

A direct numerical simulation study of post discharge plasma ignition of jet fuel in isotropic turbulence

Giulio Borghesi*, Alex Krisman**, Tianfeng Lu*** and Ji-Woong Park*** and Jacqueline H. Chen*

jhchen@sandia.gov

*Combustion Research Facility, Sandia National Laboratories, Livermore, CA 94550, USA

**FM Global Research Corporation, Norwood, MA, USA

*** University of Connecticut, Storrs, CT 06269-3139, USA

Abstract

Direct numerical simulations are performed for post discharge plasma ignition kernels of a jet surrogate fuel in fully developed isotropic turbulence at a turbulent Reynolds number, $Re_t = 2872$, at cold ambient conditions. The success or failure of the ignition kernel to ignite the reactant mixture is studied and the ignition sensitivity to the transit time through a non-flammable inert air layer before mixing with the reactants is determined. In addition to turbulence-chemistry interactions, variations to jet fuel chemistry are studied including differences induced by variations in fuel volatility and low-temperature chemistry.

Introduction

Aviation gas turbines operate over a broad range of altitudes and must be able to relight successfully following a blow-out (global extinction) event for the safe operation of the aircraft. If blow-out occurs, the temperature and pressure within the combustion chamber will decrease due to the absence of the flame and the loss of power to the compressor. This condition is exacerbated at high-altitude where the ambient air is cold and rarefied. To successfully relight, the liquid fuel stream has to undergo atomization and evaporation in order to prepare an ignitable fuel-air premixture in the vicinity of the ignition source. The ignition source must then be able to transition to a rapidly-expanding flame kernel in order to achieve a stabilized flame and, ultimately, successful relight.

There exist two central challenges in the high-altitude relight problem: (1) mixture preparation, and (2) interactions between the ignition source and the prepared mixture.

1. Mixture preparation is essential to produce locally well-mixed parcels at the required equivalence ratio. At high-altitude relight conditions, the atomization of the liquid fuel stream is impeded by the reduced momentum of the air stream, and the increased surface tension of the fuel stream. Once atomized, evaporation is affected by both the reduced pressure which favors vaporization, and the reduced temperature which lowers the fuel

volatility and impedes vaporization. Once in the fuel is in the vapor phase, it is mixed with ambient air in a turbulent environment. The combination of these mixture preparation processes will ultimately determine the distribution of fuel in the vicinity of the ignition source. A necessary condition for successful relight is that this fuel-air mixture is ignitable.

2. The ignition source, usually supplied by a spark, generates a plasma which rapidly decays to a hot gas as it expands and entrains ambient air. The interaction between the post-discharge plasma ignition source, the ambient air, and the fuel, governs the onset of combustion chemistry and the overall success of the ignition event. The ignition source must therefore deliver a sufficiently energetic impulse to a sufficiently reactive fuel-air mixture. At high altitude, the mass-density of the fuel vapor is reduced, which lowers the heat release rate due to combustion and therefore impedes the growth and stabilization of an incipient flame. Variations in fuel chemistry may also play an important role due to differences in the laminar burning rate in addition to turbulence-chemistry interactions.

Configuration and Physical Parameters

To investigate these dynamics, we performed direct numerical simulations (DNS) in a configuration inspired by the experimental facility at the Georgia Institute of Technology (Georgia Tech.), see Fig. 1 [1-3]. This experiment introduces a plasma ignition kernel into a stratified cross-flow consisting of an inert layer below a flammable reactants layer. The kernel is impulsively ejected into the inert layer, entrains ambient air and cools as it travels to the flammable layer.

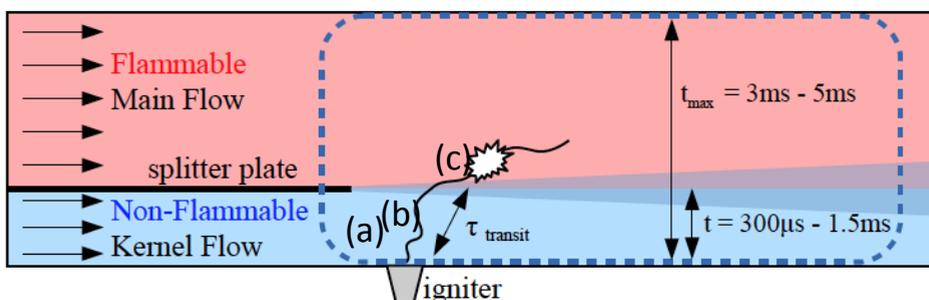


Figure 1: Overview of the experimental test facility at Georgia Tech [1]

