INTERNATIONAL JOURNAL OF HYDROGEN ENERGY 38 (2013) 9028–9042

Available online at www.sciencedirect.com

SciVerse ScienceDirect

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

Burning syngas in a high swirl burner: Effects of fuel composition

K.K.J. Ranga Dinesh [a,*], K.H. Luo [a], M.P. Kirkpatrick [b], W. Malalasekera [c]

[a] Energy Technology Research Group, Faculty of Engineering and the Environment, University of Southampton, Southampton SO17 1BJ, UK

[b] School of Aerospace, Mechanical and Mechatronic Engineering, The University of Sydney, NSW 2006, Australia

[c] Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, UK

ARTICLE INFO

Article history:
Received 21 January 2013
Received in revised form
2 May 2013
Accepted 5 May 2013
Available online 4 June 2013

Keywords:
Hydrogen
Syngas
Swirl
Vortex breakdown
Combustion
LES

ABSTRACT

Flame characteristics of swirling non-premixed H_2/CO syngas fuel mixtures have been simulated using large eddy simulation and detailed chemistry. The selected combustor configuration is the TECFLAM burner which has been used for extensive experimental investigations for natural gas combustion. The large eddy simulation (LES) solves the governing equations on a structured Cartesian grid using a finite volume method, with turbulence and combustion modelling based on the localised dynamic Smagorinsky model and the steady laminar flamelet model respectively. The predictions for H_2-rich and CO-rich flames show considerable differences between them for velocity and scalar fields and this demonstrates the effects of fuel variability on the flame characteristics in swirling environment. In general, the higher diffusivity of hydrogen in H_2-rich fuel is largely responsible for forming a much thicker flame with a larger vortex breakdown bubble (VBB) in a swirling flame compare to the H_2-lean but CO-rich syngas flames.

1. Introduction

Fundamentally all fossil hydrocarbon resources are non-renewable and a valuable gift from nature, and thus it is important to develop more efficient and effective ways to utilise these energy resources for sustainable development. Development of clean combustion technology would allow continued use of hydrocarbon fossil storage in the world without substantial emissions of greenhouse gasses such as carbon dioxide CO_2 [1]. Such clean combustion technology will rely on combustion of synthesis gas or syngas, which is mainly a mixture of hydrogen (H_2) and carbon monoxide (CO) [2].

There is growing interest in the combustion of syngas for more sustainable and cleaner power generation. One of the main current interests in hydrogen and syngas usage is the integrated gasification combined cycle (IGCC) process for electricity generation compared to traditional power generation system such as coal combustion [3,4]. Ultimately IGCC systems will be capable of reaching efficiencies of 60% with near-zero pollution. The unique advantages of IGCC systems have led to potential applications of gasification technologies in industry because gasification is the only technology that offers both upstream (feedstock flexibility) and downstream (product flexibility) advantages. Because they operate at higher efficiency levels than conventional

* *Corresponding author*. Tel.: +44 (0) 2380598301.
E-mail address: Dinesh.Kahanda-Koralage@soton.ac.uk (K.K.J. Ranga Dinesh).

0360-3199/$ – see front matter
http://dx.doi.org/10.1016/j.ijhydene.2013.05.021

fossil-fuelled power plants, IGCC systems emit less CO_2 per unit of energy. They are also well suited for application of future technologies to capture and sequester CO_2 [5,6].

In a typical IGCC plant, fuel is produced from a gasification process and burned with compressed air in a gas turbine to produce high-pressure hot gas. The high-pressure hot gas is expanded through the turbine to generate electric power. However, developing technology relevant to practical applications such as gas turbines, boilers and furnaces capable of combusting H_2-rich and CO-rich syngas requires understanding of more fundamental combustion properties [7]. Since the operability issues of burning syngas fuels in these applications generally involve complex, poorly understood interactions between swirling flow dynamics, it is necessary to establish a framework for the combustion characteristics of syngas fuels particularly in the presence of swirl [8].

