSTABILITES DE COMBUSTION 1

Lieu: Salle de visioconférence 1

16:00-16:20
18 – The flame describing function and flame dynamics under self-sustained oscillations
Guillaume Vignat – EM2C

16:20-16:40
19 – Measurements of the transfer function of partially premixed swirling flames in the PRECCINSTA gas turbine model combustor
Sylvain Marragou – IMFT

16:40-17:00
20 – Dynamical blow-out of swirling spray flames induced by transverse acoustic oscillations
Clément Patat – EM2C / CORIA

17:00-17:20
21 – Low-Order Thermoacoustic Analysis of Real Engines
Abhijeet Badhe – CERFACS

17:20-17:40
22 – Studying acoustic damping in a nonreactive pressurized chamber combining experiments, simulations and modeling
David Marchal – EM2C

16:00 >> SPRAY, GOUTTES ET ECOULEMENT MULTIPHASIQUE 1

Lieu: Salle de visioconférence 2

16:00-16:20
23 – Comparative study of interface tracking methods for the description of interface dynamics and droplet evaporation
Victor Boniou – EM2C

16:20-16:40
24 – Consistent scalar transport in front capturing methods: application to two-phase heat transfer
Yahia Atmani – CORIA

16:40-17:00
25 – Effect of drag force modelling on droplet evaporation
Artur Carvalho Santos – EM2C

17:00-17:20
26 – Analytical-experimental comparison methodology for the evaporation of liquid fuel droplets in the vicinity of a flame
Gael Parant – EM2C

17:20-17:40
27 – On the accurate prediction of preferential concentration in Large Eddy Simulation of particle-laden flow
Roxane Letournel – EM2C / POLYTECHNIQUE

Le nom associé à l'intitulé de la contribution correspond à celui de l'auteur principal de l'article

Jeudi 8 avril >> Matin

10:20 >> INSTABILITES DE COMBUSTION 2

Lieu: Salle de visioconférence 1

10:20-10:40
28 – Impact of H2 pilot injection on the acoustic response of a flow-swirled flame
Andréa Aniello – IMFT

10:40-11:00
29 – Dependence of the thermoacoustic coupling on flame power for swirling spray flames at acoustic pressure antinodes
Clément Patat – CORIA

11:00-11:20
30 – Impact of injector characteristics on combustion instabilities in a swirl-spray combustor
Preethi Rajendram Soundararajan – EM2C

11:20-11:40
31 – Detection of precursors of Thermoacoustic Instability using Deep Learning Techniques
Anthony Cellier – CERFACS

11:40-12:00
32 – Combustion stability – experimental investigation
Anthony Desclaux – ONERA

10:20 >> STABILISATION DE FLAMME

Lieu: Salle de visioconférence 2

10:20-10:40
33 – Numerical simulations of turbulent flame stabilization by nanosecond repetitively pulsed discharges
Yacine Bechane – EM2C

10:40-11:00
34 – Numerical study of a confined hydrogen-enriched premixed methane/air swirling flame using detailed chemistry
Quentin Cazères – CERFACS

11:00-11:20
35 – Numerical study of flame shape stabilisation and transitions on the BIMER combustor
Léo Cunha – EM2C

11:20-11:40
36 – Design through LES of a spinning flame combustor, Impact of operating conditions on flame stabilization and thermal load
Walter Agostinelli – CERFACS

11:40-12:00
37 – Detonation stability: New paradigms for the control of rotating detonation engines
Hassan Tofaili – CORIA

Le nom associé à l'intitulé de la contribution correspond à celui de l'auteur principal de l'article

Jeudi 8 avril >> Après-midi (1/2)

14:00 >> POLLUANTS ET GAZ A EFFET DE SERRE 2 - NUMERIQUE

Lieu: Salle de visioconférence 1

14:00-14:20
38 – Assessment of soot radiation modelling to predict heat transfer in turbulent flames
Kévin Torres-Monclard – EM2C

14:20-14:40
39 – Modeling NOx formation in turbulent spray flames using virtual chemistry
Constantin Nguyen Van – EM2C

14:40-15:00
40 – Modelling soot formation in LES of turbulent flames using virtual chemistry
Hernando Maldonado-Colman – EM2C

15:00-15:20
41 – Reconsidering the good practice guidelines for LES of turbulent sooting flames
Livia Tardelli – EM2C

14:00 >> SPRAY, GOUTTES ET ECOULEMENT MULTIPHASIQUE 2

Lieu: Salle de visioconférence 2

14:00-14:20
42 – Liquid phase envelope estimation in two-phase combustion
Axel Ivaldi – EM2C

14:20-14:40
43 – Detailed analysis of a swirl-stabilized kerosene spray flame under relevant aero-engine conditions with Phase Doppler Anemometry experiments and LES simulations
Clément Brunet – CORIA

14:40-15:00
44 – Numerical study of swirled multicomponent spray flames in gas turbine combustors
Varun Shastry – CERFACS

15:00-15:20
45 – Numerical Dual Swirl Spray Stabilized Burner: Comparison of conventional and alternative fuels
Jonathan Wirtz – CERFACS

Le nom associé à l'intitulé de la contribution correspond à celui de l'auteur principal de l'article

Jeudi 8 avril >> Après-midi (2/2)

15:40 >> INSTALLATIONS EXPERIMENTALES

Lieu: Salle de visioconférence 1

15:40-16:00
46 – Semi–technical aero-engine combustors – a glimpse on combustion processes given by in-situ optical techniques
Cornelia Irimiea – ONERA

16:00-16:20
47 – System design and preliminary evaluation of a High-Altitude Relight Test Facility - HARTUR
Marie-Eve Clavel – CORIA

16:20-16:40
48 – Investigating the effect of the injector design and of the operating conditions on soot production in a rich premixed model scale combustor
Mathieu Roussillo – EM2C

16:40-17:00
49 – Challenges and opportunities for laser diagnostics to make high-pressure aircraft engines clean and efficient
Clément Brunet – CORIA

15:40 >> SPRAY, GOUTTES ET ECOULEMENT MULTIPHASIQUE 3

Lieu: Salle de visioconférence 2

15:40-16:00
50 – Multi-fluid models for two-phase and transcritical flows, Application to rocket engine configurations with the AVBP solver
Thomas Schmitt – EM2C

16:00-16:20
51 – Massively Parallel Large-Eddy Simulations of Primary Atomization on Adaptive Unstructured Meshes- Interface capturing algorithm and multiscale coupling perspectives
Romain Janodet – CORIA

16:20-16:40
52 – Surface density evolution in Direct Numerical Simulations of periodical liquid sheet assisted atomization
Matthias Averseng – ONERA

16:40-17:00
53 – A novel methodology to simulate fuel injection in multipoint systems - Application to liquid jet in crossflow
Carlos Guillamon – CERFACS

Le nom associé à l'intitulé de la contribution correspond à celui de l'auteur principal de l'article

INitiative en Combustion Avancée

ABSTRACTS

SAFRAN

1 – Soot size assessments in a swirl stratified premixed C2H4/air flame: Comparison between in- and ex-situ measurements

A. Perrier, M. Bouvie, A. Cayre, J. Yon, G. Cabot, F. Grisch

The present work is focused on size measurement of soot particles which are produced in a turbulent, stratified (high spatial equivalence ratio gradient), swirled (rotating flow) premixed ethylene-air flame representative of aeronautic conditions. Soot particle size measurements are performed using an ex-situ sampling technique coupled with a Scanning Mobility Particle Sizer (SMPS). The angle dependence of elastic light scattering from soot was also used as a mean for determining particle size distributions. This study shows a comparison of soot size distributions that were obtained by sampling and optical techniques.

