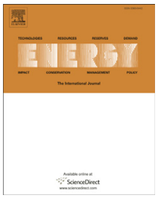
Energy 95 (2016) 211–222

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Investigation of a turbulent premixed combustion flame in a backward-facing step combustor; effect of equivalence ratio

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ARTICLE INFO

Article history:
Received 8 April 2015
Received in revised form
23 September 2015
Accepted 6 December 2015
Available online 30 December 2015

Keywords:
Flame stability
Large eddy simulation (*LES*)
Particle image velocimetry (*PIV*)
Premixed flame
Recirculation zone (*RZ*)
Step combustor

ABSTRACT

In the present study, *LES* (large-eddy simulation) is utilized to analyze lean-premixed propane-air flame stability in a backward-step combustor over a range of equivalence ratio. The artificially thickened flame approach coupled with a reduced reaction mechanism is incorporated for modeling the turbulence–combustion interactions at small scales. Simulation results are compared to high-speed *PIV* (particle image velocimetry) measurements for validation. The results show that the numerical framework captures different topological flow features effectively and with reasonable accuracy, for stable flame configurations, but some quantitative differences exist. The *RZ* (recirculation zone) is formed of a primary eddy and a secondary eddy and its overall size is significantly impacted by the equivalence ratio. The temperature distribution inside the recirculation zone is highly non-uniform, with much lower values observed close to the backward step and the bottom wall. The mixture distribution inside the RZ is also non-uniform because of mixing with reactants and heat loss to the walls. The flame is stabilized closer to the backward step as the equivalence ratio increases. At lower fuel fractions, the flame lifts off the step starting at equivalence ratio of 0.63 and the lift off distance is increased while the equivalence ratio is lowered.

1. Introduction

Most gas turbine combustors used in power plants and jet engines utilize non premixed flames because of their inherent stability under wide ranges of operating conditions. However, diffusion flames result in high temperature spots [1–3]. Consequently, this increase in temperature results in the generation of high levels of nitric oxides, *NOx* [4]. Public awareness and legislation have led to strict policies for the reduction of the pollutants. Therefore, alternatives such as *LPF* (lean premixed flames) have been proposed and their application is expanding. In this case, the fuel and oxidizer are mixed upstream in order to prevent the formation of stoichiometric zones and, hence, reduce the combustion temperature and, accordingly, reduce the *NOx* emissions [5]. Unfortunately, lean premixed flames are subjected to combustion instabilities [6,7]. Combustion instabilities are resonant phenomena that occur when a positive feedback is established between the acoustic environment and heat release. Resulting pressure fluctuations can reach critical values at which the engine operation can be affected leading to failure [8].

Combustor geometry and the associated flame anchoring mechanism are some of the most important parameters affecting combustion stability. The combustor geometry determines the size and structure of the recirculation zone formed in order to stabilize a flame [9]. Li and Gutmark [10] studied the flame stability with and without center body recess in dump combustor utilizing bluff-body for stabilization. The results showed that the flame is stabilized and the oscillations are reduced when the center body is recessed. Speth and Ghoniem [11] studied the combustion instabilities of a syngas-air premixed flame in a swirl-stabilized combustor over

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http://dx.doi.org/10.1016/j.energy.2015.12.010

Nomenclature

ATF	Artificially thickened flame
3-D	Three dimensional
CC	Catalytic combustion
DNS	Direct numerical simulation
E	Efficiency function
H	Step height
JL	Jones-Lindstedt
LES	Large-eddy simulation
LPF	Lean premixed flames
PE	Primary eddy
PIV	Particle image velocimetry
RANS	Reynolds averaged Navier–Stokes
RQLF	rich-burn quick-quench lean-burn flames
RZ	Recirculation zone
SE	Secondary eddy
SGS	Sub-grid scale
S_L^0	Laminar flame speed
TKE	Turbulent kinetic energy
δ_L^0	Laminar flame thickness

wide ranges of operating parameters. Their results showed strong dependence of the combustion instabilities on the combustor geometry [12,13], operating conditions and fuel compositions. Altay et al. [14] studied the flame–vortex interaction driven combustion dynamics of a premixed flame in a backward-facing step combustor under different fuel compositions and operating conditions. They observed unstable flames at high equivalence ratio, quasi-stable flames at intermediate equivalence ratio, and long stable flame near the lean blowout limit. Hong et al. [15] studied the impact of fuel composition (C_3H_8/H_2) on the structure of the recirculation zone and its role in lean premixed flame anchoring in a backward-facing step combustor. Their results demonstrated a complex coupling between the size and the structure of the recirculation zone and the flame anchoring. Two counter rotating eddies, a PE (primary eddy) and a SE (secondary eddy), were observed in the recirculation zone at relatively low equivalence ratio. Shrinkage of the SE size was observed while increasing the equivalence ratio until this zone completely disappeared. Adding hydrogen to the fuel resulted in higher temperatures and the motion of the flame tip toward the reactor step [15].