The computational expense of performing DNS of this experimental configuration is prohibitive. Hence, we devised a canonical configuration that encapsulates the main dynamics of the experiment in a computationally tractable manner. A box of isotropic, decaying turbulence evolving in time will model the spatial development of the ignition impulse as it traverses the inert layer to the flammable layer. This

will be achieved by decomposing the overall process into several stages summarized in Fig. 2. In the first stage denoted as (a) in Figs. 1 and 2, a mixture corresponding to the ambient non-flammable mixture undergoes linear forcing [4] to establish a physically accurate field of fully-developed isotropic turbulence. In the second stage denoted as (b) in Figs. 1 and 2, a sphere of ionized air at 3300K, determined from reduced order modeling of the spark plasma discharge [1-3], is introduced into the center of the domain, representing the post-discharge plasma ignition impulse. The DNS domain will then be evolved in time, in the absence of turbulent forcing, in order to represent the mixing of the ignition kernel that occurs during the transit time from the igniter to the flammable layer. The initial rms velocity of the turbulence is taken to be ~ 26 m/s. The turbulence integral scale and the initial spark diameter are 3.5 mm. The 3D computational domain size is 15 mm per side, and the computational grid size is $832 \times 832 \times 832$. Subsequently in stage 3 denoted as (c) in Figs. 1 and 2, a uniform premixture of fuel/air at unity equivalence ratio is introduced into the decaying turbulence and chemical reactions are activated. The turbulence-chemistry interactions are evolved until ignition success or failure is determined.

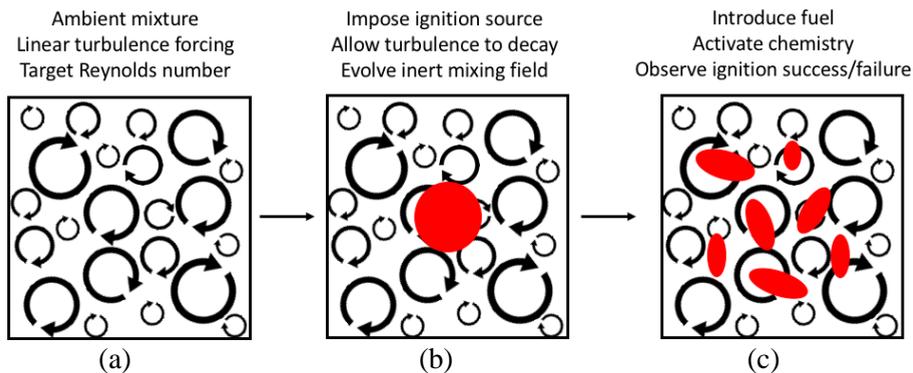


Figure 2: DNS configuration sequence of simulations.

The design of this DNS experiment sacrifices the spatial structure of the plasma impulse/cross-flow interactions, which are considered not to be of leading order importance. This claim is justified by the relatively low Reynolds number of the cross-flow and the relatively small interface between the non-flammable and flammable layers in the channel. The advantage of this configuration is the small number of design parameters and the relatively low computational cost, which allows for a parametric investigation of the key physics.

A series of DNS investigations will be presented to consider both the effects of mixture preparation and the interactions between the ignition source and the prepared mixture. As a first step, the conditions of the Georgia Tech. experiment will be presented for a selected equivalence ratio, which corresponds to ground-

level ambient conditions (or moderately compressed and heated conditions at high altitude). This will allow for validation against known experimental and LES results where the risk of failing to successfully ignite the mixture is low.

Following this baseline, variations are performed for the fuel chemistry and mixture preparation by varying:

1. The definition of the fuel stream and the governing chemical kinetics (high- and low-temperature chemistry submodels)
2. The transit time through the inert nonflammable air layer.
3. The ambient air condition, measured by the altitude above ground level for a standard atmosphere.

The description of the jet fuel chemistry is provided by the HyChem model by Hai Wang *et al.* [5]. In HyChem high-temperature chemistry of multi-component real fuels is modeled by decoupling fuel pyrolysis from the oxidation of the fuel pyrolysis products. The fuel pyrolysis is modeled by 7 lumped reactions where the stoichiometric and reaction rate coefficients are determined experimentally. The oxidation of the pyrolysis products is based on the foundational chemistry of hydrocarbon fuels obtained from USC Mech II. Here, we consider the conventional jet fuels (JetA(A2), and JP5(A3)) modeled with extensive validation including ignition delay times, laminar flame speeds and nonpremixed flame extinction strain rates. HyChem also predicts negative temperature coefficient (NTC) behaviors of jet fuels.

In the present study, three chemical models A2, A2a and A3, were selected to explore a range of jet fuel chemistries. A2a models a highly volatile fuel with high levels of low-temperature chemistry, whereas A2 is the same as A2a with the exception that it has more moderate NTC activity. A3 on the other hand is a low volatile fuel with low levels of low-temperature chemistry. Furthermore, the influence of low-temperature chemistry may be isolated for all three fuel models by neglecting the low-temperature chemistry submodel. In a future study we plan to also investigate the role of fuel volatility in the evaporation of a liquid fuel. The present study considers only gaseous fuel mixtures.

Numerical method

The DNS code S3D [6] is used to solve the compressible Navier-Stokes, total energy, and species continuity conservation equations. S3D uses higher order accurate numerical methods that are eighth-order in space and fourth-order in time.

The species thermodynamic and transport properties are evaluated using mixture-averaged properties and the chemistry is described by the HyChem surrogate jet fuel model [5] that has been reduced to 35 species for A2, 36 species for A2a, and 37 species for A3 with dynamic stiffness reduction in S3D including thermal NO chemistry.