Keywords Soot size measurement, soot sampling elastic light scattering, turbulent flame

2 – Hydrophilic properties of soot particles exposed to OH radical: a possible new mechanism involved in the contrail formation

S. Grimonprez, J. Wu, A. Faccinetto, S. Gosselin, E. Riber, B. Cuénot, M. Cazaunau, E. Pangui, P. Formenti, J-F. Doussin, D. Petitprez, P. Desgroux

This work investigates the role of soot particles in the early steps of formation of condensation trails (contrails). Contrails are thin linear clouds that form behind cruising aircrafts and can evolve into persistent clouds, and therefore can contribute to the radiative forcing of the atmosphere. Mitigating their contribution is considered an efficient way for decreasing the radiative forcing. Nucleation of ice particles in freshly formed contrails is partly due to the heterogeneous nucleation of liquid water on emitted soot particles, which then freeze rapidly. However, since fresh soot particles are hydrophobic, many theoretical and experimental approaches that investigate contrails formation introduce prior activation by surface adsorption of sulfur compounds issued from kerosene combustion. Even though the sulfur content of the fuel only has a weak impact on contrails formation, many simulations still rely on this assumption. In this work, to elucidate the role of sulfur compounds on the activation of aeronautic soot chemically aged with OH radicals, a comparative study is performed for the first time with soot sampled from a turbulent jet flame burning a sulfur-containing fuel (kerosene) and a sulfur-free fuel (diesel). Soot aging experiments are performed in the atmospheric simulation chamber CESAM, with controlled generation of OH radicals. Soot activation (ratio between the number concentrations of nucleated droplets and seeding particles) is measured in water supersaturation conditions. OH exposure significantly enhances soot activation regardless of the sulfur presence in the fuel. The possibility for soot oxidation by OH radicals formed in aeronautical engines to be sufficient to promote soot activation is explored. Large eddy simulation in the high pressure turbine is used to model the fluid particle trajectories and their chemical evolution. Residence time in the turbine is found sufficient to activate soot particles, opening a new possible route to explain ice particles formation.

Keywords Combustion stability, Reduced order modeling

3 – Experimental investigation of soot production in a swirl stratified premixed flame using various optical diagnostics

M. Bouvier, A. Perrier, A. Vandel, F. Lefebvre, G. Godard, G. Cabot, J. Yon, F. Grisch

Soot formation and oxidation are investigated in swirl stratified premixed ethylene/air flames at atmospheric pressure. The effects of both swirl and stratification are studied to understand the relationship between the flame structure, soot precursors and soot. The topology of the flame is obtained with particle image velocimetry (PIV) and planar laser-induced fluorescence (PLIF) on hydroxyl radical (OH). The production of polycyclic aromatic hydrocarbons (PAHs) is investigated using PLIF by mainly probing the aromatic compounds with two benzene rings (i.e. naphthalene) that are known to actively participate in soot nucleation and growth. Soot production is investigated using laser-induced incandescence (LII), giving quantitative data on the soot volume fraction and on the primary particle diameters, and high-speed 2D angular scattering, providing information on the aggregate sizes and on the soot number concentration. Extensive information on the flame structure and the mechanisms of formation/consumption of soot is gathered based on the coupling of these laser diagnostics. It enables us to propose a scenario that describes the link between the inception, growth, aggregation and oxidation processes. In particular, the data reveal the presence of distinct zones for these processes: a thermal decomposition region in which PAHs contributes to nascent soot formation, organised as filaments along the interface between the PAH region and the inner recirculation zone (IRZ); a mixing region controlled by large moving structures that favour the growth and aggregation of nascent soot into mature soot; and an oxidation region leading to the fast consumption of soot particles. These processes are impacted to varying extents by the intensities of swirl and stratification.

Keywords Premixed flame, Swirl, Stratification, Soot, PAH, OH

4 – Primary particle diameters in sooting flames: a challenge for LII measurements and for validation of numerical modeling

A. Bodor, A. Cuoci, J. Yi, B. Betrancourt, N. Darabiha, B. Franzelli

While validating the numerical modeling of primary particle size in sooting flames, a common practice is to compare the numerical results to the experimental data obtained from the temporal evolution of the Laser-Induced Incandescence (LII) signal in terms of mean diameter. However, since this quantity is not directly measured but derived with a post-processing procedure, various uncertainties and errors can potentially affect the consistency of such comparison requiring the estimation of many input parameters. In this work, some of the difficulties in comparing experimental to numerical results for mean primary particle diameters are presented. To overcome them, a forward approach for the generic validation of numerical models is proposed here. It is based on the numerical reconstruction of the temporal evolution of the incandescence from the numerical results and its comparison with the measured signal. The feasibility of the proposed procedure is proven by comparing synthesized signals to the experimental ones for a laminar coflow ethylene/air sooting flame.

Keywords Soot, Mean primary particle size, Time-resolved LII

5 – Machine learning for CPU efficient detailed combustion chemistry in computational fluid dynamics

K. Wan, C. Barnaud, L. Vervisch, P. Domingo

A chemistry reduction approach based on machine learning is proposed and applied to direct numerical simulation (DNS) of a turbulent non-premixed syngas oxy-flame interacting with a cooled wall. The training and the subsequent application of artificial neural networks (ANNs) rely on the processing of 'thermochemical vectors' composed of species mass fractions and temperature (ANN input), to predict the corresponding chemical sources (ANN output). The training of the ANN is performed aside from any flow simulation, using a turbulent non-adiabatic non-premixed micro-mixing based canonical problem with a reference detailed chemistry. Heat-loss effects are thus included in the ANN training. The performance of the ANN chemistry is then tested a-posteriori in a two-dimensional DNS against the detailed mechanism and a reduced mechanism specifically developed for the operating conditions considered. Then, three-dimensional DNS are performed either with the ANN or the reduced chemistry for additional a-posteriori tests. The ANN reduced chemistry achieves good agreement with the Arrhenius-based detailed and reduced mechanisms, while being in terms of CPU cost 25 times faster than the detailed mechanism and 3 times faster than the reduced mechanism when coupled with DNS. The major potential of the method lies both in its data driven character and in the handling of the stiff chemical sources. The former allows for easy implementation in the context of automated generation of case-specific reduced chemistry. The latter avoids the Arrhenius rates calculation and also the direct integration of stiff chemistry, both leading to a significant CPU time reduction (25 faster than detailed chemistry and 3 times faster than an analytically reduced scheme for the same number of species).

Keywords Combustion chemistry, Machine learning, Pollutants prediction

6 – Fully conservative Lattice-Boltzmann modelling of reactive flows - Is LBM worth the effort when dealing with combustion ?

P. Boivin, S. Zhao, G. Farag, M. Tayyab

The first fully conservative, fully compressible hybrid Lattice-Boltzmann model is presented for reactive flows. As in our previous contribution (Tayyab & al. C&F 2020), mass and momentum are resolved by LBM with a single probability density distribution, while energy and species conservation are simulated via finite difference method. The coupling between the Lattice-Boltzmann and finite difference solvers has however been revisited in-depth, to increase accuracy and robustness in the vicinity of curved flame fronts. To that end, we extended our recent contribution (Farag et al. Phys. Fluids 2020) to multi-component, reactive flows. The solver is made fully conservative by introduction of our new specific numerical scheme presented earlier this year (Zhao et al. Phys. Fluids 2020). The resulting model preserves the advantages of classical LBM in that its cost is about an order of magnitude lower than classical Navier-Stokes solvers.

