Computers & Fluids 80 (2013) 429–440

Contents lists available at SciVerse ScienceDirect

Computers & Fluids

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

Large-eddy simulations of unsteady hydrogen annular flames

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ARTICLE INFO

Article history:
Received 16 September 2011
Received in revised form 16 January 2012
Accepted 22 January 2012
Available online 30 January 2012

Keywords:
Large-eddy simulation
Swirl
Recirculation zone
Buoyancy

ABSTRACT

Large-eddy simulation (LES) of three-dimensional non-premixed hydrogen flames in a confined annular configuration has been conducted in order to clarify the interactions between different instabilities and swirling motion in the reacting jet flow field. The LES approach in parallel implementation follows a dynamic $k-\Delta$ subgrid-scale (SGS) model in which the SGS stress is modelled by the eddy viscosity hypothesis using the sub-grid scale turbulent kinetic energy. The results show a geometric central recirculation zone because of the bluff body configuration and a near-wall recirculation region for all the cases considered. The swirling flames also developed a toroidal recirculation zone with a collar-like shear structure around it that ended up in a vortex-breakdown bubble (VBB) for the case of moderate swirl number. As the degree of swirl was increased, the VBB increased in size and strengthened up to create a large central recirculation zone. It was shown that these regions with flow reversal enhance the air and fuel mixing and thus, improve the entire combustion process.

1. Introduction

Global warming concerns are leading to major efforts in utilising both renewable energy sources and hydrogen or hydrogen-enriched fuels for power generation. In this context, hydrogen- or syngas-fired gas turbines as clean combustion devices are becoming a real future option for power generation due to its high reduction in pollutant emissions such as carbon dioxide (CO_2), carbon monoxide (CO) and others hydrocarbon gases [1]. However, there are some problems that need to be addressed when current hydrocarbon fuels are replaced by hydrogen in practical gas turbine combustors. Firstly, hydrogen cannot be easily found as an isolate compound in nature and it has to be produced either externally by thermal conversion or electrolysis for instance, or integrated into a so-called Integration Gasification Combined Cycle (IGCC), where the gas turbine and the gasification system are coupled. Hydrogen fuelled gas turbines are not exempted of contaminant emissions since nitrogen oxides (NO_x) are always present in high temperature combustion systems using air as oxidizer. The formation of NO_x is related to both high temperature regions and long combustor residence times. Unfortunately, these conditions can be encountered in such applications and research work on this topic is constantly reported [1–3]. In order to reduce NO_x emissions in practical gas turbines, lean-premixed combustion technique has been used globally because of its effectiveness, although it is susceptible to problems such as flashback phenomena, instabilities or CO formation because of the very low temperatures [2].

As an alternative of lean-premixed combustion, non-premixed flames may provide a safer operation and avoid the undesirable flashback or autoignition [4]. Non-premixed flames are established when fuel and oxidizer are not mixed before they enter the combustion chamber. The mixing process of fuel and oxidizer plays an important role in the combustion process, since the reactant species have to reach the reaction region for combustion to proceed. Among various burner configurations, annular burners can be of particular interests to hydrogen burning. Compared with hydrocarbon fuels, hydrogen is more flammable and the flame can easily develop instabilities. As annular burners provide a means of geometrical stabilisation for flames because of its bluff body configuration, they are suitable for gas turbine applications. This configuration allows for the formation of an intense recirculation zone at the burner mouth which enhances mixing and combustion [3,5–9]. This configuration prevents extinction because of the highly strained recirculation zone brings the hot products of combustion back to the burner nozzle, thus reigniting and sustaining the flame [6]. On the other hand, swirl is also often encountered in gas turbine combustors as well as in many other industrial applications such as internal combustion engines, industrial burners or boilers. Swirling flows may be used to provide another flame stabilisation mechanism as a result of the establishment of an internal recirculation in the core region which improves the mixing and the rate of combustion [9]. The presence of swirl enhances the combustion process because the azimuthal momentum introduced by the swirl increases the entrainment of air to the jet core leading to a more stirred mixture and hence, an improved combustion process. The coupling of these two stabilisation mechanisms have been well characterised numerically [3,5,9,10] and

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doi:10.1016/j.compfluid.2012.01.013

experimentally [12], but it is not yet well understood in the case of non-premixed hydrogen flames in confined geometries.

Stability is one of the major concerns in gas turbines applications where reaching low NO_x emissions and high efficiency are key priorities. The flame can develop instabilities for various reasons. For instance, instabilities might be subject to the coupling between the flow and the acoustic field and this coupling may induce combustion oscillations, which could affect the performance of the system [2]. The instabilities can also arise from the buoyancy acceleration that the flow experiences because of the low density of the hydrogen and the flame, forcing the appearance of large-scale vortical structures. Some authors have reported these dynamic structures in the literature where buoyancy effects have been studied [13–15]. An additional source of instability accounted for in the present work that arises in practical applications is the Kelvin–Helmholtz type shear-layer instability. This instability can be triggered by a perturbation at the inlet plane and its effects in the flow field have been analysed in the literature [14–16]. These results showed that this perturbation may completely dominate the unsteady vortical structures which appear in the flow field.

Numerical simulations are nowadays a very powerful tool to obtain insight into the physics of complex flows involving various instabilities. Large eddy simulation (LES) is a technique that has been widely used to capture the unsteady vortical structures that appear in swirling flows due to Kelvin–Helmholtz type shear-layer instabilities as well as buoyancy effects. Unlike Reynolds-average Navier–Stokes (RANS) modelling approach that is not capable of reproducing unsteady flows with highly dynamic structures, LES has demonstrated its success at it [5–8,10,11]. Although there has been a large amount of research on investigating the various individual instabilities, the combined effects of annular configuration and swirl on a hydrogen flames have not been systematically investigated. This study was motivated by the lack of understanding on this important subject. The flow under investigation comprises the interaction between the two adjacent circular layers due to an annular configuration, the buoyancy instability which leads to large vortical structures, as well as the Kelvin–Helmholtz type shear-layer instability triggered by a perturbation. In the following, the theoretical approach and the governing equations are presented first, followed by numerical results and discussions for the studies performed. Finally, some conclusions are drawn.

