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Turbulent jet ignition assisted combustion in a rapid compression machine

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ABSTRACT

Numerical simulations of turbulent jet ignition (TJI) and combustion in a rapid compression machine (RCM) are conducted by a hybrid Eulerian–Lagrangian large eddy simulation/filtered mass density function (LES/FMDF) computational model. TJI is a novel method for initiating combustion in ultra-lean mixtures and often involves one or several hot combustion product turbulent jets, rapidly propagating from a pre-chamber (PCh) to a main chamber (MCh). An immersed boundary method is developed and used together with LES to handle complex geometries and to decrease the complexity and computational cost of the Monte Carlo (MC) particle operations, while maintaining the high accuracy of the hybrid LES/FMDF model. Analysis of numerical data suggests three main combustion phases in the RCM-TJI: (i) cold fuel jet, (ii) turbulent hot product jet, and (iii) reverse fuel-air/product jet. The effects of various parameters (e.g., the igniter location, mixture composition, and wall heat transfer) on these phases are studied numerically. It is found that the turbulent jet features and the MCh combustion are very much dependent on the PCh ignition details. Igniting the PCh at the lower locations close to the nozzle forces the PCh charge to fully participate in the PCh combustion and prevents the unburned fuel leaking to the MCh. It also leads to longer discharge of the PCh hot products into the MCh with more uniform jet velocity, enhancing the MCh combustion. The results predicted by LES/FMDF are found to be comparable with the available experimental data, both qualitatively and quantitatively.

1. Introduction

Turbulent jet ignition (TJI) is an ignition enhancement method for the combustion of ultra-lean and low temperature mixtures. TJI-assisted combustion systems typically consist of a relatively small pre-chamber (PCh), a main chamber (MCh), and a nozzle connecting them. A spark plug and injectors are installed in the PCh to ignite the charge with desired amounts of auxiliary fuel and air. The strong hot product jet, which is created by the PCh and a low spark ignition energy, efficiently initiates and controls the MCh combustion much better than the conventional ignition systems [21]. The physics of various TJI-assisted combustion systems with different PCh-MCh configurations have been reviewed in references [47,54,56]. More recently, TJI has been used in rapid compression machines (RCMs) [6,7,17,18,22,36,38,53]. These machines are typically used for studying autoignition and combustion kinetics by compressing fuel-air mixtures uniformly to engine-like conditions. Here, in the simulated RCM-TJI combustion system (Fig. 5a), a PCh is installed at the end side of the RCM, referred to as the MCh. The PCh is connected to the MCh through a nozzle (or several nozzles), creating one or more high speed hot product jets rapidly entering/propagating in the MCh [15]. Ideally, the incoming jet(s) initiates “nearly homogeneous” premixed combustion, in which the hot pockets of energy sources ignite the main charge as the flame/combustion products propagate throughout the system. This method enables the implementation of highly efficient lean burned technology in various combustion systems including RCMs and internal combustion (IC) engines.

The performance of TJI-assisted RCM is dependent on the complicated and often coupled effects of various factors such as the initial thermo-chemical conditions, the PCh and MCh geometries, the ignition parameters (timing, location, amount, and duration of discharged energy), the fuel-air-products mixing, and the fuel chemistry. It is not trivial to experimentally predict the RCM-TJI behaviour for various operating conditions. High-fidelity computational models such as those developed based on the large eddy simulation (LES) concept [13,40,43–46] can greatly help with the development and assessment of new TJI-assisted combustion concepts and systems. However, LES models have not been fully used

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Nomenclature and list of abbreviations

Abbreviations

CFD	Computational fluid dynamics
EDM	Energy deposition model
FD	Finite difference
FDF	Filtered density function
FMDF	Filtered mass density function
IB	Immersed boundary
IC	Internal combustion
LES	Large eddy simulation
MC	Monte Carlo
MCh	Main chamber
PCh	Pre chamber
PDF	Probability density function
RCM	Rapid compression machine
SDE	Stochastic differential equation
SGS	Sub-grid scale
SI	Spark ignition
SU	Service unit
TJI	Turbulent jet ignition