Keywords Combustion, LBM, HPC

7 – Machine learning for modeling particulate and soot emissions from aeronautical engines

A. Seltz, P. Domingo, L. Vervisch

Numerical modeling of soot dynamics may be addressed by solving a population balance equation (PBE). In addition to space and time, a discretisation is required also in the soot-size space, covering a large range of variation controlled by strongly nonlinear phenomena. A novel approach is presented in which a hybrid stochastic/fixed-sectional method solving the soot PBE is used to train a combination of an artificial neural network (ANN) with a convolutional neural network (CNN) and recurrent long short-term memory artificial neural layers (LSTM). The hybrid stochastic/fixed-sectional method decomposes the problem into the total number density and the probability density function (PDF) of sizes, allowing for an accurate treatment of surface growth/loss. After solving for the transport of species and temperature, the input of the ANN is composed of the thermochemical parameters controling the particle physics and of the increment in time. The input of the CNN is the shape of the particle size distribution (PSD) discretised in sections of size. From these inputs, in a flow simulation the ANN-CNN returns the PSD shape for the subsequent time step or a source term for the Eulerian transport of the particle size density. The method is evaluated in a canonical laminar premixed sooting flame of the literature and for a given level of accuracy (i.e., a given discretisation of the size space), a significant computing cost reduction is achieved (6 times faster compared to a sectional method with 10 sections and 30 times faster for 100 sections). Then it is applied to the MERMOSE combustion chamber and results are compared against measurements.

Keywords Soot, Machine learning, Aeronautical engine

8 – Light-round simulation of an annular spray-flame combustor with ambient temperature walls

K. Topperwien, R. Vicquelin

Numerical simulations of ignition in annular aeronautical combustors have made progress thanks to experimental data on the burner-to-burner flame propagation. This last phase of ignition is known as light-round. Large-Eddy simulations of light-rounds in the liquid-fuelled annular combustor MICCA-spray featuring sixteen swirled injectors have followed the trends observed in experiments. In particular, simulations in pre-heated conditions have shown good agreement with experimental data, but fell somewhat short of predicting the light-round duration for ambient temperature walls. Several issues have been identified and investigated so far: as a priori studies suggest, variable thermodynamic properties of the boundary layer must be taken into account to improve the prediction of wall heat losses. Furthermore, the combustion model previously relied on the assumption of a constant flame wrinkling parameter. This appears to be inappropriate as shown by dedicated simulations in which the wrinkling parameter is computed dynamically. Both issues, which have only been studied separately before, are addressed in a light-round simulation of the MICCA-spray combustor using an Euler-Lagrange formalism for the liquid phase, a dynamic evaluation of the wrinkling parameter and a novel approach for wall modelling. The impact of this improved setup on the light-round duration is analysed and compared to available experimental data.

Keywords Gas turbine ignition, Two-phase flows, LES, Wall heat losses

9 – Comparison of LES and experiments of methane-air ignition in a closed chamber under various turbulent conditions

J. Crespo-anadon, B. Cuénot, E. Riber, S. Richard, M. Bellenoue, J. Sotton

SAFRAN HE has developed the spinning combustion technology in which the burnt gases from one injector travel tangentially along the combustor annulus towards the following injectors. In order to select the best methodology using Large Eddy Simulation (LES) to study ignition in these combustors, experiments and LES have been performed in a cylindrical combustion chamber where the flow is injected tangentially. Three cases are considered with different values of strain and turbulence levels representative of real combustor flows. LES are performed with a 19-species and 184-reactions analytical chemical scheme allowing the description of the first instants of ignition and the ensuing flame propagation. Results show that LES is able to capture the flame kernel formation and trajectory as well as the time to reach maximum pressure within an average error of 10% when selecting the thermal thickness and laminar flame speed which correspond to the mean pressure for each case.

Keywords Ignition, LES, Experiments, Strain, Turbulence, Premixed methane/air mixture

10 – A reduced-order model to predict the stability of combustion chambers for relight conditions

H. Musaefendic, G. Parant, R. Mercier, J. Leparoux, S. Puggelli

This study presents a reduced model to predict stability limits of combustion chambers under conditions for relight conditions. The approach relies on elementary physical models to minimize the computation cost to allow its use during the design and preliminary studies.

Keywords Combustion stability, Reduced order modeling

11 – High-fidelity one-dimensional boundary model of solid propellant combustion for the simulation of the ignition transients of complete solid rocket motors

L. François, J. Dupays, M. Massot

In this contribution, we introduce a high-fidelity unsteady one-dimensional model of solid propellant combustion, and the associated adaptive solver. The model will be used as a boundary condition in order to simulate ignition transients of complete solid rocket motors at relatively low cost, relying on the CEDRE ONERA multiphysics code for the simulation of the flow field inside the combustion chamber. A mathematically well-defined unsteady model is designed and resolved through a high-order time integration method with time adaptation and error control is designed, accounting for the differential-algebraic nature of the discretised system. This model is then incorporated as a dynamic boundary condition in the CEDRE code for the simulation at large scale of a combustion chamber ignition transient.

Keywords Solid propellant combustion, Ignition dynamics, CFD, High order adaptive time integration, numerical methods, differential-algebraic equations

12 – Experimental investigation of the deflagration/autoignition/detonation transition mechanisms in a closed vessel with n-decane/O2/Ar mixtures: influence of the temperature gradient in the end-gas.

H. Quintens, C. Strozzi, M. Bellenoue

End-gas autoignition of n-decane/O2/Ar mixtures is investigated experimentally in a closed optical vessel, with a focus on the deflagration/autoignition/detonation transition mechanisms. Using a multi-zone temperature control systems, different initial temperature profiles are set, leading to various thermal gradients in the unburned end-gas at the onset of auto-ignition. Percentages of transitions to detonation are analyzed at the light of different criterion and approaches. A particular attention is paid to the repeated emission of pressure waves during the autoignition fronts propagation for the weakest gradient values.

Keywords CVC, Autoignition detonation transition, Superknock

13 – Surface temperature measurements in combustors: accuracy improvement of the phosphor thermometry technique

S. Petit, P. Xavier, G. Godard, F. Grisch

An optimization method that improves the temperature accuracy of the spectral-based phosphor thermometry technique is presented. This routine is developed and implemented to select collection optical filters that minimizes the mean temperature error as well as its variation on a given temperature range. Emission spectra collected at various temperatures are processed with various virtual optical filter specifications. Compared with a filter set from the literature that is in connection with the main phosphorescence emission peaks, the optimization routine leads to select collection filters that enhance the relative sensitivity at the expense of the signal-to-noise ratio. Thus, narrow-band filters are used, one of them being located on the red-wing of the emission spectrum to be more sensitive to the effect of temperature. This method gives a temperature uncertainty of 2.5% between 300 and 750 K. The validation conducted with an ICCD camera and commercial filters confirms a significant improvement of this measurement methodology, raising new opportunities in high-temperature environments.

Keywords Surface temperature, Phosphor thermometry, Temperature uncertainty, Combustion

14 – Insight into the ozone-assisted low-temperature combustion of DME by means of stabilized cool flames

T. Panaget, S. Batut, Y. Fenard, L. Pillier, G. Vanhove

A burner dedicated to the study of the low-temperature combustion phenomena has been developed at the PC2A laboratory. Stabilization of cool flames was made possible by seeding a premixed flow of DME/O2 with ozone (O3), enabling the initiation of the combustion in these conditions. Planar Laser Induced Fluorescence (PLIF) of formaldehyde has been used to measure the flame position in a wide range of strain rate, equivalence ratio and ozone concentration conditions. Temperature profiles were measured, along with reactant and major products along the burner axis for selected flames. Simulations were performed using the Aramco 1.3 model, coupled with an ozone sub-mechanism by Foucher et al.. They showed good performance in predicting cool flame occurrence, position and temperature, some discrepancies being however observed regarding to the fuel conversion and the formation of oxygenated products, highlighting some missing direct reaction pathways between dimethyl ether and ozone.

Keywords Low temperature combustion, Cool flame, Kinetic modeling, Plasma-assisted combustion

15 – Optical flow and POD based processing for non-linear dynamic description of a two-phase flow

M. Truffot, A. Ivaldi, A. Renaud, L. Zimmer, F. Richecoeur

The dynamics of two-phase swirled turbulent flows involved in combustors are often problematic to capture as many temporal and spatial scales come into play. Even when an upstream harmonic modulation tries to force a simplified dynamic, these flows respond with a spatial and temporal richness that is difficult to characterize. To simultaneously improve the resolution of the experimentally measured velocity fields and their dynamic analysis, we propose to combine optical flow processing of the Mie scattering images to generate streamlines and plotting of the phase portraits of the most energetic POD modes. On an inverted Bunsen burner operating with a global equivalence ratio equal to 0.91, we show how this combined approach highlights the different non-linear responses of a pulsed two-phase jet at the injector output according to the upstream modulation frequency varying between 10 and 150 Hz.

