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Large-eddy simulation of a supersonic lifted jet flame: Analysis of the turbulent flame base

Lisa Bouheraoua, Pascale Domingo*, Guillaume Ribert

Normandie Univ, INSA Rouen, UNIROUEN, CNRS, CORIA, 76000 Rouen, France

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ABSTRACT

Large-eddy simulation of a supersonic hydrogen–air non-premixed lifted jet flame is reported in the configuration studied by Cheng et al. (1994). The emphasis of the study is on the mechanism driving flame stabilization. The resolution issue is first addressed by considering three meshes of, respectively, 4, 32 and 268 millions of cells. The highest resolution of 60 µm allows for resolving the flame with a reduced chemical kinetics. LES results are found in good agreement with experimental data and previous simulations of the literature. It is observed in the simulations that the highly unstable flame base exhibits a cyclic period of around 0.25 ms, with the transient occurence of shock diamonds. These shocks may enhance the mixing of the reactants and control the autoignition processes occurring in the vicinity of the burner exit. The flame also exhibits a transient bow shock shape structure. The dynamics of the turbulent flame base, and the fluctuations of its streamwise position, thus appears to be controlled by the intricate coupling between autoignition and the upstream propagation of strong pressure waves sustained by combustion, pertaining to an intermittent detonation-like mechanism. From these highly-resolved unsteady simulations, a scenario is drawn to explain the cyclic time evolution of the structure of the unsteady turbulent flame base, in direct relation with its fluctuating streamwise position.

1. Introduction

Identifying and predicting the stabilization mechanism of hydrogen combustion is of practical interest in the design of future propulsive systems. For subsonic flames, Lu et al. [1] highlight an important literature with several scenarios for the mechanism of hydrogen flame stabilization. For supersonic flames, the literature is less prolix certainly because of the difficulty to experiment with high-enthalpy conditions in ground-based combustion facilities [2]. Available experiments are scarce [3,4] and, among these, the supersonic turbulent burner of Cheng et al. [4] provides a reliable set of data for dynamics, mixing, temperature and species concentrations. Other experiments available in the literature are mainly related to scramjets configurations [5–8], which are out of the scope of this study.

Despite the increase in high-performance computing, it remains challenging to ensure both the accuracy of the numerical methods and of the models for the phenomena unresolved by the mesh. Table 1 summarizes a panel of studies reporting simulations of supersonic combustion. A first remark is that the number of experimental studies, which serve as validation test-cases, is rather small (10) especially if compared to the number of studies available in the context of subsonic turbulent combustion. A second remark is that the number of combustion models tested is roughly the same than the number of experimental test-cases. One can then conclude that no definitive agreement on what would be the best strategy for supersonic combustion modeling has yet been reached. One can also notice that only four papers [9–12] propose a combustion model specific to supersonic flows.

Following the work done by Boivin et al. [13] and Moule et al. [14], the stabilization mechanisms associated to the supersonic lifted flame of the Cheng et al. [4] experiment is addressed. The experimental and numerical set-ups are introduced in the subsequent section, with a model strategy for turbulence and combustion. A systematic comparison with experimental data and with previous numerical simulations [13,14] are reported in the next section. The resolution of the turbulence and of the reaction zones is discussed for various meshes, in order to assess the modeling strategy. The dynamics of the flame base is finally studied. The analysis suggests that the turbulent flame base is controlled by a combination of autoignition and detonation-like processes.

2. Experimental set-up and modeling issues

2.1. Experimental configuration

Two families of experimental rigs are mostly found in supersonic combustion: jets and cavity flows. The latter facilities

* Corresponding author.
E-mail address: domingo@coria.fr (P. Domingo).

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Table 1
Summary of published works on simulation of supersonic combustion. References in **bold** correspond to studies where a model was specifically developed for supersonic combustion. ∅: no explicit subgrid model for the source terms; PDF: Probability Density Function; MIL: Model Intermittent Lagrangian; EDC: Eddy-Dissipation Concept; TFM: Flame Thickened Model, PaSR: Partially Stirred Reactor; ISCM: Ingenito Supersonic Combustion Model.

