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Combustion for aerospace propulsion

Foreword

The widespread use of combustion in energy conversion, industrial processes, automotive transport and propulsion has had an important impact on the environment. This has introduced many challenges for a cleaner and more efficient use of fossil fuel resources. In this context, advances in combustion science provide the basis for novel engineering analysis tools and for new concepts and novel systems and components. Research in this field is exemplified in this special issue which considers combustion applications to aeronautical and space propulsion. As an interdisciplinary subject combustion integrates complexities of fluid dynamics, chemical kinetics, multispecies thermodynamics and transport phenomena. Combustion kinetics involves a myriad of species and elementary reactions which need to be considered in detailed analysis of the process. Problems are mathematically stiff due to the exponential nature of the Arrhenius law governing the rates of reaction and the high activation energies involved. In most situations combustion is characterized by a wide range of scales with thin reactive layers and much larger scales corresponding to the system geometry. The existence of multiple scales is characteristic of most practical applications where combustion proceeds in a turbulent flow. Combustion also features critical conditions defining ignition and extinction giving rise to multiple solutions and S-shaped response curves. Its dynamics is highly nonlinear including a vast number of intrinsic instabilities. In many circumstances one of the reactants is injected as a liquid in the form of a spray of droplets which vaporize in a turbulent stream and react in gaseous form. This two-phase nature of injected flows introduces further technical and scientific challenges. Other difficulties are encountered when combustion takes place at very high pressure, above the critical value. This is the case in high performance devices like liquid rocket engines where liquid oxygen is injected at a low temperature but at a pressure exceeding its critical value. The combustion process is also coupled to a variety of other phenomena. Coupling with acoustic waves give rise to a range of instabilities which under resonant conditions may induce large amplitude oscillations augmenting structural vibrations, enhancing heat fluxes to the chamber walls and eventually leading to damage and in extreme case to a failure of the system. Finally, the coupling with radiative transfer needs to be considered if one wishes to estimate heat fluxes to the chamber walls and calculate the effects of radiation on the reaction zone.

This special issue gathers a set of articles dealing with many of the previous problems and mainly focusing on topics of importance in propulsion and energy applications including aero-engines, gas turbines, ramjets or liquid rocket engines. These contributions correspond to a joint effort designated as INCA (Initiative on Advanced Combustion) gathering CNRS laboratories, CERFACS, the French Aerospace lab ONERA and the Safran group. This research network was formed to advance knowledge and develop novel solutions for propulsion applications.

Articles in this issue

The twenty three articles collected in this issue are grouped around four main scientific issues. The contents are briefly reviewed in what follows. This is admittedly only a limited description of the many projects developed in the INCA framework. These articles were selected among fifty contributions presented at the second INCA workshop held in October 23–24, 2008 at CORIA in Rouen.

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Combustion modeling

The first group of six papers is concerned with combustion modeling problems. Most of these papers explore the application of Large Eddy Simulation (LES) methods to combustion. The first two articles deal with the modeling of chemical kinetics and the coupling with turbulent combustion models for LES. Albouze et al. consider the coupling with a tabulated chemistry. Chemistry is either reduced or complete and turbulence is modeled with a presumed PDF approach or with the dynamically thickened flame model. Simulations are compared with experimental data. Vicquelin et al. present a new model exploiting tabulated chemistry for LES and focus on the fundamental properties of premixed flames. The model is developed to conserve the correct burning velocity and chemical structure for unresolved turbulent wrinkles. A 3D numerical simulation of a turbulent flame is performed with this model. In their paper, Sainte-Rose et al. model combustion with the simultaneous use of averaged equations (RANS) and Large Eddy Simulations (LES). RANS is used close to the wall to effectively describe the wall/flow interaction while LES is used in the reaction region where unsteady and compressible flows have to be correctly simulated. Results of this detached eddy simulation (DES) are compared with experimental data in a backward facing step combustor geometry. Large Eddy Simulations of a ramjet are performed by Roux et al. with two different numerical solvers with different combustion models and integration methods. The stable operating point of a laboratory scale ramjet is calculated by the two codes and the average results are similar but there are significant differences in the dynamics. Izard and Mura consider the modeling and simulation of a non-premixed GH_2/GO_2 flame stabilized in a supersonic stream. The combustion model relies on a Lagrangian description. This simulation allows to describe different regimes of combustion in the high Mach number range. Finally, Orain et al. discuss experimental Planar Laser Induced Fluorescence (PLIF) images of kerosene combustion in a multipoint injection configuration. PLIF of vaporized kerosene and OH radicals provide basic information on the spatial distribution of kerosene correlated to the flame front location for different injection configurations, equivalence ratios and air temperatures.