Keywords System dynamics, Proper Orthogonal Decomposition, Optical flow

16 – X-ray computed tomography to measure 3D gas-temperature in multi-phase combustion systems

E. Boigné, M. Ihme

X-ray Computed Tomography (CT) is proposed as a flexible diagnostic to measure 3D gas-temperature in diverse combustion systems. The method benefits from the highly penetrating nature of X-ray, and can complement traditional diagnostics in applications with limited optical access or multi-phase dynamics. X-ray CT is employed using a tabletop system to image a premixed laminar flame, the heterogeneous combustion of a solid fuel, and the interstitial flame structure of a porous media burner.

Keywords Heterogeneous combustion, X-ray computed tomography, Experimental diagnostics

17 – Chirped-probe-pulse femtosecond coherent anti-Stokes Raman scattering for gas-phase temperature measurements in high-pressure kerosene/air flames

S. Legros, B. Barviau, F. Grisch

Chirped-probe-pulse femtosecond coherent anti-Stokes Raman scattering (CPP-fs CARS) thermometry at 1 kHz in kerosene/air flames developed at a pressure of 0.75 MPa. The measurement strategy employed is based on the frequency-spread dephasing rate after an initial excitation of the Raman coherence on N2. Temperature is deduced from the single-shot CARS spectra adopting a genetic algorithm. Details of the CARS spectra data reduction are discussed. Problems issued from the presence of liquid droplets are also investigated. The temperature accuracy determined in a near-adiabatic laminar flame was found to be better than 1.5% at 2250 K. The results demonstrate the applicability and usefulness of CPP-fs CARS for investigating high-pressure two-phase flames under representative aircraft model combustor regimes.

Keywords CARS, Combustion diagnostics, High-pressure kerosene/air flame, Temperature

18 – The flame describing function and flame dynamics under self-sustained oscillations

G. Vignat, P.R. Soundararajan, A. Renaud, D. Durox, S. Candel

Transfer function concepts that appear in many areas and most notably in control systems have been extensively used to represent the flame response in low order models of combustion instability. Much of the theoretical work is based on flame transfer functions (FTF). In recent years the nonlinear extension of the flame transfer function, namely the flame describing function (FDF), was used to get a more accurate representation of the flame response when the level of oscillation becomes large and the system reaches a limit cycle. Despite their wide use, the validity of using FTF/FDF to represent flame response still remains to be experimentally substantiated. This article is aimed at providing a direct assessment of the capacity of the FDF to suitably describe the flame behavior under self-sustained oscillations (SSO). This is accomplished by making use of an experimental combustion configuration which exhibits unstable oscillations but which can also be used to modulate the flame using a set of driver units. The flame dynamics and response are determined under well established oscillations. The chamber length is then modified to obtain a stable regime and the flame is modulated externally at the frequency of the self-sustained oscillation observed in the first stage. The amplitude of incident velocity modulations is then progressively varied until it coincides with that found under self-sustained oscillations. This allows a direct comparison of the flame dynamics in these two situations. Gain and phase of the describing function are measured for the various input levels and found to approximately match those measured under SSO. It is shown that the best match is obtained when the amplitude of external modulation induces a level of velocity oscillations that is closest to that prevailing under SSO demonstrating that the FDF suitably captures the nonlinearity of the flame response, at least in the configuration investigated in this research.

Keywords Combustion dynamics, Flame describing function, Transfer function, Limit cycle oscillations

19 – Measurements of the transfer function of partially premixed swirling flames in the PRECCINSTA gas turbine model combustor

S. Marragou, I. Boxx, L. Selle, T. Poinsot, T. Schuller

The dynamics of the PRECCINSTA combustor is investigated for partially premixed injection conditions. Flame transfer functions (FTF) are determined for a methane/air and a hydrogen/methane/air flame at global equivalence ratio Phi = 0.8 and constant power P = 10 kW. It is first confirmed that self-sustained combustion oscillations that may take place are accompanied by disturbances of the mixture composition at the burner outlet. Under these conditions, the flame is submitted to flowrate and mixture composition oscillations and the heat release rate is no longer proportional to the chemiluminescence intensity of CH* or OH* radicals. A relation linking the flame luminosity and heat release rate is derived based on experiments carried out at constant equivalence ratio by varying the mixture flowrate and at constant fuel mass flowrate by varying the air flowrate. It is used to infer the heat release rate response for forced flow conditions. Results for the FTF are presented for the CH* signal and for the reconstructed heat release rate as a function of the velocity modulation level at the burner outlet. The effect of hydrogen enrichment is then briefly discussed.

Keywords Swirled flame, Flame transfer function, Partially premixed flames, Hydrogen combustion

20 – Dynamical blow-out of swirling spray flames induced by transverse acoustic oscillations

C. Patat, F. Baillot, J-B. Blaisot, E. Domingues, G. Vignat, P.R. Soundararajan, A. Renaud, D. Durox, S. Candel

Recent experiments on a laboratory scale annular system comprising multiple injectors (namely, MICCA-Spray) indicate that combustion instabilities coupled with azimuthal modes may induce large amplitude oscillations, which under certain conditions, lead to blow-out of some of the flames established in the system, a phenomenon designated as dynamic blow-out (DBO). An attempt is made in the present investigation to reproduce this phenomenon in a linear array of injectors (namely, TACC-Spray), where the sound field is externally applied to flames established by injector units that are identical to those used in the annular combustor. The sound field is generated by driver units placed on the lateral sides of a rectangular cavity. The pressure level induced in TACC-Spray can reach a peak value of 1700 Pa in a frequency range extending from 680 to 780 Hz, which corresponds to the typical frequency of azimuthal instabilities observed in the annular system. A theoretical model based on dimensional analysis serves to guide the choice of operating conditions that may lead to the DBO phenomenon. Experiments carried out in TACC-Spray and MICCA-Spray are then used to determine the DBO boundary, define the conditions that need to be fulfilled to observe this phenomenon, and gather high-speed visualizations providing some insights on the mechanisms that induce blow-out.

Keywords

21 – Low-Order Thermoacoustic Analysis of Real Engines

A. Badhe, C. Laurent, C. Lapeyre, F. Nicoud

This article illustrates the capability of the recently introduced low-order acoustic-network modeling (LOM) approach (Laurent et al., Combust. Flame, vol. 206, 2019) based on the 'generalized modal-expansions' and the 'state-space' framework to study thermoacoustic combustion instabilities in complex realistic configurations under the assumption of zero-Mach mean flow conditions. The acoustics modeling is essentially an improved and generalized version of the classical modal expansions (Galerkin series) technique. Here, one can use as the basis functions either an over-complete set of acoustic eigenmodes (called an Over-Complete (OC) Frame) or a simple orthogonal (OB) basis as has been the norm so far. The former, where deemed necessary, offers enhanced convergence, correct representation of acoustic variables at the interfaces of the subdomains in the network fixing issues such as Gibbs oscillations, and at the same time, presents the opportunity for interconnecting subdomains with 1D/2D/3D acoustics and even modeling advanced features such as complex boundary impedances and multi-perforated liners (Laurent et al., J Comp. Phy., vol. 428, 2021). The potential of the tool is illustrated by performing a linear stability analysis of a real SAFRAN aeronautical engine combustor with twenty 3D quasi-compact flames while keeping all the geometrical complexities intact. The results are similar to those obtained by a 3D finite element based Helmholtz solver but with CPU-time significantly lower (by 2 orders of magnitude). These observations suggest the feasibility of exploiting the tool for extensive parametric studies.

