Laser-induced ignition in a methane/oxygen rocket combustor

D. Passiatore*,, M. Di Renzo*,**, D. Rossinelli**, J. Wang**, G. Iaccarino****
dodipass@stanford.edu
*Department of Engineering for Innovation, University of Salento, Italy
**Center for Turbulence Research, Stanford University, USA

Abstract

This study investigates laser-induced ignition in a model-rocket combustor through computational simulations. The focus is on characterizing successful and unsuccessful ignition scenarios in this extremely stochastic configuration and elucidating the underlying physical mechanisms. Large eddy simulations (LESs) are utilized to explore laser-based forced ignition in a turbulent fresh methane-oxygen mixture, with attention given to the intricate interplay of factors such as initial condition variability and turbulent flow field. Perturbations in laser parameters and initial flow conditions reproduce the stochastic behavior of realistic applications, revealing critical insights into ignition location relative to the fuel-oxidizer mixture. Results will highlight the interplay between hydrodynamic ejections from the laser spark and jet entrainment.

Introduction

In rocket combustors, laser ignition is gaining consideration owing to its mechanical simplicity, controllability, elevated kernel deposition energy, and more efficient lean ignition [1]. Nevertheless, throughout forced ignition, stochasticity arises from the interplay of the ignition kernel with the turbulent fuel-air mixture, along with variations in kernel deposition and location. Characterizing the statistical behavior of stochastic ignition phenomena becomes pivotal for the secure and dependable deployment of these ignition systems. This motivates the investigation of the present work, focusing on laser-forced ignition in a model-rocket combustor [2,3]. The goal of the study is to expose the extreme sensitivity of the process and to use computational tools to gain insights into the physical mechanism at play. To this purpose, large eddy simulations (LESs) are performed to investigate the behavior of laser-based forced ignition in gaseous methane (CH4)/molecular oxygen (O2) subscale rocket combustors. Three cases are carried out, one in which the laser is fired in the fuel/oxidizer jet and two in which the laser is fired just outside the fresh reactants; perturbation of some controlling parameters for these last two simulations will lead to different ignition outcomes.

Investigated test case

A sketch of the considered computational geometry is shown in Figure 1. The combustor is discretized by a curvilinear mesh with a total of 220 million mesh points. Gaseous pure methane (coflow) and oxygen (core center) are injected through the shear coaxial injector and the two streams are separated by an annular wall. The boundary conditions used in the simulations are the Navier-Stokes characteristic boundary conditions (NSCBC), used both at the injector and at the nozzle the inlet velocity profile is set such that the total mass flow rates of oxygen (6.44 g/s) and methane (1.66 g/s) are constant in time. All walls of the combustor are modeled as a no-slip isothermal wall at 300K.

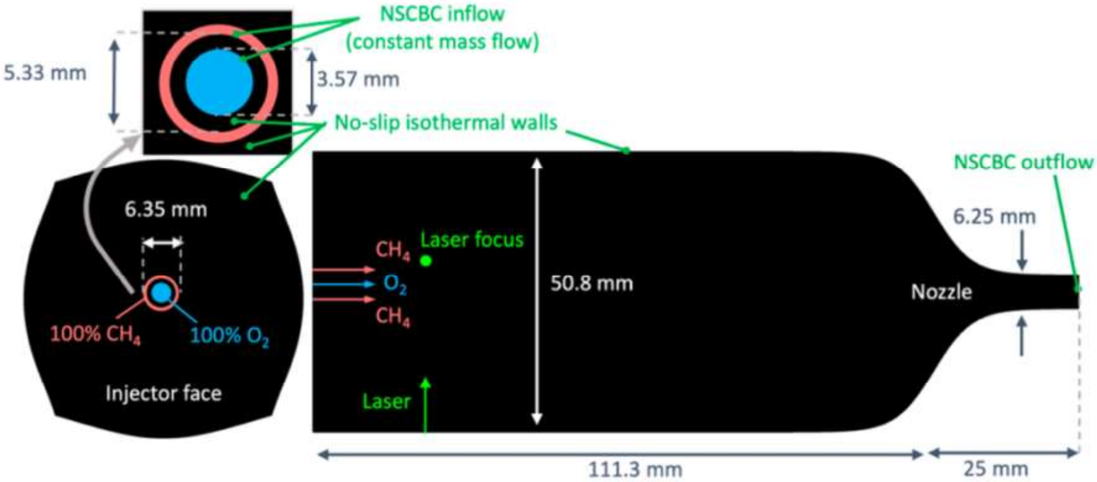

Figure 1. Schematic of the geometry and boundary conditions.

The gas in the chamber is initialized with 100% oxygen at 125 kPa and 300K to approximate the pressure composition after a long priming sequence. To analyze the relatively short dynamics of laser-induced ignition, we target a simulation time window of approximately 11ms, beginning 10ms before laser deployment.