Acoustic coupling

The second group of five articles deals with various aspects of acoustic coupling in combustion systems and its consequences in terms of instabilities. Wolf et al. perform LES of two industrial configurations with small geometrical differences but with different dynamics. The study shows that LES can be used to correctly predict the dynamical behavior of a complex industrial combustor. An experimental study is carried out by Palies et al. to characterize the response of premixed swirling flames to incident acoustic perturbations. The response is characterized by the unsteady heat release of the flame which is measured with respect to the mean heat release. A generalized transfer function (a flame describing function) is used to describe the nonlinear behavior of the system as a function of the relative velocity modulation amplitude. Combustion oscillations appear in practical systems when the rate of amplification associated with combustion exceeds the rate of damping. It is then important to study this parameter, a problem considered by Gullaud et al. The study focuses on the multiperforated plates used for cooling in practical combustors which modify the acoustic characteristics of the system and influence resonance conditions. This is studied numerically using a multidimensional Helmholtz solver. Leyko et al. envisage the problem of combustion noise and focus their numerical and analytical study on the generation of indirect noise when entropy fluctuations associated with the combustion process are accelerated in a nozzle, a situation which idealizes that found in aero-engines where the hot stream exhausted by the combustor passes through the inlet guide vanes of the high pressure turbine. Many recent studies indicate that this may be an important source of noise. An excellent comparison with experimental data is achieved. The last paper of this section by Mery et al. presents experimental and numerical simulations of a high amplitude pressure wave generator used to modulate cryogenic flames at elevated pressure. The system is specifically designed to operate at high pressure and to generate transverse modulations. The sound level in the chamber is sufficiently high to allow detailed measurements of the acoustic velocity distribution. The data are also compared with calculations of the sound field using a Helmholtz solver.

Spray and injection dynamics

A set of nine papers discusses various items related to injection dynamics. De Chaisemartin et al. develop simulations of a polydisperse evaporating spray in an unsteady gaseous flow. The Eulerian multi-fluid model in combination with novel numerical schemes are used to accurately simulate droplet trajectory crossing. Results of the multi-fluid Eulerian simulation are in excellent agreement with calculations using the more standard Lagrangian method. Laurent et al. focus on the simulation of multi-component droplets vaporization. Droplet composition is described with a presumed PDF and different test cases are analyzed to validate this approach. Senoner et al. use two numerical codes to simulate the evaporating two-phase flow encountered in an experimental burner. Comparisons are carried out between the two codes. Numerical simulations suitably retrieve experimental data. The problem considered by Lhuissier and Vuillermaux concerns the transition between a uniform liquid sheet and the dispersed droplets observed in the injection process of liquid fuel. An analogy with planar soap films is developed to describe the structure and evolution of the film. Primary atomization is investigated by Fernandez et al. in the case of a planar sheet of water at 0.6 MPa. Different momentum flux ratios are analyzed and the main features of the space time evolution of the sheet are collected from Oscillometry by Laser Intensity Reflexion (OLIR) and Laser Doppler Velocity (LDV). Boukra et al. analyze the possible enhancement of atomization by Faraday instabilities triggered by an electric field. Another use of an applied field is considered by Grisch et al. who show experimentally the effect of non-equilibrium pulsed nano-second discharges on ignition and flammability limits of a methane/air premixed flame. The reaction zone is characterized by electron density measurements, CARS thermometry and by planar OH and CH laser induced fluorescence.

The last two papers in this group deal with flame simulations under transcritical conditions (pressure exceeds the critical value while the injection temperature is below the critical value). Pons et al. calculate the structure of counterflow diffusion flames under transcritical conditions. The simulations are carried out in a multidimensional geometry to validate a transcritical version of a standard flow solver. Results are provided for flames fed by one or two reactants in a transcritical state. Schmitt et al. discuss multi-dimensional LES of transcritical gaseous hydrogen/liquid oxygen flames. The oxygen is injected at low temperature and features a high density. Results are compared with experimental data recorded under the same injection conditions.

Heat transfer

The last group of articles is concerned with heat transfer problems. Zhang et al. focus on the coupling between combustion and radiation. Combustion is represented with Large Eddy Simulations while radiative transfer is calculated with a Monte-Carlo method. Results obtained in a 3D configuration indicate that the dynamics of the flame is modified by radiation. Duchaine et al. deal with the coupling of unsteady combustion and heat transfer at the wall. Two codes are used to simulate the temperature evolution of the wall as it is submitted to the unsteady release of heat from combustion. The method is applied to a cooled turbine blade and results are compared with experimental data. Michel et al. compare the cooling efficiency measured experimentally with RANS simulations. The configuration features a multiperforated wall used to cool down a main hot jet and different injection models are tested numerically.

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