Keywords Thermoacoustics, Combustion Instabilities, Low-order Modeling, Acoustic network, Modal expansion, Galerkin series, State-space

22 – Studying acoustic damping in a nonreactive pressurized chamber combining experiments, simulations and modeling

D. Marchal, A. Fougnie, T. Schmitt, S. Ducruix

Acoustic damping, a key element for the accurate prediction of combustion instabilities, is studied in this work through the combined analysis of the NPCC test bench. This gaseous nonreactive test bench, developed for the study of acoustic damping in a coupled-cavity configuration, is composed of a dome, a chamber and 3 injectors. It mimics the geometry of a LRE in a simplistic way. An acoustic modulation at three different frequencies - corresponding to acoustic modes of the system - is achieved using a perforated wheel. Large Eddy Simulation (LES) properly reproduces the experimental pressure signal for the 3 cases. Then, a Reduced Order Modeling (ROM) approach is presented with a modal expansion, which retrieves numerical results in a linear framework.

Keywords Thermoacoustic, High-frequency, Instability, Liquid Rocket Engine, LES, Reduced Order Modeling, Damping

23 – Comparative study of interface tracking methods for the description of interface dynamics and droplet evaporation

V. Boniou, T. Schmitt, A. Vié

The numerical simulation of aeronautical combustors requires to model the evolution of the liquid fuel in the combustion chamber. Especially, when the liquid fuel is atomized into droplets, predicting their evolution requires the use of models for their interaction with the gaseous carrier phase. Focusing on evaporation and heating, numerous solutions based on different assumptions and correlations are found in the literature. Unfortunately, there is no consensus on the most accurate method, and experimental results are hard to be found in relevant conditions for aeronautical engines. To circumvent this issue, high-fidelity simulations of droplet vaporization can be used as a reference for validating and constructing model for droplet evolution. To this aim, we have develop a numerical platform at the EM2C laboratory: the structured TITAN solver. Its objective is to develop and compare modelling strategies and numerical methods for interfacial flows with and without phase change and heat transfer. The present work focuses on the low Mach part of TITAN, in which both Volume-Of-Fluid and level set methods are implemented for tracking the interface. The different interface tracking methods coupled with up-to-date numerical methods are compared using several benchmark cases, focusing on the accuracy and performance in our specific setting for capturing interface dynamics, vaporization and heating.

Keywords Two-phase flow, Interface tracking, Low-mach, Droplets, Vaporization

24 – Consistent scalar transport in front capturing methods: application to two-phase heat transfer

Y. Atmani, F. Pecquery, M. Cailler, V. Moureau

Accurate numerical simulations of heat transfers in 3D liquid-gas flows are of first importance in multiple industrial applications. Robust and accurate algorithms are then necessary to transport the flow variables consistently with the liquid-gas interface. This work presents a front-capturing method which enables a consistent transport of the scalars with the liquid-gas interface. It ensures conservation of the transported scalars while controlling accurately the flux at the interface. The interface represented by a hyperbolic tangent profile is reinitialized as well as the liquid and gaseous scalars. The method is implemented in the YALES2 low-Mach number flow solver and takes advantage of adaptive unstructured grids to handle complex geometries. It has been assessed on various test cases and good results have been obtained.

Keywords Two-phase flow, Front capturing, Discontinuous scalar, Consistent transport, Heat transfers

25 – Effect of drag force modelling on droplet evaporation

A. Carvalho Santos, A. Vié

To predict the evaporation of droplets on the simulation of realistic turbulent spray applications, it is still impossible today to describe the whole process by discretizing each droplet and its surrounding individually. Such simulations require the use of zero-dimensional models based on the resolution of internal variables such as the droplet velocities or temperature. Among these models, we focus on the most used one, the Abramzon-Sirignano (A-S) model [1], which is implemented in several CFD solvers and considered as a reference. This model is also classically used for comparing different solvers on the same benchmark case. Interestingly, when implementing the A-S model, there are still various degrees of freedom that can be adapted to improve the fidelity or to match the constraints of the host solver: transport and thermodynamic properties, vapor pressure law, film composition, convection characteristics, among others. In the present work, simulations are performed for single-component N-decane droplets evaporating into air for the same test conditions presented in the original publication. Particularly, we investigate the sensitivity of the evaporation prediction to the Drag modelling and the overall droplet's velocity evolution which is paramount to describe how the source terms will be distributed during a droplet lifespan.

Keywords Evaporation, Sensitivity, Sprays, Droplet

26 – Analytical-experimental comparison methodology for the evaporation of liquid fuel droplets in the vicinity of a flame

G. Parant, L. Zimmer, A. Renaud, F. Richecoeur

Keywords

27 – On the accurate prediction of preferential concentration in Large Eddy Simulation of particle-laden flow

R. Letournel, F. Laurent, M. Massot, A. Vié

Lagrangian simulations are today widely used for simulating aeronautical chambers. The way droplets are spatially distributed strongly affect the combustion, and accurate modelling strategies are required. The objective of the present contribution is to investigate how to correctly reproduce preferential concentration in Large Eddy Simulation (LES) of particle-laden flows. The question of whether a model is accurate or not raises two questions: (1) what is the reference measure and (2) which model to choose for capturing the decided measure. In this work, we address these two concerns. Firstly, we recall the link between the LES model for the particulate phase and its underlying kinetic equation, and we highlight that both capturing LES or DNS particulate fields are acceptable choices, up to the modeller. Secondly, we investigate the use of up-to-date stochastic models to reproduce segregation of the LES filtered field. We show that such models can capture such measure, while being not able to reproduce DNS statistics. Looking for a way to recover the DNS statistics, we highlight that stochastic models can fail in retrieving the tracer limit for non-inertial particles. We suggest a new strategy in the spirit of kinetic modelling of turbulence, which makes use of a random field with enforced divergence-free condition.

Keywords Particle dynamics, Turbulence, Stochastic modelling, Kinetic simulations

28 – Impact of H2 pilot injection on the acoustic response of a low-swirled flame

A. Aniello, D. Laera, L. Selle, T. Schuller, T. Poinsot

Keywords Hydrogen, Hybrid, Swirled flame, FTF

29 – Dependence of the thermoacoustic coupling on flame power for swirling spray flames at acoustic pressure antinodes

C. Patat, F. Baillot, J-B. Blaisot, E. Domingues

Lean combustion is one of the most promising technology to reduce polluting emissions in aeronautical engines. However, lean flames are more prone to develop thermoacoustic instabilities, which can lessen the combustion efficiency and even lead to structural damages. It is therefore of great interest to be aware of the mechanisms causing these instabilities. For this purpose, a linear array of three swirling spray flames stabilized by an original solution is placed in an acoustic cavity, which simulates an unfolded sector of an annular combustor. Acoustic forcing is performed in order to excite the 2T1L mode of the cavity. Recent experiments carried out at a pressure antinode have shown the strong dependence of the thermoacoustics coupling on the flame thermal power P. The present work focuses on the understanding of mechanisms responsible for this dependence. The flame mostly responds to acoustics in a central region, the size of which is practically unchanged with P. The interference between heat release rate and pressure fluctuations is destructive for the lowest P and constructive for the highest P. The spray quantification shows the enhanced spray evaporation that may facilitate the increase of the flame response to acoustics as P is increased.

Keywords

30 – Impact of injector characteristics on combustion instabilities in a swirl-spray combustor

P.R. Soundararajan, G. Vignat, D. Durox, A. Renaud, S. Candel

The influence of the injection system on combustion instabilities is investigated in this work by making use of systematic experiments with three swirlers having similar geometries, but different pressure losses and swirl numbers. The swirling injectors are tested in a laboratory-scale swirl-stabilized combustor called SICCA-spray that represents one segment of the MICCA-spray annular combustor. Measurements are performed with liquid heptane fuel, delivered as a hollow cone spray by a pressure atomizer. Self-sustained oscillations are examined for the different swirlers by varying the chamber length. Test results show differences in oscillation frequency and oscillation amplitude between the different swirlers. Acoustic damping estimated for each swirler under cold flow conditions reveal their distinct behavior. This, however, is not enough to explain the differences observed in the unstable behavior of the various systems.

