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The impact of hydrogen enrichment and bluff-body lip thickness on characteristics of blended propane/hydrogen bluff-body stabilized turbulent diffusion flames

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ABSTRACT

At the beginning of this study, the well-known turbulent bluff-body stabilized diffusion flame of HM1 is simulated by a coupled flamelet/radiation approach. The HM1 flame comprises a CH_4:H_2 [50:50 Vol.] jet flame at a Reynolds number of 15,800. The results showed reasonable agreement for the flow field and species. Afterwards, the abovementioned approach is employed to investigate the effects of hydrogen addition on bluff-body stabilized flames of propane–hydrogen. Adding hydrogen to the blended fuel of propane/hydrogen shifts the recirculation zone outwards the bluff-body and thus culminates in increased flame length. Besides this, the flame length is predicted to be enhanced with decreasing the lip thickness of the bluff-body configuration. The CO emission level is found to be decreased with hydrogen addition in near-burner and far field regions which might be attributed to the decrease of inflow carbon atoms. The local radiative heat power reveals higher values for fuel blends with decreased contents of hydrogen at the recirculation and jet-like zones. This might be attributed to the increased local heat release rate due to breaking further carbon bonds.

1. Introduction

The progressive rise of energy demand and relevant concerns on combustion generated pollutants forces scientists to develop viable techniques to reduce harmful emissions from burning devices. Blended hydrocarbon/hydrogen fuels have been emerged as an attractive solution to decline emission levels while increasing performance efficiency of the combustors in regard to conventional hydrocarbon fuels [1,2]. These fuels accelerate the reaction rate of burning which achieves improved ignitability and flame holding. This implies the burner to operate stably in lean and ultra-lean fuel to air ratios which in itself reduces the emission of pollutants such as carbon monoxide (CO), unburned hydrocarbons (UHC) and nitrogen oxides (NO_x) [3].

Bluff-body configuration has been utilized in many terrestrial and aerial combustors such as gas turbines to improve the flame stability. This occurs under geometrical flame holding mechanisms, in which a recirculation zone formed in the wake behind the bluff-body, anchors the flame [4]. This flame holder not only increases the residence time of mixture gases to reach augmented flame stability but also enhances the mixing between reactants [5]. Besides, the products enclosed inside the recirculation zone might be applied as a burning source by consecutively igniting the crossing mixture. In an axisymmetric configuration, the outgoing flow emanates from an annular gap created through involving a bluff-body into the incoming stream. The flow ejected from this gap deflects somewhat radially outward and embraces the recirculation zone. The turbulence level in the zone is preserved by consecutively receiving energy from the incoming streams. Downstream of the recirculation zone, there is a neck-shaped zone. Robust interactions between finite-rate chemistry and turbulent mixing are observed in this zone. Farther downstream, the flame behaves comparable to a fully-developed annular jet [6].

Extensive efforts have been utilized to demonstrate the characteristics of blended hydrogen–hydrocarbon flames. Safer et al. investigated the characteristics of hydrogen-rich syngas counter-flow flames and reported further NO_x at lower strain rates [7]. Yilmaz et al. contrasted two turbulence models including Reynolds stress models (RSM) and Renormalized Group (RNG) k–ε in predicting propane–hydrogen diffusion flames and reported better predictions for RNG model. [8]. Kang et al. observed significant changes in blended dimethyl ether–hydrogen flame structure when H_2 addition was above 60% (volume fraction) [9]. Mishra and Kumar observed flame length reduction in LPG-H_2 coaxial flames with hydrogen addition to the fuel stream [10].

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Nomenclature

χ	scalar dissipation rate
Y_k	mass of species k produced per unit volume per unit time
$\mathcal{W}_i$	molecular weight of species i
$P(Z)$	probability density function of mixture fraction
ν'_{ji}	stoichiometric coefficients of ith reaction in forward direction
ν''_{ji}	stoichiometric coefficients of ith reaction in backward direction
k_{fi}	rate coefficients of ith reaction in forward direction
k_{bi}	rate coefficients of ith reaction in backward direction
p_i	partial pressure of species i in atmospheres
$erfc^{-1}$	inverse complementary error function
ρ	density
$\dot{\omega}_k$	chemical source term
T	temperature
Z	mixture fraction
a_S	characteristic strain rate
ϕ_H	enthalpy defect
σ_B	Stefan–Boltzmann constant
Q	radiative loss per unit volume
$a_{p,i}$	Planck mean absorption coefficient
$\widehat{H}_k$	enthalpy of species k