2. Modelling and mathematical formulation

2.1. Physical problem and computational domain

The application addressed is a non-premixed hydrogen jet flame, where the fuel issues from an annular burner into ambient air with possible swirling motion in a confined geometry. This configuration is available at Tsinghua University as a laboratory burner. The geometry was based on an annulus with an outer diameter D_1 = 42 mm and an inner bluff body with diameter D_2 = 32.5 mm, leading to a blockage ratio of 0.60. The fuel discharges from the annular nozzle as shown in Fig. 1 at bulk velocity 160 cm/s that corresponds to a Reynolds-number of 1000, based on the inflow conditions. As the fuel comes out from the nozzle, it mixes with atmospheric air and subsequently, the chemical reactions take place when the mixture ignites in the stoichiometric region. The computational domain was setup as a cylindrical region above the jet nozzle plane with a length of $5D_1$ in the stream direction and a diameter of $3.5D_1$. Three different meshes with 0.5, 0.8 and 1.2 million of computational cells were considered in order to carry out a grid-dependence analysis of the numerical simulation.

2.2. Modelling approach and governing equations

The equations governing reactive flows in combustion processes are well known as the reactive Navier–Stokes equations which include the conservation of mass, momentum and energy as well as the conservation of the reactive species that appear/disappear after combustion takes place. In the LES approach, the turbulent large eddies of the flow are solved directly, while the smaller ones are described using closure rules. This procedure is followed by considering that the large eddies contain the major fraction of energy and play a more significant role in the transport of conserved quantities as well as in the control of the dynamics of the turbulence than the smaller eddies. Further, small eddies show a more isotropic behaviour and are therefore easier to represent by modelling approaches [4]. Thus, the LES equations were obtained by filtering the full compressible Navier–Stokes equations using the spatial Favre filter $\tilde{f} = \overline{\rho f}/\bar{\rho}$ that denotes filtered quantities. The governing equations for LES are presented here by the mass conservation equation, the momentum equation, the conservation of species and the internal energy conservation equation.

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_j}{\partial x_j} = 0 \tag{1}$$

$$\frac{\partial \bar{\rho}\tilde{u}_i}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_i\tilde{u}_j}{\partial x_j} = \frac{\partial}{\partial x_j}(\bar{\tau}_{ij} - \bar{\tau}_{ij}^{sgs}) + (\bar{\rho} - \rho_\infty)g \tag{2}$$

$$\frac{\partial \bar{\rho}\widetilde{Y}_m}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_i\widetilde{Y}_m}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\bar{\rho}\widetilde{D}_m\frac{\partial \widetilde{Y}_m}{\partial x_j}\right) - \frac{\partial \Phi_{j,m}^{sgs}}{\partial x_j} + \overline{\dot{\rho}^c} \tag{3}$$

$$\frac{\partial \bar{\rho}\widetilde{I}}{\partial t} + \frac{\partial \bar{\rho}\tilde{u}_i\widetilde{I}}{\partial x_j} = -\bar{p}\frac{\partial \tilde{u}_j}{\partial x_j} - \frac{\partial \bar{q}_j}{\partial x_j} + \frac{\partial \tilde{u}_i\bar{\tau}_{ij}}{\partial x_j} - \frac{\partial h_j^{sgs}}{\partial x_j} - \Theta^{sgs} + \overline{\dot{Q}^c} \tag{4}$$

In Eqs. (1)–(4), the variables $\tilde{u}$, $\bar{\tau}_{ij}$, $\bar{\rho}$, $\widetilde{Y}_m$ and $\widetilde{I}$ represent the velocity, stress tensor, density, mass fraction of species m and internal energy of the filtered flow field respectively. The stress tensor in the momentum equation and the heat flux from the species conservation are given by:

$$\bar{\tau}_{ij} = -\bar{p}\delta_{ij} + 2\bar{\rho}\bar{\nu}\left(\bar{S}_{ij} - \frac{1}{3}\bar{S}_{kk}\delta_{ij}\right) \tag{5}$$

$$\bar{q}_j = -\overline{K}\frac{\partial \widetilde{T}}{\partial x_j} - \bar{\rho}\sum_{m=1}^{N}\tilde{h}_m\widetilde{D}_m\frac{\partial \widetilde{Y}_m}{\partial x_j} \tag{6}$$

The buoyancy effects were included in the momentum equation to account for the density inhomogeneity in the flow field. The SGS diffusive mass flux was ignored from the conservation of the reactive species equations following [17] since this term may be considered much smaller than the SGS species mass flux $\Phi_{j,m}^{sgs}$. This assumption is based upon the mechanisms of chemical species in a turbulent flow field. The transport of species depends on the convection and diffusion as well as the chemical source terms. It is known the convection term is usually much more significant than the diffusion term in a turbulent flow field, which makes the scalar transport phenomenon strongly dependent on turbulent convection. Accordingly, the SGS diffusion was neglected in the calculation. For the energy transport of chemically reactive turbulent flows, the transport of internal energy is governed mainly by pressure, convection and heat release effects. The dissipative effects including the contributions from the viscous work and turbulent dissipation may be dominated by turbulent dissipation, since the work related to viscous effects is negligible. Based on this, the only terms that need to be modelled in the internal energy equation were the SGS heat flux h_j^{sgs} and the SGS viscous work Θ^{sgs}.