Details of the dynamics and phenomenology of near blow off flames were explained by Shanbhogue et al. [16]. They showed that temporally localized extinction, like holes in the flame structure, occurs close to the blow off conditions. The number of holes increases as the conditions of blow off are approached. Kedia and Ghoniem [17] investigated the anchoring mechanism of a laminar premixed flame anchoring close to a heat-conducting bluff-body. They used a fully resolved unsteady two-dimensional simulations coupled with detailed chemical kinetics for methane-air combustion. Their results showed a shear-layer stabilized flame in the vicinity and downstream of the bluff-body, where favorable ignition conditions are established; and a recirculation zone was formed by the combustion products. Altay et al. [18] investigated the effect of the oscillations in the equivalence ratio on the dynamics of combustion of a lean premixed propane-air flame in a backward-facing step combustor. Equivalence ratio oscillations were performed by altering the location of the fuel injector. They reported that flame–vortex interactions are the primary source of the combustion dynamics and the oscillations in the equivalence ratio have secondary effects.

The effects of the enthalpy of reaction and fuel composition on combustion dynamics were examined by Ferguson et al. [19] utilizing two different combustors, laboratory scale and atmospheric pressure combustors. Different fuel blends of natural gas, ethane and propane were considered for the combustion with air. They observed different dynamic response with increased fraction of propane. Fritsche et al. [20] performed an experimental study of thermoacoustic instabilities in a premixed flame on a swirl stabilized combustor under different inlet temperature and air to fuel ratio. The results showed the existence of two stable flames, one is lean and the other is rich, separated by a range of unstable flames. The unstable flames exhibited different shapes, and pressure oscillations. Seo [21] studied the effect of the operating temperature, combustion chamber pressure, and equivalence ratio on combustion dynamics of a lean-premixed flame on single-element swirl injector using gaseous fuel. Unstable flames were recorded when the equivalence ratio was in the range between 0.5 and 0.7. Also, unstable flames appeared when the inlet temperature was greater than 650 K. Venkataraman et al. [22] studied the effects of inlet Reynolds numbers, swirl number, and equivalence ratio on combustion instabilities of a premixed natural gas-air flame in a coaxial dump combustor stabilized using a bluff-body. Unstable flames were recorded near the lean blowout limit and close to stoichiometric conditions. Combustion stability was affected negatively when the inlet velocity was raised.

In all of these studies, the flame stability, or potential for becoming unstable, was shown to depend on the equivalence ratio. In the present study, LES is used to predict the impact of the equivalence ratio on combustion in a rearward facing step combustor. Wide range of equivalence ratios from lean to near stoichiometric is investigated. High resolution, high speed *PIV* (particle image velocimetry) is used to validate the numerical results. The present work focuses on predicting the location of the flame and the structure of the recirculation zone since they contribute significantly to overall combustion dynamics.

2. Combustor set up and PIV system

A planar combustor in which there is a step (change in plane level) in the flow direction was used to conduct the present experimental work and the simulations. In this combustor, a premixed flame is stabilized near a backward-facing step. Fig. 1(a) shows a schematic representation of this step combustor and the relevant dimensions. The inlet section of the combustor consists of a rectangular cross section stainless steel duct of a 160 mm span wise width and 40 mm height. Air is fed to the combustor inlet by an Atlas-Copco-GA-30-FF air compressor through a flow meter. The inflow is choked. At an axial location of 0.45 m downstream the choke plate, the cross section of the duct is contracted gradually to a height of 20 mm over an axial distance of 0.15 m, followed by a 0.4 m long and 20 mm height duct of constant cross section area. This is followed by the backward facing step where the height expands with an expansion ratio of 2:1 back to 40 mm. This acts as the nominal anchoring point for the flame. The fuel flow rate is measured using a Sierra C100M mass flow controller before its injection, 20 mm downstream of the choke plate, through a number of holes in the manifold. The mass flow controller allows a maximum flow rate of 2.36 g/s for propane with uncertainty in the measurement of ±1% of the full scale. The distance between the fuel injection point and the backward step is enough to mix the gases very well (see Altay et al. [14]). The length of the combustor downstream the step is 0.5 m and the combustor is opened to the atmosphere. The combustor length is sufficiently short to prevent