Keywords Combustion instability, Injector dynamics, Spray-swirl combustor, Self-sustained instabilities, Damping

31 – Detection of precursors of Thermoacoustic Instability using Deep Learning Techniques

A. Cellier, C.J. Lapeyre, G. Oztarlik, T. Poinsot, T. Schuller, L. Selle

Finding precursors of thermoacoustic instability is a promising way to guarantee both safety and good performances of aerojet engines over its operability range. Based on Deep Learning techniques, this study proposes a tool able to detect and translate precursors of combustion instability by analyzing time samples of acoustic pressure, unsteady heat release rate and velocity. Proof is made on a laboratory scale model gas turbine combustor, consisting in a ducted swirled injector. The model obtains information on the proximity of unstable operating points on a bi-parameter bulk velocity/equivalence ratio plane. It gives promising results for new data-centered methods for the online diagnostic of critical events.

Keywords Thermoacoustic instability, Precursors detection, Deep learning, Convolutional recurrent neural networks

32 – Combustion stability – experimental investigation

A. Desclaux, P. Gajan, M. Orain, J. Garraud, V. Bodoc

This paper deals with the description of the experiments s performed at ONERA on the LACOM test bench (LOTAR setup) in order to investigate the combustion instabilities occurring at ambient pressures for two different fuels Jet A-1 and C1. They have been tested in order to account for their influence onto the thermoacoustic instability occurrence.

Keywords Thermoacoustic instabilies, Two port acoustic method

33 – Numerical simulations of turbulent flame stabilization by nanosecond repetitively pulsed discharges

Y. Bechane, V. Blanchard, N. Minesi, C. Laux, B. Fiorina

Nanosecond Repetitively Pulsed (NRP) discharges are an efficient way to promote turbulent flame stabilization in lean regimes. The energy released by NRP discharges leads first to an ultra-fast species dissociation and heating phenomena, followed by a slow heating process. A phenomenological plasma model has been developed to capture the influence of NRP discharges on the combustion process at low CPU cost. The model is here implemented in a LES flow solver to simulate the stabilization of a lean bluff-body turbulent premixed flame by NRP discharges. The results show that without discharge the flame is weak and confined to the recirculation zone above the bluff-body. The flame is close to the lean extinction limit and a large amount of fresh gases is unburnt. When NRP discharges are applied, the flame front propagates to high-speed flow regions and the flame is stabilized. The combustion when NRP discharges are applied is enhanced and the fuel is almost completely consumed. The chemical analysis performed on this case shows that a significant amount of OH is produced by the NRP discharge in the discharge zone. Due to its long lifespan the OH convected by the flow reaches the flame front where it increases the flame speed allowing the flame to propagate and stabilize in high-speed flow regions.

Keywords Plasma-assisted combustion, Nanosecond repetitively pulsed discharges, Turbulent premixed flame, LES

34 – Numerical study of a confined hydrogen-enriched premixed methane/air swirling flame using detailed chemistry

Q. Cazères, E. Riber, B. Cuénot

Among the strategies to reduce the pollutant emissions coming from fossil fuel, hydrogen enrichment is an interesting competitor. In particular, enriching natural gas with hydrogen shows many fields of application. The objective of this work is to study the impact of hydrogen enrichment on a turbulent methane-air flame for a lean equivalence ratio under a moderate enrichment level (60% in volume) and a high enrichment level (90% in volume) in the VALOGAZ academic burner operated at EM2C. Non-adiabatic Large Eddy Simulations (LES) are performed with Analytically Reduced Chemistry (ARC) coupled to DTFLES combustion model. Previously observed transition from V-shaped flame to M-shaped flame when increasing the enrichment level is well recovered. In addition, predictive capabilities of ARC on OH* fields and NOx predictions are presented.

Keywords LES, Methane-hydrogen/air flames, ARC, OH*, NOx

35 – Numerical study of flame shape stabilisation and transitions on the BIMER combustor

L.C.C. Mesquita, A. Vié, S. Ducruix

Lean Premixed Prevaporised (LPP) burners have been investigated as an efficient technology to achieve cleaner and more efficient combustion, leading to both less pollutant and greenhouse gas emissions. At the EM2C laboratory, the BIMER combustor has been operated for many years to shed light on the complex behavior of such burners. Complementary experimental and numerical studies have highlighted its complicated coupled physics, in particular the multiple flame archetypes that can be obtained, depending on ignition, operating conditions or fuel staging. In the present work, we summarize recent numerical results to highlight the different paths leading to each flame archetypes, demonstrating the complexity of staged burners, especially when fed with liquid fuel.

Keywords Multi-stage burner, Liquid fuel injection, Multi-stability, Bifurcations, Ignition

36 – Design through LES of a spinning flame combustor – Impact of operating conditions on flame stabilization and thermal load

P.W. Agostinelli, Y.H. Kwah, S. Richard, G. Exilard, J. Dawson, L. Gicquel, T. Poinsot

A great challenge in aeronautical combustors development lies in the capability to ensure ignition and resistance to Lean Blow Off (LBO) at all flight conditions. To overcome this difficulty, Safran Helicopter Engines (SHE) has recently developed and patented the revolutionary spinning combustion technology (SCT) for its next generation of combustors. This technology has indeed great flexibility when it comes to ignition and blow-off capabilities compared to classical lean combustors. To better understand the various physical mechanisms occurring in a SCT combustor, after a preliminary design thanks to LES, the NTNU atmospheric annular combustor has been modified following the SCT concept. During the design phase, to provide insights on the flame stabilization, ignition capability and thermal load, coupled LES / heat-transfer simulations of the test bench have been carried out at CERFACS. In the end, the experimental behavior of the new test rig turned out to be in agreement with the preliminary LES design. In that respect, the analysis on the thermal load clearly shows that is possible to check the combustor durability in advance and that LES is useful to design and set-up new test beds, being able to predict the effect of the operating conditions on the flame stabilization.

Keywords Spinning Combustion Technology, LES, Combustor design, Coupled simulation

37 – Detonation stability: New paradigms for the control of rotating detonation engines

H. Tofaili, G. Lodato, L. Vervisch, P. Clavin

Stability of gaseous detonations is revisited using both asymptotic analysis and high-order numerical simulations. The double limit of a small heat release and a ratio of specific heats close to unity is considered, and attention is focused on weakly unstable detonations in the Chapman-Jouguet regime. It is shown that the time-dependent velocity of the lead shock can be obtained as the eigenfunction of a hyperbolic problem reducing to a single hyperbolic equation for the flow. The solution is then expressed in the form of an integral equation for the shock velocity. The activation energy level at which the instability occurs and the frequency of its oscillations are predicted. These findings are validated against a set of direct numerical simulations of one-dimensional detonations in the same limit, performed using a high-order spectral difference scheme in which particular care is taken to ensure a high resolution of the flow with minimal numerical dissipation, while also suppressing postshock numerical aberrations. Values of detonation parameters at the instability threshold obtained from numerical simulations are systematically compared against their theoretical counterparts, confirming the validity of the proposed asymptotic theory. Then, multi-dimensional unstable detonation waves are simulated with the high-order accuracy numerical formalism.

