Applied Energy 111 (2013) 401–415

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Experimental and numerical investigations of an atmospheric diffusion oxy-combustion flame in a gas turbine model combustor

Medhat A. Nemitallah [a,b,c,*], Mohamed A. Habib [a]

[a] KACST TIC #32-753, KACST and Mechanical Engineering Department, Faculty of Engineering, KFUPM, Dhahran 31261, Saudi Arabia
[b] Mechanical Engineering Department, Alexandria University, Egypt
[c] Mechanical Engineering Department, Massachusetts Institute of Technology, USA

HIGHLIGHTS

- Experimental and numerical study of oxy-combustion flame in gas turbine combustor.
- Modified 2-step methane oxycombustion reaction kinetics model is introduced.
- Wide range of operating parameters was considered experimentally and numerically.
- Oxycombustion and emission characterization and flame stabilization are studied.
- Validation of the oxycombustion reaction kinetics model is also presented.

ARTICLE INFO

Article history:
Received 15 December 2012
Received in revised form 4 May 2013
Accepted 12 May 2013
Available online 4 June 2013

Keywords:
Emission characteristics
Flame stabilization
Gas turbine model combustor
Oxy-combustion model
Swirl stabilized flames

ABSTRACT

An atmospheric diffusion oxy-combustion flame in a gas turbine model combustor has been investigated experimentally and numerically. Oxy-combustion and emission characterization, flame stabilization and oxy-combustion model validation analyses are the main goals of the present research work. The combustor is fuelled with CH_4 and a mixture of CO_2 and O_2 as oxidizer. A modified two-step oxy-combustion reaction kinetics model for methane–oxygen combustion has been used in order to predict accurately the oxy-combustion characteristics. The conducted experimental results were used to validate the numerical model. Wide ranges of different operating parameters have been considered including equivalence ratio, percentage of O_2/CO_2 in the oxidizer mixture and fuel volume flow rate. The stability of the oxy-combustion diffusion flame is also investigated both experimentally and numerically. The experimental and numerical results showed that the stability of the oxy-combustion flame is affected when the operating percentage of oxygen in the oxidizer mixture is reduced below 25%. In all cases, flame was extinct for conditions of less than 21% oxygen in the oxidizer mixture. Flame visualization over a wide range of operating parameters has been carried out experimentally and comparisons with the numerical results have been conducted. The flames have been characterized in detail by measuring the exhaust gas temperatures and emissions and comparing them with those from the numerical model. The combustion was found to be improved with increasing the percentage of O_2 at inlet however there is a limitation in temperature. Both experimental and numerical results are in good agreement. The modified two step reaction kinetics model was found to be capable of capturing the trends of temperature and the overall flame shape of the experimental data. Flame zone is also characterized in details by plotting the axial and radial temperatures, species concentrations and flow velocities using the numerical model.

1. Introduction

Global climate change is one of the greatest challenges in the present century. The greenhouse gas making the largest contribution to global climate change from human activities is carbon dioxide (CO_2). Strong evidence suggests that both the average global temperature and the atmospheric CO_2 concentration have significantly increased since the onset of the industrial evolution, and they are well correlated [1]. CO_2 emissions from the fossil fuel-based large power plants are of main concern as they are the largest sources of CO_2 in the coming decades [2]. Concerns over climate change have led to mounting efforts on developing technologies to reduce carbon dioxide emissions from human activities [3,4]. Technological solutions to this problem ought to include a substantial improvement in energy conversion and utilization

* Corresponding author at: KACST TIC #32-753, KACST and Mechanical Engineering Department, Faculty of Engineering, KFUPM, Dhahran 31261, Saudi Arabia.

E-mail addresses: medhatahmed@kfupm.edu.sa, medhat.ahmed35@yahoo.com, mahmed@mit.edu (M.A. Nemitallah).

0306-2619/$ - see front matter
http://dx.doi.org/10.1016/j.apenergy.2013.05.027

Nomenclature

CFD	computational fluid dynamics	CCS	carbon capture and storage
3D	three dimensional	κ	absorption coefficient
R_l	mass rate of creation or depletion	RTE	radiative transfer equation
u_j	velocity component	Φ	equivalence ratio
Γ_Φ	diffusion coefficient	$\bar{\rho}$	fluid density
c_μ	constant	$e_{b\lambda}$	blackbody spectral emissive power
μ_t	turbulent viscosity	σ_Φ	constant
σ_s	scattering coefficient	σ_V	oxygen vacancy conductivity
ε	epsilon		

efficiencies, carbon capture and storage (CCS), and expanding the use of nuclear energy and renewable sources such as biomass, hydro-, solar, wind and geothermal energy [3]. Carbon capture from large point sources such as power plants gives the possibility of a relatively quick response to climate changes with a reasonable low cost. Several approaches have been evaluated and reviewed for capturing CO_2 in the utility industry, namely carbon capture and storage technology (CCS), including pre-combustion capture, oxy-fuel combustion, and post-combustion capture [5].

