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Editorial

Combustion, spray and flow dynamics for aerospace propulsion

Combustion provides most of the primary energy worldwide by effectively converting a variety of fuels (natural gas, oil, coal, wood, solid waste, ...) in a broad range of systems encompassing domestic burners, automotive engines, gas turbines, aero-engines, numerous industrial processes and large scale thermal power plants. There are important technological challenges in many of these processes. One always wishes to (1) enhance performance and efficiency, (2) augment reliability, stability, range of operation, (3) reduce pollutant emissions, (4) avoid instabilities and diminish radiated noise. These objectives are important for aerospace propulsion but they are also prevalent in many other applications. These technological objectives raise a variety of scientific issues implying a broad range of disciplines including fluid dynamics, chemistry, thermodynamics, transport phenomena and heat transfer. The problems are difficult because they feature a wide range of time and spatial scales. To complicate matters, combustion takes place in geometrically complex devices and in many cases under high pressure. Such intricate technological issues can only be tackled through an intense collaboration between engineers and scientists, between fundamental research and industrial applications. This is the goal of INCA, an initiative on advanced combustion which gathers scientists from CNRS laboratories, ONERA (the French aerospace research laboratory) and SAFRAN engineers belonging to the aero- and helicopter engine divisions (Snecma and Turbomeca) and to the solid and liquid rocket engines (Herakles and Snecma, liquid rocket engine division). INCA shares common roadmaps targeted at improving combustion in these areas of application.

On the industrial level, one expects progress from novel simulation models and tools capable to cope with the complexity of modern systems, providing reliable predictions and allowing design optimization. Research laboratories are actively engaged in developing these models and tools, by systematically building the knowledge basis, exploring novel numerical schemes, exploiting high performance computing capacities and performing detailed experiments. Model-scale experiments are specifically important because they provide an essential insight on controlling physical mechanisms and yield data required for validation of computational software.

Research carried out in the INCA framework is coordinated at the national level by working groups involving all partners. A workshop on combustion for aerospace propulsion is organized on a regular basis to discuss ongoing projects, measure progress and underline new challenges. The present issue of Comptes Rendus Mecanique contains a selection of papers prepared for the last workshop. Investigations cover a range of topics in spray, flow dynamics and combustion for aerospace propulsion. The format of the present issue is essentially that adopted in 2009 for the previous volume [1].

Contributions are arranged in three disciplinary fields, but it is worth underlining that research often belongs to more than a single group and that there are bridges and interfaces between the various topics.

1. Multi-phase flows and combustion

Injection issues are specifically important in aero-engines and liquid rocket motors. The efficiency and stability of the engines are directly linked to injection dynamics. This aspect is investigated experimentally by Providakis et al. who consider the multipoint-injection technology. This promising technique requires a detailed analysis of effects of the staging factor on the stabilization process. This is based on laser induced fluorescence and high speed velocity field measurements.

Zuzio et al. report recent developments in numerical modeling for the simultaneous computation of primary and secondary atomization. Mechanisms of these two phenomena are physically different and the calculation has to deal with large density ratios, surface tension and polydisperse droplet sprays. Atomization is investigated by Marty et al. and, Matas and Cartellier who base their analysis on the stability characteristics of liquid mixing layers and jets. The calculation of polydisperse sprays resulting from primary atomization may be carried out with different numerical strategies. Doisneau et al. investigate the unsteady motion of alumina particles created in solid propellant rockets taking into account the coalescence and coupling between the disperse phase and the carrier gas. A high-order moment method is developed and used by Vié et al. to compute polydisperse sprays in the Eulerian framework. Evaporation of droplets in these sprays is investigated numerically by Bodoc et al. and experimentally by Dunand et al. These studies mainly deal with the coupling between droplets and heat transfer, either by convection in the flow or interactions with the walls. An adaptation of the *Phase Doppler*

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Interferometry is described by Desnous et al. and is used by these authors to measure velocities and size distributions of a dense spray formed by a sudden depressurization.