Keywords Detonation, Stability, Asymptotic theory, High-order numerical simulation

38 – Assessment of soot radiation modelling to predict heat transfer in turbulent flames

K. Torres-Monclard, O. Gicquel, R. Vicquelin

In this work, radiative heat transfer is quantified in two turbulent configurations using high-fidelity models. The radiative heat transfer equation (RTE) is solved using a Monte-Carlo method, accounting for accurate spectral properties for gaseous and soot phases. Absorption, emission, and scattering by soot particles are considered, using the state-of-the-art Rayleigh Debye Gans for Fractal Aggregates theory (RDGFA). Unlike the classic Rayleigh model, soot particles are not considered as spheres but as complex aggregates. These models are applied first on the Sandia's atmospheric turbulent jet flame. Soot morphology and particle size distribution are significantly affecting the impact of scattering in the radiative power. Therefore, not only the soot volume fraction is required to assess soot radiative heat transfer contribution, but also the size distribution of particles. In a second time, the impact of soot volume fraction (fV) levels and pressure are assessed in the DLR FIRST non-premixed turbulent swirled flame at 3 bars. For fV values around 80 ppm, soot contribution has the same order of magnitude as the gaseous phase and represents 50% of the radiative power. At 30 bars, the contribution of gaseous phase on the radiative power increases. However, experimental levels of fV reached at 30 bars and the soot size distribution are required to draw definitive conclusions at high pressure.

Keywords Soot radiation, aggregates, Monte-Carlo, Scattering

39 – Modeling NOx formation in turbulent spray flames using virtual chemistry

C. Nguyen Van, R. Mercier, M. Cailler, B. Fiorina

This article presents Large Eddy Simulations of the CORIA Rouen Spray Burner (CRSB) with the FPI and the virtual chemistry methods. A focus is made on the prediction of NOx formation. Results are compared against experimental data. Virtual chemistry captures well the production of nitrogen oxydes unlike tabulated chemistry which overestimates it.

Keywords Virtual chemistry, LES, Two-phase, NO

40 – Modelling soot formation in LES of turbulent flames using virtual chemistry

H. Maldonado Colman, N. Darabiha, B. Fiorina

The objective of this work is to extend virtual chemistry approach to predict soot formation. Also a virtual technique is proposed to account for radiative heat transfer in sooting flames. The objective is to perform LES of turbulent sooting flames using virtual chemistry at a very low computational cost in a wide range of operating conditions. This is done by directly focusing on the soot volume fraction. Here, soot virtual sub-mechanism is obtained by targeting a database including 1-D freely-propagating premixed flames and 1-D non-premixed counterflow flames.

Keywords Soot, Combustion, Virtual chemistry, Virtual Radiation

41 – Reconsidering the good practice guidelines for LES of turbulent sooting flames

L. Tardelli, N. Darabiha, D. Veyante, B. Franzelli

Numerical simulations of soot production in an industrial system via an LES approach represent a great challenge. In addition to the fact that soot production in turbulent flames is governed by complex multi-scale coupled physical processes, it is shown in this paper that the good practice guidelines for LES of turbulent flames should be reconsidered. By looking at LES of an aero-engine model combustor, the sources of unsteadiness for soot production are discussed and soot intermittent nature is characterized. Time-averaged gaseous and solid fields are considered to illustrate the difficulties in getting a statistical description of soot quantities and in validating new soot models.

Keywords Soot, LES modeling, Intermittency

42 – Liquid phase envelope estimation in two-phase combustion

A. Ivaldi, L. Zimmer

This article presents a work in progress method for liquid phase envelope estimation in two-phase combustion. This method is based on the determination of the droplets' positions and their typical nearest distance. Those quantities are used to estimate the region where droplets have fully evaporated. This paper presents the different processing and post-processing steps to obtain an estimation of those regions. Typical statistics in laminar cases are presented and further improvements as well as experimental validation of the method are presented.

Keywords Combustion, Liquid phase distribution, Boundary, Two-phase flow

43 – Detailed analysis of a swirl-stabilized kerosene spray flame under relevant aero-engine conditions with Phase Doppler Anemometry experiments and LES simulations

C. Brunet, P. Domingo-Alvarez, G. Godard, M. Caceres, F. Frindt, S. Richard, G. Cabot, V. Moureau, F. Grisch

Droplet size measurement were performed in the HERON high-pressure combustion facility on a Lean Premixed aeronautical injector, by means of Phase Doppler Anemometry. The results bring information on droplet size, location and velocity in representative high-pressure operating conditions. Measurements are then compared with data issued from a parametrical LES study that has been carried out to simulate the flame properties. The impact of the initial conditions of the droplet size distributions at the outlet of the injector in LES on the agreement that could exist between the experiment and the simulation was highlighted and only a given inlet droplet size distribution allowed to find a very convincing agreement between the simulation and the experiment. Moreover, this result reinforces the conclusions obtained in a previous study devoted to compare the experimental flame structure, fuel vapor and velocity distributions with the numerical simulations carried out under the same conditions as those of this study.

Keywords Phase Doppler Anemometry, LES, Two-phase flow, Lean premixed, High-pressure turbulent combustion, Kerosene

44 – Numerical study of swirled multicomponent spray flames in gas turbine combustors

V. Shastry, E. Riber, B. Cuénot, L. Gicquel, L. Voivenel

Large Eddy Simulations of the realistic liquid fueled gas turbine combustor LOTAR operated at ONERA Fauga are performed. Two fuel descriptions are utilized to denote conventional JetA-1 and an alternative jet fuel AtJ (alcohol to jet), each modeled by a 3-component surrogate. Analytically Reduced Chemistry and multicomponent spray evaporation models coupled to DTFLES turbulent combustion model are employed to understand the complex processes involved in turbulent spray flames in large scale configurations. Focus is made on understanding the staged vaporization and consumption of the fuel components. The simulated cases show the role of volatile components in stabilizing the flame base close to the injector and the possibility of heavier less volatile components to exit the domain as unburnt hydrocarbons.

Keywords Multicomponent fuel, Spray flame, Gas turbine, Reduced chemistry, Preferential evaporation

45 – Numerical Dual Swirl Spray Stabilized Burner: Comparison of conventional and alternative fuels

J. Wirtz, E. Riber, B. Cuenot

A suggested solution for reducing global emissions in the short run for the aeronautical field is the use of alternative drop-in fuels in combustors. For this purpose, the Stabilized Spray Burner (SSB) developed by the DLR was tested on a various range of fuels and validated with many different measurements. The numerical Large-Eddy Simulation (LES) of one conventional Jet-A1 fuel and an alternative At-J fuel were conducted and results were compared to the experiments on one operating condition. Chamber wall temperatures were imposed from phosphor thermography measurements and Analytically Reduced Chemistry (ARC) was used to describe accurately the kinetics. Liquid fuels were modelled with a two phase flow multi-component modelling. Results show that the computation is able to reproduce the experimental difference between the two fuels, although these are minor.

Keywords Multicomponent turbulent spray flame, LES, ARC

46 – Semi–technical aero-engine combustors – a glimpse on combustion processes given by in-situ optical techniques

C. Irimiea, A. Vincent, J.P. Dufitumukiza, K.P. Geigle, A. Ristori, Z. Yin, J. Yon, F. Guichard, N. Fdida, P. Cherubini, D. Carru, D. Gaffie, X. Mercier, A.K. Mohamed

The high-pressure combustion of kerosene is studied on a semi-technical aeronautic combustor equipped with a single-swirled injector using laser optical techniques. These experiments answer to nowadays milestones encountered in the aeronautic sector relating to energy consumption and emissions reduction. With a focus on these objectives, our study presents a close look into the complex physicochemical processes taking place in severe combustion conditions representative of airplane engine landing-take-off (LTO) operation modes. The primary energy source (combustion) is studied with diagnostics as laser induced fluorescence/incandescence, scattering and particle image velocimetry. These techniques bring information about the precursors of soot particles, namely polycyclic aromatic hydrocarbons, soot particles, fuel spray characteristics, and velocity fields. Combined results are used to understand and identify the main principles governing the behavior of combustion, production of particulate and gas pollutants, as well as their radiative effects. The feasibility of selected optical techniques in these specific environments is discussed as well.