As discussed earlier, the ignition process is stochastic and sensitive to various sources of uncertainty. The inert simulation (i.e., pre-deployment stage) is performed only once, with a two-species inert mixture of methane and oxygen. This stage is necessary to let the turbulent flow field develop and to initiate a good level of premixing of the reactants. Stochasticity of turbulence is reproduced by selecting different laser deposition instants by the end of this pre-ignition phase. The second stage of the simulation is characterized by the deployment phase. The kernel used in [4], and described hereafter, is placed at a specific focal location in the combustor. Different deployment phases (i.e., different simulations) are characterized, not only by the different laser deposition instants but also by perturbations in the deposited energy and geometrical parameters of the kernel (R1 and R2). Reasonable values of both the deposited energy and radii aspect ratio R1/R2 are informed by literature [3,5,6]. A set of these perturbed parameters is selected for each of the following simulations.

Methodology

The LESs described below are conducted using the Hypersonic Task-based Research (HTR) solver described in [7]. Details on the physical models, underlying assumptions, and numerical methods utilized can be found in [2,8,9].

The chemical mechanism considered to compute the reaction rate models combustion of methane, evaluated with a 35-step, 12-species neutral chemical-kinetic reduced mechanism FFCMy-12 extended to near-atmospheric pressures, as previously done in [4]. The laser-induced deposition of thermal energy is modeled through a source term in the total energy conservation, according to [4]. This source term is a function of a target energy value deposited by the laser in the gas, windowed in time by a Gaussian function. An ovoid shape of the kernel is imposed, controlled by the radii of two hemispherical lobes, R1 and R2, connected by a truncated cone. This geometry can faithfully capture laser-induced hydrodynamic effects [5,6].

Results preview

Case 1

For the test case analyzed in this section, the laser is focused inside the jet. This mode of ignition is referred to as direct ignition [3], as the laser deposition occurs in regions where both fuel and oxidizer coexist within the classical flammability limits of the equivalence ratio. If the deposited energy is above the minimum ignition value, sensitivity to the aforementioned parameters is almost negligible, and successful ignition is very likely to occur, as observed in [3]. Therefore, only one case is presented for this ignition mode. Figure 2 shows the flow field of density at different time instants after the laser pulse; an isosurface of temperature is also used to better visualize the flame development. The laser deposition generates a kernel of hot gases that reaches an extremely high temperature by 5μs. At the same time, the laser-generated shock wave can be appreciated. The high temperature generated by the laser, together with the local composition, initiates combustion in the form of a turbulent premixed flame, already at 50μs. The subsequent thermal expansion generates a pressure wave that spans the combustor and is subsequently reflected by the curved walls of the nozzle.

Case 2 and 3

The indirect ignition mode [3], refers to a situation in which the laser is fired outside the propellant jet. This ignition mechanism demonstrates that the interaction between the laser-generated flow and the instantaneous flow field can produce unexpected ignition scenarios. We compare two test cases, nominally identical, with a different combination of the perturbed parameters. Differences between the two sets of control parameters are guided by experimental evidence and will be highlighted in the presentation. Figure 3 shows the kernel evolution for both cases. The shape of the kernel at the first instant is similar, despite the perturbation in the kernel parameters. The origin of the laser-induced ejecta is also visible. By 470μs, the hot gases are transported close to the region with composition within the flammability limit, initiating combustion.

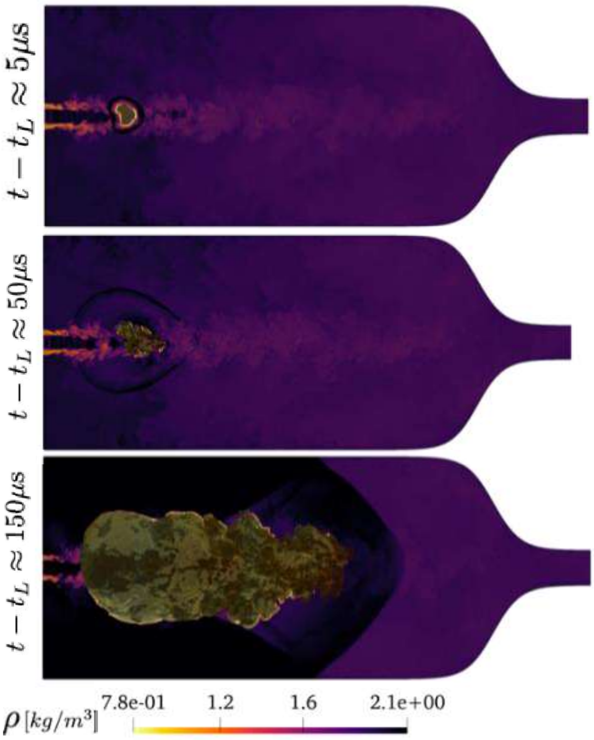

Figure 2. Contour of density field for the direct ignition case. The flame is represented by an isosurface of temperature equal to 1800 K, with arbitrary color scale.