Conventions

$\bar{()}$	Filtered value
$\tilde{()}$	Favre filtered value

Symbols

δ	Dirac delta function
Δ_G	Filter size, m
$\dot{Q}$	Heat release rate, J/Kg.s
$\dot{S}_\alpha$	Reaction rate of species α, 1/s
Γ, Γ_t	Molecular and turbulent diffusion coefficients, Kg/m.s
κ, κ_e, κ^*	Thermal, effective, and artificial conductivity coefficients, J/m.s.K
$\mid \tilde{S} \mid$	Strain rate magnitude, 1/s
μ, μ_e, μ^*	Molecular, effective, and artificial viscosity coefficients, Kg/m.s
Ω_m	Mixing frequency, 1/s
Φ	Composition vector
ϕ_α	Compositional value of scalar α
Ψ	Composition sample space vector
ρ	Density, Kg/m^3
σ	Fine-grained density
a	Speed of sound, m/s
C_m	MKEV model constant
C_ω	Mixing model constant
E	Total internal energy, J/kg
G	Filter function
h	Sensible enthalpy, J/Kg
n	Normal direction to the immersed surface
N_s	Number of species
p	Pressure, Pa
Pr_t	Turbulent Prandtl number
R	Mixture gas constant, J/Kg.K
Sc	Schmidt number
T	Temperature, K
t	Time, s
W	Wiener process, $s^{0.5}$
$w^{(n)}$	Weight of the nth Monte Carlo particle
x_i	ith component of the position vector, m
X_i^+	Probabilistic representation of position, m

for this purpose partly due to the challenges in modeling sub-grid scale (SGS) correlations, particularly in compressible turbulent reacting flows [60]. Additionally, in the TJI-assisted combustion systems a broad range of flame types including flamelet, distributed, premixed, non-premixed, and diffusion flames could exist simultaneously [57]. The combustion models developed for one type of flame might not be able to predict the other types and therefore the overall behaviour of TJI-assisted combustion systems.

The models developed based on the solution of the SGS probability density function (PDF), known as the filtered density function (FDF) [10,19,20,23–27,32,52,61], are among the most promising models developed for LES of turbulent reacting flows. In the FDF approach, the joint SGS statistics of turbulent variables are obtained from the FDF transport equation. The main advantage of the FDF is that all single-point statistics such as the reaction terms appear in a closed form in its formulation. However, the single-point FDF still needs modelling for multi-point correlations. Jaberi et al. [24] developed a FDF model for variable density turbulent reacting flows based on the mass weighted filtered value of the fine-grained density of energy and species mass fractions, termed as scalar filtered mass density function (FMDF). The scalar FMDF has been used to simulate a variety of reacting flows including low Mach number [49,63] and high speed compressible flows [9]. It has been extended to the velocity-scalar [39,50] and velocity-scalar-frequency FMDF [51] and it was used for simulating flows in cylindrical geometries [3,8,9] using H-H O-H grids [30]. Despite its applicability to flows in complex geometries, the Monte Carlo (MC) particle search and locate algorithm in the FMDF solver is much more efficient and accurate when Cartesian grids are utilized. To incorporate a uniform Cartesian mesh in complex geometries, we developed a version of immersed boundary (IB) method [37], compatible with the underlying LES/FMDF solver. The IB method was first introduced by Peskin [42] to compute the blood flow in the cardiovascular systems and it has been applied to a wide range of applications [12,55,62] such as compressible [16,33] and turbulent flows [28,41] to assess its accuracy and stability. The LES/FMDF solver together with the IB method is found to be quite accurate and computationally efficient. Also, it allows the maximum use of available computational capacity, since the computational loads are equally divided between all parallel processors.

In this study, we use the LES/FMDF model to investigate the physiochemical processes involved in the TJI-assisted RCM combustion and the effects of various parameters on them. We simulate and study the flow and combustion in the PCh and MCh of the TJI-RCM as not two independent systems, rather as a fully coupled and highly unsteady combustion system. We try to provide a better understanding of RCM-TJI combustion and how various flow/combustion parameters can be adjusted to achieve the optimum performance of the system. In Section 2, the governing LES equations, the compressible FMDF formulation, the numerical approach, and the IB method are described. In Section 3, the simulated RCM-TJI setup and computational domain are described. The simulation results are presented in three parts: Section 4.1 compares LES/FMDF predictions with the available experimental data; Section 4.2 examines various combustion phases in the RCM-TJI in details; and Section 4.3 discusses the parametric study results. Section 5 summarizes the main findings and conclusions.

2. Governing equations

The hybrid compressible LES/FMDF methodology involves two sets of Eulerian and Lagrangian equations, which are solved conjointly for velocity and scalar (species mass fractions and enthalpy) fields. The fully compressible LES equations and the FMDF equation are presented in the following two sections.