Keywords Semi-technical combustor, Aeronautics, Optical techniques, Laser induced fluorescence, Laser induced incandescence, Scattering, Particle image velocimetry

47 – System design and preliminary evaluation of a High-Altitude Relight Test Facility – HARTUR

M-E. Clavel, A. Vandel, B. Quevreux, F. Colin, A. Cayre, F. Grisch, G. Cabot, B. Renou

In order to develop joint research projects between academic and industrial partners into improving high-altitude lean blow-out (LBO) and relight performance of aeronautical injection systems, the high altitude relight test facility HARTUR was designed and manufactured at the CORIA laboratory (France). This paper details an overview of the facility, the methodology used to report the combustion efficiency and its abilities to facilitate optically-accessible combustion and spray testing for aero-engine combustor hardware at simulated high-altitude conditions.

Keywords High-altitude relight, Combustion efficiency, Aeronautical injection system test facility

48 – Investigating the effect of the injector design and of the operating conditions on soot production in a rich premixed model scale combustor

M. Roussillo, P. Scouflaire, N. Darabiha, D. Veynante, S. Candel, B. Franzelli

Investigations of soot formation in turbulent flames are of considerable fundamental importance and practical interest. The present investigation is carried out in a model scale swirled combustor developed at the EM2C laboratory to investigate soot production under premixed rich conditions. This device allows studies over a limited range of parameters where the production of soot is strong enough to be measurable. The influence of the injector geometry on soot production is investigated in this work to assess whether a reduction of this pollutant emission can be achieved by slightly modifying the injector design. It is found that a small modification of the geometry can notably influence the flame stabilization mechanism inducing a change in the flame structure and, consequently, reducing the production of soot for the same operating point. A reference flame is then characterized both in terms of soot volume fraction measured using the LII technique and of PAH presence obtained with PLIF-PAH. Finally, the evolution of soot production with equivalence ratio, flame power and wall temperature is characterized.

Keywords Soot, Optical diagnostics, Rich premixed gas turbine model combustor

49 – Challenges and opportunities for laser diagnostics to make high-pressure aircraft engines clean and efficient

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A Lean Premixed injection system designed for helicopter engines was studied using the Particle Image Velocimetry (PIV), Phase Doppler Anemometry (PDA) and Planar laser-induced fluorescence (PLIF) of OH, kerosene vapor and NO. These diagnostics were applied individually or in combination for custom-made solutions for accessing to detailed information on the spatial distributions of velocity, droplets size, OH, kerosene and NO molar fractions in pressure conditions ranging from 0.4 to 1.8 MPa. Complementary large-Eddy simulations were performed using the PCM-FPI tabulated chemistry approach in conjunction with a polydisperse Euler-Lagrangian approach. Comparison of simulations with experiments highlighted the importance of the size distribution of the droplets injected into the flow on the mutual predictions of the aerodynamic field, the structure of the flame and its anchorage point as well as the spatial distribution of the fuel and OH species.

Keywords Laser diagnostics, Gas turbine combustion, High-pressure kerosene/air swirled flames, LES

50 – Multi-fluid models for two-phase and transcritical flows – Application to rocket engine configurations with the AVBP solver

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In various industrial combustion devices, such as liquid rocket engines or Diesel engines, the operating point varies over a wide range of pressure. These pressure variations can lead to a change of thermodynamic regime, switching from two-phase injection to transcritical injection. This change may modify the topology of the flow and the mixing, thereby impacting the flame dynamics. In the present contribution, a framework that is able to simulate compressible flows under both subcritical and supercritical states within the same solver is presented. This is achieved using a multifluid approach coupled with a cubic equation of state (EoS). Liquid/vapor equilibrium is computed within the binodal region to ensure the convexity of the EoS. Examples of coaxial flame simulations are provided, showing good agreements with experimental visualizations.

Keywords Two-phase flow, Supercritical flow, Non-ideal thermodynamics, LES

51 – Massively Parallel Large-Eddy Simulations of Primary Atomization on Adaptive Unstructured Meshes – Interface capturing algorithm and multiscale coupling perspectives

R. Janodet, C. Guillamon, V. Moureau, R. Mercier, G. Lartigue, P. Bénard, T. Ménard, A. Berlemont

This work presents a robust and efficient procedure to simulate turbulent incompressible interfacial liquid-gas flows on massively-distributed dynamically-adapted unstructured meshes in complex geometries. The present strategy extends the Accurate Conservative Level Set (ACLS) / Ghost-Fluid interface-capturing framework of Desjardins et al. (2008) and Chiodi et al. (2017) to unstructured grids, and combines it with an isotropic Adaptive Mesh Refinement (AMR) technique for triangular and tetrahedral meshes. The computational cost of the ACLS method is reduced by using a narrow-band to compute level set variables only in a restricted region around the liquid-gas interface. In the ACLS method, the interface is defined as the isosurface of a hyperbolic tangent function, which is transported by the fluid, and then reshaped using a reinitialization equation. Several forms of this reinitialization exist: the original form proposed by Desjardins et al. involves numerical estimation of the hyperbolic tangent gradient, which is susceptible to induce spurious deformation of the interface, especially on unstructured meshes. Chiodi et al. proposed a new form, which much better preserves the interface shape. The implementation of this new equation on unstructured grids is not straightforward and thus requires special attention. In this work, a robust implementation of this new form for unstructured meshes is proposed and implemented in the YALES2 low-Mach flow solver. In order to compute interface normals and curvature, the signed- distance function is reconstructed in parallel at nodes in the narrow band using the second-order Geometric-Projection Marker Method (GPMM) of Janodet et al. (2019). Spatial convergence and physical meaning of the overall procedure are demonstrated through classical interface transport tests and canonical two-phase flow simulations, respectively. Then, to point out the large computational gain using dynamic mesh refinement, two Large-Eddy Simulations (LES) of atomizing liquid jets are presented, namely a water jet in quiescent air from a low-pressure compound nozzle and a high-pressure kerosene jet in air crossflow. Both simulations are validated against experiments, demonstrating the potential of the overall procedure to accurately and efficiently handle primary atomization with large-density ratios using unstructured grids. Eventually, the ongoing developments and perspectives of a multiscale coupling of the Eulerian interface-capturing ACLS/AMR technique with a Lagrangian Point-Particle (LPP) modeling of the small droplets are discussed.

Keywords Multiphase flows, Atomization, Unstructured grids, Incompressible flow LES, Conservative level set, Adaptive mesh refinement, Multiscale modeling

52 – Surface density evolution in Direct Numerical Simulations of periodical liquid sheet assisted atomization

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Assisted atomization is a key mechanism in spray generation. While a general consensus is met on which physical phenomena are involved, prediction of the outcome in terms of spray characteristics is still challenging. Numerical simulations struggle to capture all the spatial scales involved in this process, so that sub-grid topology models have become of particular interest. Interfacial density is an interesting quantity used in the modelling of those small scales. However, very few information on its actual behavior are available. This paper proposes a study of the interfacial density evolution in a simplified periodical liquid sheet assisted atomization test case. In particular, the influence of the gas velocity on the liquid topology and therefore to the interfacial density is investigated.

Keywords Atomization, DNS, Interfacial density

53 – A novel methodology to simulate fuel injection in multipoint systems – Application to liquid jet in crossflow

C. Guillamon, R. Janodet, L. Voivenel, R. Mercier, V. Moureau

A novel strategy to build lagrangian injectors for spray injection in disperse phase computations is proposed. These injectors can reproduce the spray state (injection location, flow rates, droplets sizes and velocities) extracted from resolved atomization simulations performed with a sharp-interface approach (ACLS/GFM) [1]. The application case is a high-pressure, non-reactive kerosene jet in crossflow (JICF) atomizer configuration [2]. Resolved simulations of atomization for this configuration are performed and validated with the experimental correlation for the jet trajectory. The models learn the spray from these simulations and process it to create spatially distributed injectors for lagrangian droplets injection. Finally, the models are applied to the same configuration and compared to experimental data.

Keywords Multi-phase flows, Atomization, Lagrangian simulations, Jet-in crossflow