In the other case, the jet oscillations in the downstream section are out of sync with the laser deposition and the hot gases happen to be further away from the flammable region. The last row shows a well-established flame for the igniting case, whereas hot gases in the second one continue to cool down. We use the mixture fraction Z to depict the amount of fuel and oxidizer in a certain region. To achieve ignition, high-temperature gases reaching a well-mixed region of the flow is a necessary (but not sufficient) condition. Tracking the interaction of the stochiometric region and the hot gases provides insights into the early combustion process. In Figure 4, we show a scatter plot of conditioned temperature greater than 1000 K, colored by the heat release rate, as a function of Z; in the same figure, the stochiometric value is marked by a dashed vertical line. This diagram is useful to quantitatively corroborate the two different outcomes of forced ignition, at different time instants.

Conclusive remarks

In the present work, Large Eddy Simulations of laser-induced ignition are performed. The prediction target is a subscale rocket combustor model, composed of partially

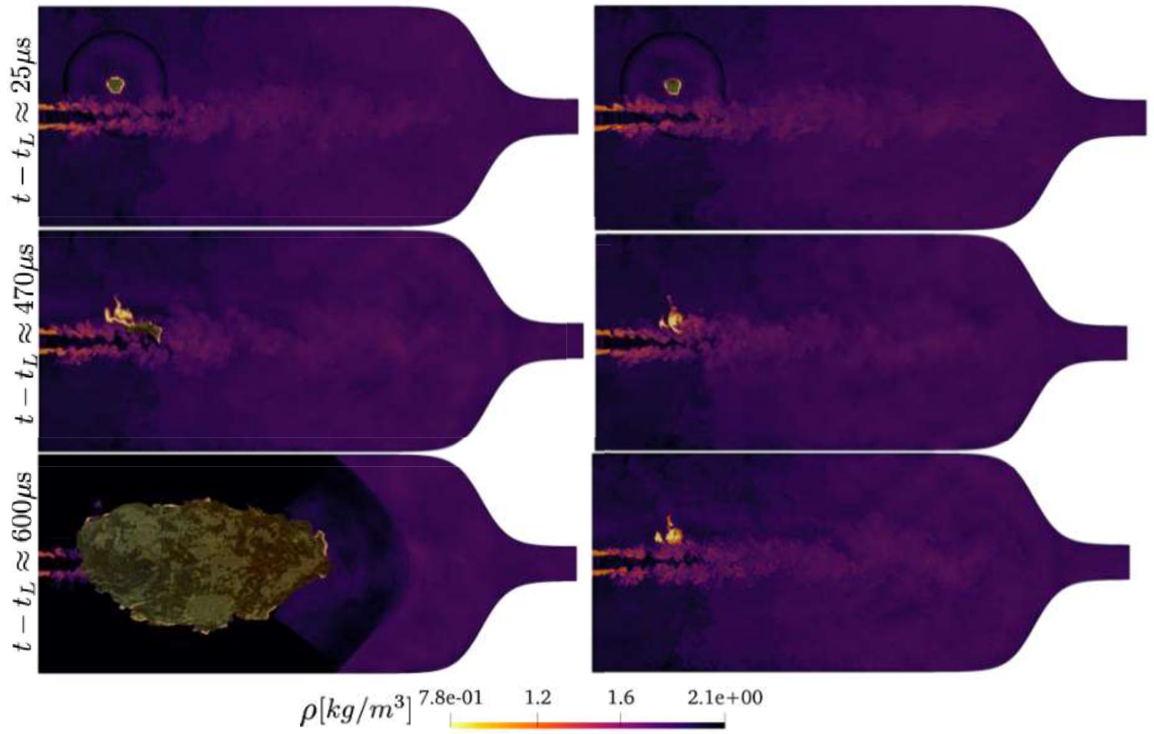

Figure 3. Contour of density field for the indirect ignition case. Igniting case (left column) and not-igniting case (right column).