2. Combustion dynamics and noise

Combustion dynamics covers a wide range of problems giving rise to unwanted consequences. When oscillations occur they degrade the engine performance, reduce life duration and the engine integrity. In advanced systems, the coupling between acoustics and combustion gives rise to unacceptable levels of pressure oscillations which need to be reduced. These dynamical phenomena affect aircraft combustors, liquid rocket thrust chambers and solid propellant engines. Coupling between transverse acoustic modes and cryogenic jet flames is investigated by Méry et al. in a model scale unit equipped with five coaxial injectors fed with LOx and methane reactants. The flames are submitted to transverse acoustic perturbations through external harmonic modulations. A novel actuator is used to reach high amplitude modulations reproducing oscillation levels observed in full scale engines undergoing high frequency instability. More fundamentally, Lespinasse et al. report experiments on the effect of transverse acoustic modulations on laminar V-shaped flames. Such transverse acoustic perturbations appear in unstable annular combustors typical of aircraft engines or industrial gas turbines. Core noise from combustion, originating directly from the flame surface area fluctuations, or indirectly from the entropy acceleration at the chamber exhaust, has become an important issue and needs to be understood and controlled. Direct noise is studied by Hernandez et al. with the LES code AVBP while Duran et al. develop a strategy to compute combustion noise by combining Large Eddy Simulations (LES) and analytical tools. This enables the simultaneous computation of acoustic sources from direct and indirect origins. An issue of interest is also to understand how the chamber acoustics interacts with the other elements of the system. Richecoeur et al. show the influence of the feeding lines acoustic impedance characteristics on the eigenmodes of the chamber with a low-order model based on acoustic networks. Giovangigli and Rahman propose a numerical analysis of the propagation of acoustic waves near solid propellant boundaries. To damp acoustic waves in combustors, Scarpato et al. investigate biased flow through perforated plates backed by a cavity. They analyze the absorption properties of such systems and show how to optimize the design by taking into account the amplitude excursion range and the frequency domain characterizing the incident waves.

One objective of research in combustion dynamics is to be able to predict limit cycle pressure oscillations. For this, Cuquel et al. investigate the nonlinear frequency response of laminar flames in order to predict the flame response while Boudy et al. demonstrate that the *Flame Describing Function* (FDF) can be used to analyze a variety of limit cycles and to identify regions where the oscillation is sustained by two modes and gives rise to fluctuations in amplitude.

Combining the numerical and experimental approaches is clearly suitable if one wishes to gain an understanding of transient phenomena like ignition. Cardin et al. report experimental observations of the ignition of a lean turbulent flow by laser-induced sparks and measure the minimum energy required to ignite depending on the location. This can be used to improve the ignition performance. Linassier et al. describe calculated ignition sequences both with RANS and LES strategies.

3. Numerical tools

The spectacular increase in computational power, together with the expansion of accessible high performance resources, support the development of numerical strategies to improve the understanding of fundamental mechanisms and the predictive capabilities of computational codes. Numerical codes have reached a good degree of maturity and can be used to investigate complex geometries. Bourgouin et al. demonstrate that a tiny change in blade geometry can strongly modify the dynamics of a swirling flow of the type used to stabilize combustion in aero-engines. Garby et al. use LES to investigate combustion instabilities in combustors featuring a variable length.

Considerable efforts are focussed on improving the representation of chemistry and the coupling between combustion and radiative heat transfer. Lecocq et al. and Hernandez et al. respectively compute, soot formation in a complex geometry, and in a more fundamental counterflow configuration. This requires the coupling of different computational codes to simultaneously deal with the local combustion process and the long range radiative effects. Chemistry has also a strong impact when it comes to deal with partially premixed combustion. Problems emerge from the coexistence of premixed and non-premixed reactive layers. Franzelli et al. deal with this issue in a complex geometry. Similarly, Auzillon et al. perform the simulation of a helicopter combustion chamber using LES in combination with a tabulated chemistry description of the chemical reactions.

Two contributions respectively report an original strategy and detailed comparisons of numerical tools for combustion simulations. Rochoux et al. apply data assimilation to combustion, exploiting measurements to increase the precision of numerical simulations. Barré et al. compare low-Mach number and compressible numerical codes to compute combustion in a lab scale swirl burner, with a special emphasis on head losses and CPU costs of the two approaches.

This special issue covers a wide range of problems encountered in combustion, from the most fundamental investigation to the most ready-to-use tools. It witnesses the positive dynamics of the initiative on advanced combustion (INCA) and illustrates the strong support of industry and research institutions to the considerable challenges facing energy and propulsion.

References

[1] Sébastien Candel, Franck Richecoeur, Foreword, C. R. Mecanique 337 (6–7) (2009) 315–317, Combustion for aerospace propulsion.

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