Evolution of Inert Mixing Field

The fully developed turbulence field is shown in Fig. 3a for the u component of the velocity fluctuations and the imposed spherical ignition source of ionized air superimposed on the fully developed isotropic turbulence field is shown in Fig. 3b. After 30 microseconds the kernel has been wrinkled by the turbulence as the turbulence decays and evolves the inert air field as shown in Fig. 3c. In the final step the wrinkled kernel will be imposed in a field of uniform reactants and evolved by the turbulence until ignition success or failure is observed.

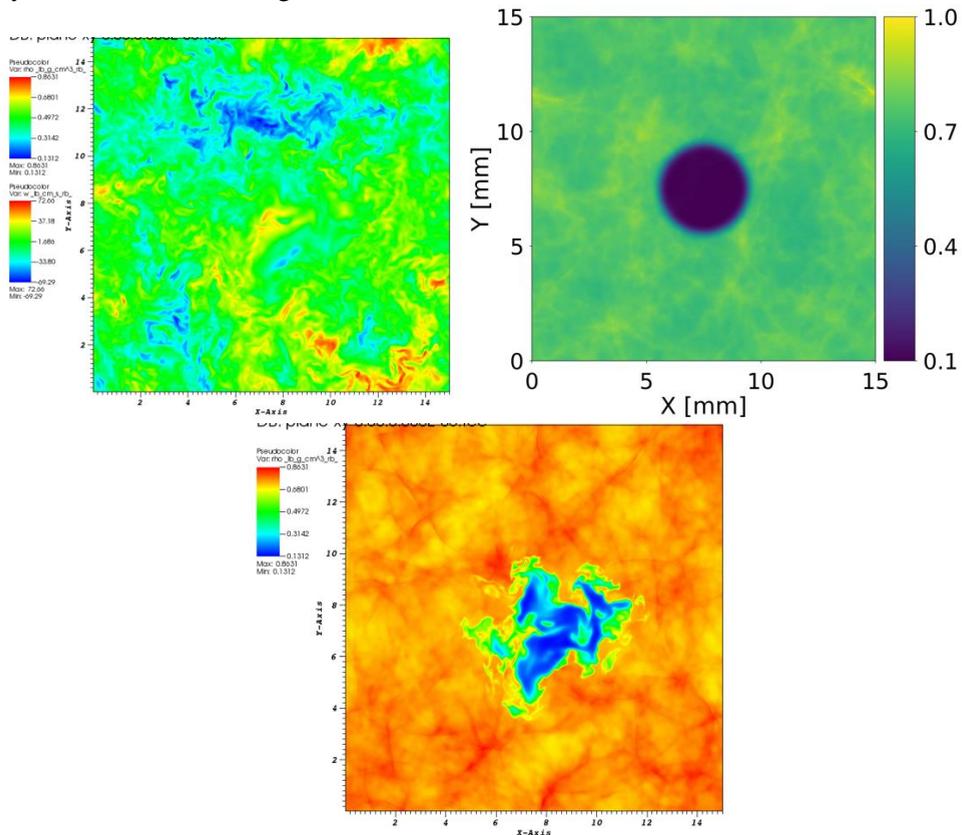


Figure 3. a) u component of velocity fluctuation from fully-developed turbulence prior to spark; b) initial density field of the ionized gas; and c)

density field in isotropic turbulence after 30 microseconds of inert mixing.

References

- [1] Jaravel, T., Labahn, J., Sforzo, B., Seitzman, J. and Ihme, M., “Numerical study of the ignition behavior of a post-discharge kernel in a turbulent stratified crossflow”, *Center for Turbulence Research Annual Research Briefs*. 176: 63-76 (2017).
- [2] Sforzo, B. A., “High energy spark ignition in non-premixed flowing combustors”, Ph.D. Thesis, Georgia Institute of Technology (2014).
- [3] Sforzo, B. A., Kim, J., Jagoda, J. and Seitzman, J., “Ignition probability in a stratified turbulent flow with a sunken reigniter”, *J. Eng. Gas Turb. Power* 137, 011502 (2014).
- [4] Rosales, C. and Meneveau, C., “Linear forcing in numerical simulations of isotropic turbulence: physical space implementations and convergence properties”, *Physics of Fluids* 17 (2005).
- [5] Xu, R., Wang, K., Banerjee, S., Shao, J., Parise, T., Zhu, Y., Wang, S., Moaghar, A., Lee, D. J., Zhao, R., Han, X., Gao, Y., Lu, T., Brezinsky, K., Egolfopoulos, F., Davidson, D., Hanson, R., Bowman, C., and Wang, H., “A Physics-based approach to modeling real-fuel combustion chemistry – II. Reaction kinetic models of jet and rocket fuels”, submitted to *Combustion and Flame* (2018).
- [6] Chen, J.H., Choudhary, A., de Supinski, B., DeVries, M., Hawkes, E.R., Klasky, S., Liao, W.K., Ma, K.L., Mellor-Crummey, J., Podhorski, N., Sankaran, R., Shende, S., Yoo, C.S., “Terascale direct numerical simulations of turbulent combustion using s3d,” *Computational Science and Discovery* 2 (2009).