Reference	Model	Context	Test-case	Comments
Boivin et al. (2012) [13]	∅	LES	Cheng's burner [4]	Three steps reduced chemistry for H_2/Air [15].
Edwards et al. (2012) [16]	'No model'	RANS/LES	Burrows and Kurkov's burner [17]	Seven and nine species mechanism for H_2/Air.
Won et al. (2010) [18]		DLES	Jet in cross-flow [19]	Eight species mechanism from GRI-Mech 3.0 .
Baurle et al. (1994) [20]	**PDF**	RANS	Cheng's burner [4]	Multivariables presumed PDF of Girimaji [21] with Jachimowski mechanism [22]. Comparison with ∅ approach.
Gerlinger et al. (2001) [23]		RANS	Evans' burner [3]	
Baurle and Girimaji (2003) [24]		RANS	Cheng's burner [4]	
Xiao et al. (2007) [25]		RANS	Burrows and Kurkov's burner [17]	
Möbus et al. (2003) [26,27]		RANS	Cheng's burner [4]	Comparison between two transported PDF approaches and comparison with ∅ approach.
Zheng and Bray (1994) [28]	**Flamelet**	RANS	Evans' burner [3]	Flamelet modeling: infinitely fast chemistry and strained flamelets.
Sabel'Nikov et al. (1998) [9]		RANS/LES	Evans' burner [3]	Compressible effects added to Zheng and Bray [28] model.
Oevermann (2000) [29]		RANS	DLR Combustor [30]	Strained diffusion flamelets with Le=1.
Berglund and Fureby (2007) [31]		LES	DLR Combustor [30]	Flamelet modeling: strained diffusion flamelets and premixed flamelets are compared.
Saghafian et al. (2015) [12]		RANS/LES	Jet in cross-flow [32,33]	Compressible extended flamelet table and compressible flamelet/progress variable model.
Saghafian et al. (2015) [34]		LES	HiFire [35]	Compressible extended flamelet table and compressible flamelet/progress variable model [12].
Izard et al. (2009) [10]	**MIL**	RANS	Cheng's burner [4]	Modification of the model MIL to include compressible effects.
Gomet et al. (2012) [36]		RANS	Cheng's burner [4]	Improvement of the model from Izard et al [10].
Fureby (2009) [37]	**EDC**	LES	LAERTE (ONERA / JAXA) [38]	Comparison between EDC and thickened flame model (TFM).
Cecere et al. (2011) [39]		LES	Hyshot II [6]	Fast mixing impacting reaction zone. Discussion of the broken flamelet regime.
Berglund et al. (2010) [40]		LES	LAERTE (ONERA / JAXA) [38]	Chemical reaction time is linked to the one from a premixed stoichiometric flame.
Fureby et al. (2011) [41]	**PaSR**	RANS/LES	Hyshot II [6]	
Fedina and Fureby (2011) [42]		LES	Gould's burner [43]	Comparison between four models: Flamelet, TFM, EDC and PaSR.
Moule et al. (2014) [14]		LES	Cheng's burner [4]	Model U-PaSR (*Unsteady-PaSR*).
Ingenito and Bruno (2010) [11]	**ISCM**	LES	SCHOLAR [5]	Based on the EDC concept and adapted to supersonic combustion by relating the chemical source terms to the Mach number.

ressemble most to a scramjet configuration, such as the Scholar [5], the HyShot [6], the UV-SCF [7] configurations or the cavity recently investigated by Tuttle et al. [8]. However, less experimental measurements are available in cavity-flows than on jet flames. This is mainly due to limited optical access in the former, while rather detailed measurements exist on jet flame configurations, such as reported in the experiments by Evans et al. [3] or more recently by Cheng et al. [4], which is retained in this work.

The burner by Cheng et al. [4] is composed of a sonic hydrogen round jet surrounded by an annular jet of hot, vitiated air flowing at Mach 2. This coflow of vitiated air is generated by a lean combustor, in which hydrogen burns with air enriched with oxygen. A convergent–divergent nozzle accelerates the products up to Mach 2. The burner exit conditions of both inner and outer streams are given in Table 2.

The measurements report mean and root mean square (rms) for temperature and major species, using ultra-violet Raman scattering and laser induced fluorescence techniques. These measurements are available at 7 downstream distances: $x/D = 0.85$, 10.8, 21.5, 32.3, 43.1, 64.7 and 86.1, where $D = 2.36$ mm is the fuel jet diameter. Measurements are also available on jet axis.

This experiment has served for validation of numerous Reynolds Averaged Navier–Stokes simulations [10,20,26,27,44–48]. More recently, LES, which allows for capturing some of the unsteady effects of the flows, have been reported. Dauptain et al. [49] first discussed LES of this burner with chemistry reduced to two global steps, which led to an important underestimation of the autoignition distance from the burner exit. This work was revisited by Boivin et al. [13], using a 3-step reduced chemical mechanism [15] and a mesh resolution varying between 100 μm and 400 μm. The modeling of the transport by subgrid velocity fluctuations was expressed with the well-know Smagorinsky formalism [50]. No subgrid model for combustion was employed, in other words,

Table 2
Operating conditions of the burner [4].

Parameters	
Air mass flow rate (±2%)	0.0735 kg/s
H_2 mass flow rate (±2%)	0.000173 kg/s
O_2 mass flow rate (±3%)	0.0211 kg/s
Fuel mass flow rate (±3%)	0.000362 kg/s
Nozzle exit inner diameter	17.78 mm
Fuel injector inner diameter	2.36 mm
Fuel injector outer diameter	3.81 mm
Vitiated air inlet conditions	
Pressure	107 kPa
Temperature	1250 K
Mach number	2.0
Bulk velocity	1420 m/s
O_2 mole fraction	0.201
N_2 mole fraction	0.544
H_2O mole fraction	0.255
Fuel inlet conditions	
Pressure	112 kPa
Temperature	545 K
Mach number	1.0
Bulk velocity	1780 m/s
H_2 mole fraction	1.0