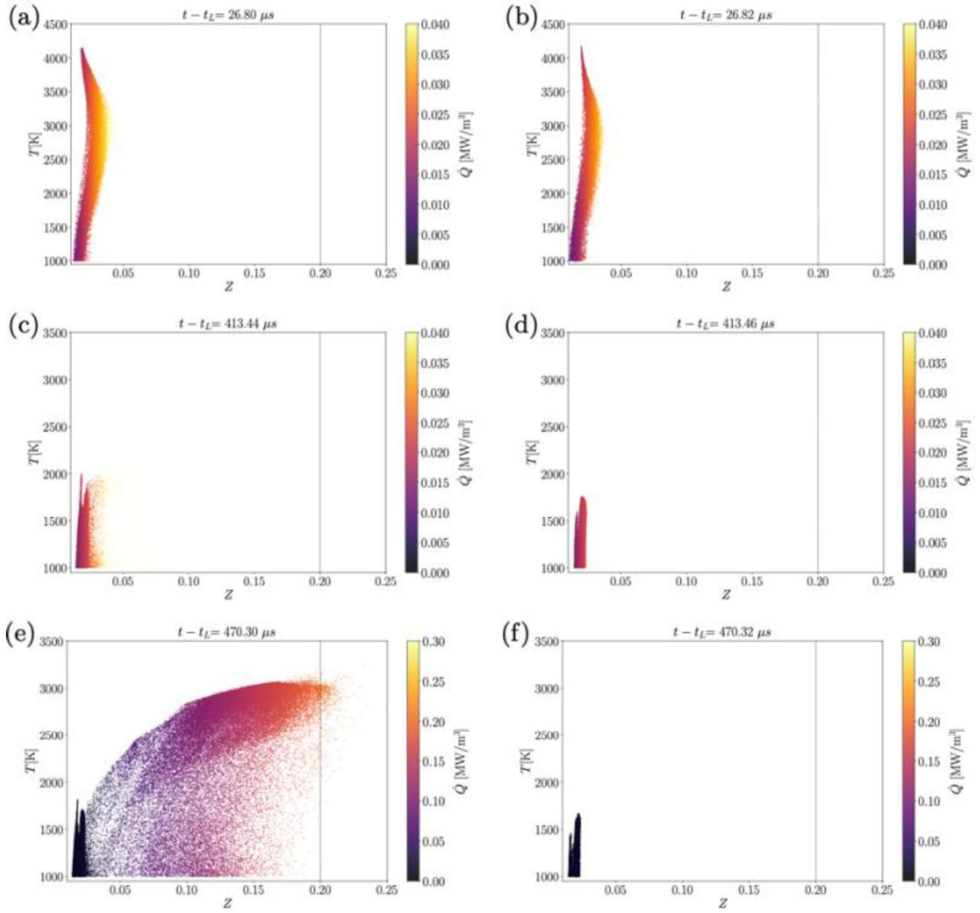

Figure 4. Scatter plot of temperature values greater than 1000 K, plotted against mixture fraction Z for igniting case (left) and not-igniting case (right).

premixed methane and oxygen, locally ignited by a laser-induced spark. It has been shown that, depending on where the energy is focused, the ignition outcome can be particularly sensitive to flow conditions. In realistic configuration, the sources of uncertainties derive mostly from difficulty in controlling the operating conditions, i.e., instantaneous turbulence, focal location, kernel shape. Specific combination of these uncertainties can lead to ignition failure. In this work, we will numerically characterize the sources of uncertainties and prove the coexistence of both ignition and no-ignition for nominally identical conditions.

References

[1] C. Manfletti. Laser ignition of an experimental cryogenic reaction and control thruster: pre-ignition conditions. *Journal of Propulsion and Power*, 30(4):925–933 (2014)

[2] J. Wang, M. Di Renzo, C. Williams, J. Urzay, and G. Iaccarino. Progress on laser ignition simulations of a ch4/o2 subscale rocket combustor using a multi-gpu task-based solver. Center for Turbulence Research Annual Research Briefs, pages 129–142 (2021)

[3] R. Strelau, M. Frederick, W. C Senior, R. Gejji, and C. D Slabaugh. Modes of laser spark ignition of a model rocket combustor. *In AIAA SCITECH 2023 Forum*, page 2377, 2023.

[4] J. M. Wang, M. Di Renzo, G. Iaccarino, H. Wang, and J. Urzay. Laser- induced indirect ignition of non-premixed turbulent shear layers. *Combustion and Flame*, 264:113426 (2024)

[5] J. M. Wang, D. A. Buchta, and J. B. Freund. Hydrodynamic ejection by laser-induced optical breakdown. *Journal of Fluid Mechanics*, 888, 2020.

[6] J. M. Wang, J. F. MacArt, and J. B. Freund. Flow dynamics of laser-induced breakdown at a fuel–oxidizer interface and its effect on ignition. *Combustion and Flame*, 229:111375 (2021)

[7] M. Di Renzo, L. Fu, and J. Urzay. HTR solver: An open-source exascale-oriented task-based multi-GPU high-order code for hypersonic aerothermodynamics. *Computer Physics Communications*, 255:107262 (2020)

[8] T. Zahtila, D. Passiatore, and G. Iaccarino. Progress on multi-fidelity simulations of a laser ignited rocket combustor. *Annual Research Briefs, Center for Turbulence Research*, 2023.

[9] D. Passiatore, J. M. Wang, M. Di Renzo, G. Iaccarino. Computational study of laser-induced modes of ignition in a coflow combustor. *Private communication* (2024)