The configuration considered for the current research is the unconfined bluff-body stabilized burner known as the Sydney bluff-body burner [11]. This burner is studied numerically by distinct researchers addressing various aspects of bluff-body stabilized flames utilizing the high-fidelity large eddy simulation (LES) and steady flamelet combustion model [12]. Malalasekera et al. [13] demonstrated the capability of LES approach to predict the formation of vortex breakdown and recirculation zones. Ranga Dinesh et al. [14] observed a more rapid variation from turbulent to non-turbulent flow for the velocity than the mixture fraction in the Sydney burner which was ascribed to the occurrence of recirculation zone. LES predicted results of Sydney bluff-body stabilized swirl burner indicated two types of instability modes in the vicinity of fuel jet region and bluff-body stabilized recirculation zone region [15]. Kempf et al. [16] emphasized on the importance of resolved kinetic energy in the accuracy of LES predictions. Ranga Dinesh and Kirkpatrick reported the precession mode of instability in the center jet of Sydney bluff-body stabilized swirl burner which constitutes a precessing vortex core. They stressed on capabilities of LES approach in prediction of unsteady oscillations in turbulent swirling flow fields [17].

The unsteady and 3 dimensional nature of turbulence implies that LES must always be implemented as 3D simulations. To achieve accurate predictions, a very fine mesh must be employed. This brings problems in the vicinity of walls where no large scales are present. Hence, LES is anticipated to be well applicable for flow systems governed by large turbulent structures which can be captured by roughly coarse grids. On the other hand, if attached boundary layers are of interest, very fine grids must be deployed with LES. Otherwise, poor predictions are obtained [18,19]. In this context, Unsteady Reynolds Averaged Simulation (URAS) approach in which the Reynolds averaged equations and models are solved with time dependence [19,20] is expected to outperform classical LES.

The primary objective of the current research is to identify the impact of hydrogen enrichment on bluff-body driven recirculation zone and flame characteristics variations thereof. The thin radiation model is coupled with the steady flamelet combustion model to describe the chemistry–radiation interaction. This model accounts for the molecular radiation present in hydrogen-enriched flames. The modified k–ε model is employed for closing the Reynolds stresses in momentum equation. To this end, this paper is prepared as follows. In Section 2, the coupled steady flamelet/radiation approach is described in detail. Section 3 is devoted to the validation of numerical approach by simulating the well-known Sydney bluff-body burner [21]. A description of the flow and mixing effects in the presence of bluff-body is provided. Subsequently, in Section 4, the impact of hydrogen enrichment and lip thickness on bluff-body driven recirculation zone is investigated for blended propane/hydrogen fuel stream. Attention is given to the thermal and emission characteristics of the targeted flames. Concluding remarks are collected in Section 5.

2. Governing equations, modeling and numerical methods

In this study, the Open Field Operation and Manipulation (OpenFOAM) C++ library is employed as the computational platform [22] and developed according to our requirements. The provided computational code solves the Favre averaged three dimensional time-dependent Navier–Stokes and continuity equations. The equations are considered for describing the flow field in variable density continuums.

2.1. U-RAS modeling

The Favre averaged governing equations are solved in three-dimensions with time dependency. A standard k–ε model and a second-order closure (Gaussian integration) are selected owing to well-known applicability for complex flows. The balance equations are discretized on a structured cylindrical boundary fitted collocated grid applying finite-volume approach. The Pressure Implicit with Splitting of Operators (PISO) method is used for pressure–velocity coupling. The resulting distinct matrix equations are solved iteratively. The time step quantity was adopted to give a Courant number of the order of 5 for the U-RAS computations. In our numerical scheme, spatial and temporal fluctuations of density and pressure are related to chemistry (high-Mach number assumption). The equations of continuity, momentum, mixture fraction and its variance are spatially discretized using central schemes. The accuracy of approximation is 2nd order for all convective and diffusive terms.

The decay and spreading rate of a round jet is over-predicted by the k–ε model [23]. Some modifications have been proposed in order to smooth this shortcoming. Dally et al. [24] have reported that the use of $C_{\varepsilon 1} = 1.60$ (the constant in the dissipation transport equation) gives a much better prediction. Hence, this constant is set to 1.60 in the current study. This value has also been recommended by the TNF workshop for bluff-body flames [25].

2.2. Modeling of combustion and radiation

The thermo-chemistry is accounted for by a steady flamelet approach comprising comprehensive chemistry with 82 species and 1485 reactions [26]. The laminar flamelet model visualizes the turbulent flame as an ensemble of one-dimensional locally laminar structures engulfed by the turbulent eddies [27]. In steady laminar flamelet model all scalar values are functions of the