Swirl has been commonly used for the stabilisation of high intensity combustion which acts as a source to improve flame stability, reduce combustion lengths, ensure minimum maintenance and extend life for the unit [9]. Unlike the jet flames, most significant effects of swirling flow are produced by recirculation. Numerous experimental and theoretical investigations with the aim of contributing to the understanding of swirl stabilised combustion systems have been reported over the past three decades, which have mainly focused on instabilities and onset of vortex breakdown in combustion systems [10–12]. Swirl has two roles in a combustor. In the combustor, it creates features such as jet precession, recirculation, vortex breakdown (VB) and a coherent structure referred to the precessing vortex core (PVC) [13]. In combustion systems, these phenomena can promote coupling between heat release, flow dynamics and acoustics and control most aspects of the flame including heat release rate, flow properties, flame evolution and emissions [14]. Therefore elucidating the underlying combustion characteristics of swirling flames has been the central focus of fundamental research particularly on hydrocarbon combustion.

Numerical simulation has the potential for closing the gap between theory and experiment and enabling dramatic progress in combustion science and technology [15]. The predictive capabilities of numerical models is advancing rapidly, and future research will further increase the accuracy and efficiency of these computational tools, ultimately leading over the next decade to the generalisation of computer-aided design and optimisation as a fundamental engineering tool. The large eddy simulation (LES) technique is widely accepted as a potential numerical tool to simulate turbulent combustion problems corresponding to laboratory and practical scale configurations [16,17]. In LES, the large scale turbulence structures are directly computed and small dissipative structures are modelled. State-of-the-art numerical computations have been reported in literature which demonstrates the ability of LES to capture the unsteady flow field in complex swirl configurations including multiphase flows and combustion processes such as gas turbine combustion, internal combustion engines, industrial furnaces and liquid-fuelled rocket propulsion [18–20]. Other investigations including validation of LES calculations for a model gas turbine combustor [21] and more complex General Electric aircraft engines and Pratt and Whitney gas turbine combustors were also reported [22,23]. More investigations on other important aspects of LES based combustion calculations such as effect complex mesh resolution [24] and ignitability characteristics [25] for gas turbine combustion were also carried out.

While the flame characteristics and stabilisation mechanisms of swirl stabilised systems have been fairly well investigated for conventional hydrocarbon-air systems, not much is known about the characteristics of alternative gaseous fuels such as H_2-rich and CO-rich syngas. The fundamental issue with syngas combustion is associated with the significant variation in their fuel compositions that changes the combustion characteristics such as flame speed, heat release ratio, local fuel consumption rate and flame instability mechanisms. The responses of swirling flames to these changes are not well characterised or understood. Because of the presence of high hydrogen concentration in a syngas mixture the combustion process of swirl stabilised system could develop into an undesirable flame flashback phenomenon, in which the flame propagates into the burner. The hydrogen-rich swirl flame with high diffusivity can travel upstream and even attach to the wall of the combustor. In general, many existing combustors which are currently in use for traditional hydrocarbon combustion may need substantial improvements for the burning of syngas. Furthermore, accurate prediction of the scalar and velocity fields of H_2-rich syngas combustion processes in swirl stabilised combustion system is a challenging task in that it requires the solution of a three-dimensional, highly unsteady turbulent reacting flow. As such, the present work investigates the flame characteristics of swirl stabilised non-premixed H_2/CO syngas flames using large eddy simulations. In previous studies, we have focused on direct numerical simulation (DNS) of hydrogen [26] and syngas combustion [27] for low Reynolds number impinging jet flames and LES of syngas combustion for high Reynolds number turbulent jet flames [28]. The present work is a continuation of our previous investigations more towards fuel variability and flame dynamics of practical engineering application with the ultimate aim of providing valuable insights on future clean combustion applications. The laboratory scale confined combustion configuration is the TECFLAM swirl burner which has been widely investigated for swirl stabilised natural gas combustion [29,30]. The objective of the research was to analyse the important physics of the effects of fuel variability on the flame characteristics of syngas combustion. The structure of the paper is as follows. Section 2 describes details about the confined simulated swirl burner. Computational details of LES solver and numerical test cases are presented in Section 3. Results of the simulations are discussed in Section 4. Finally conclusions are summarised in Section 5.

2. Simulated swirl burner

The computational domain (filtered axial velocity) of the TECFLAM confined swirl burner is shown in Fig. 1, which has been used for both non-premixed and premixed natural gas combustion. Extensive details have been reported in the literature for a range of TECFLAM swirling flames including