As a promising CCS technology, oxyfuel combustion can be used for existing power plants and also for new ones. Oxyfuel combustion gives different characteristics of heat transfer, ignition, burnout as well as NO_x emission [6]. During oxyfuel combustion process, a mixture of oxygen and recycled flue gases are used for the combustion of the fuel. The exhaust gases consist of a mixture of CO_2 and H_2O. A large portion of the flue gases should be recycled in order to substitute the removed nitrogen to ensure there is enough gas to carry the heat through the boiler and in order to control the flame temperature. Another way of particular interest is the use of oxyfuel combustion in gas turbines. For oxy-fuel gas turbine cycles, researches have been focused on thermodynamic studies of system performance. The combustion behavior, e.g. the flame dynamics and reaction zone structures in the gas turbine combustors, is less addressed. Swirl stabilized flames are used extensively in practical combustion systems because they enable high energy conversion in a small volume and exhibit good ignition and stabilization behavior over a wide operating range. In order to reduce the flame temperature and thereby the remaining oxygen in the flue gas, it is beneficial to premix the oxygen and CO_2 or steam before introducing them to the combustor. Also, to generate a stable combustion in a gas turbine combustor through oxy-fuel combustion, certain minimal oxygen level in the oxidizer has to be maintained. This is because of the need to have the required high temperature inside the reaction zones for the chain reactions to proceed. Heil et al. [7] reported that poor burnout and lifted dark flames appeared when the oxygen mole fraction in the O_2/CO_2 stream was set to 21%; when the oxygen volume fraction was increased to 27% and 34%, full burnout and stable flames were obtained. In order to burn the fuel with lower oxygen level in the oxidizer (O_2/CO_2) stream the burner had to be modified to allow for recirculation of hot gases to the flame. With this high level of oxygen in the oxidizer mixture the combustion products however become hot and this may lead to high level of oxygen in the flue gas due to the dissociation reactions that occur at high temperatures. There is an optimal "window" of oxygen/diluent ratio in the oxidizer stream [8].

Stable combustion and low turbine inlet temperature can be obtained simultaneously by optimizing the ratio of oxygen to CO_2 supplies in the oxidizer mixture to the combustion chamber. Liu et al. [8] reported that the primary oxidizer which is supplied in the upstream through the dome of the combustion chamber should have minimal oxygen level of 24% under the oxidizer temperature 520 K condition. Kutne et al. [9] have checked the stability of a swirl stabilized oxyfuel/CH_4 flames for O_2/CO_2 percentages of 20/80–40/60%, equivalence ratios of 0.5–1 and thermal powers of 10–30 kW. They reported that attempts of operating the burner with less than 22% O_2 were unsuccessful even at stoichiometric conditions. Syngas and methane flames for premixed swirl stabilized conditions for two different oxidizers of air and $O_2/CO_2/N_2$ have been studied by Williams et al. [10]. They report lower nitrogen oxides concentrations (NO_x) for the quasi-oxyfuel flames and higher carbon monoxide concentrations (CO), suggesting stoichiometric operation at 20–24% O_2 as ideal for low emissions. Ditaranto and Hals [11] studied the influence of stoichiometric operation and high Oxygen content in the oxidizer mixture on thermo-acoustic oscillations in sudden expansion jet configuration. They reported occurrence of thermo-acoustic instabilities as O_2 content in the oxidizer was increased, characterizing different instability modes dependent on flow velocity and flame speed variations. Anderson and Johnsson [12] have performed experiments on a 100 kW test unit for air and two O_2/CO_2 test cases with different recycled feed gas mixture concentrations of O_2 (OF 21 at 21 vol.% O_2, 79 vol.% CO_2 and OF 27 at 27 vol.% O_2, 73 vol.% CO_2). They showed that the fuel burnout is delayed for the OF 21 case compared to air-fired conditions as a consequence of reduced temperature levels. Instead, the OF 27 case results in more similar combustion behavior as compared to the reference conditions in terms of in-flame temperature and gas concentration levels, but with significantly increased flame radiation intensity. A detailed literature about the application of oxy-fuel combustion technology into gas turbines is there in our recent review work [5].

In the present research work, experimental and numerical investigations of an atmospheric diffusion oxy-combustion flame in a gas turbine model combustor are presented. Oxy-combustion and emission characterization, flame stabilization and oxy-combustion model validation analyses are the main goals of the present work. The combustor was supplied with CH_4 and CO_2 and O_2 as oxidizer mixture. Large range of operating parameters was considered including equivalence ratio, percentage of O_2/CO_2 in the oxidizer mixture, and fuel volume flow rate. The goals for the present work is to check the stability of the oxy-combustion diffusion flame experimentally and numerically and also to check the minimum permissible percent of O_2 in the oxidizer mixture required in order to get a stable flame. Visualizations of the flame at the above mentioned operating conditions were conducted. Different flames were characterized by measuring the exhaust gas temperatures and comparing them with the numerical model results. A modified two-step oxy-combustion reaction kinetics model for methane–oxygen combustion has been used in order to predict a clearer oxy-combustion characteristics and then more accurate numerical results in order to correctly validate the numerical model using the experimental results.