Applied Thermal Engineering 113 (2017) 490–498

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Research Paper

Numerical study of hydrogen enrichment effects in oxy-flame turbulent of three separated jets

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HIGHLIGHTS

- The effects of hydrogen addition to oxy-methane flame were numerically investigated.
- The use of H_2 improve the homogenization of jets and the reaction between them.
- With the addition of H_2 to oxy-combustion, pollutant emissions decreases (CO, CO_2).
- Hythane flame affects to the radiative heat flux and increases the maximum temperature.

ARTICLE INFO

Article history:
Received 3 September 2016
Revised 13 October 2016
Accepted 30 October 2016
Available online 1 November 2016

Keywords:
Oxy-flame
Hydrogen enrichment
Diffusion flame
Turbulent
Separated-jet
Flame stability

ABSTRACT

The development of oxy-fuel combustion in a burner with separated jets presents a promising technology ensuring higher thermal efficiency, better flame stability and more safety compared to premixed combustion. This paper presents a numerical investigation of burner of 25 kW power consisting of a central methane and hydrogen jet surrounded by two oxygen jets. This study aims to evaluate the effect of hydrogen on the dynamics, the distribution of temperature, the stability of the flame, the variation of species mass fraction (CO, CO_2...) and the radiative heat flux. Results show that the addition of hydrogen has a considerable effect on the dynamic behaviour and flame temperature. Indeed, using hydrogen increases the temperature maximum, accelerates the fusion of three jets, and favours the mixing between them. Therefore, it ensures the flame stabilization. Moreover, the results show that the mass fraction of CH_4, CO and CO_2 are highly reduced with the addition of hydrogen. Furthermore, adding hydrogen attenuates the radiative heat flux.

1. Introduction

Fire is a major step forward in the process of our evolution. Today, *anti*-pollution standards evolve and the performances of the combustion chambers are optimized, which require the development of new types of burners. Manufacturers are turning to the use of burners with separate injections. Generally, there are three types of the flame: the diffusion flame (non-premixed flame), premixed flame, and partially premixed flame. It is difficult to overstate the importance of energy research in today's dynamic and globally competitive environment. Analysts expect worldwide energy consumption to increase by approximately 50% by the year 2030 compared to 2005. The Energy Information Administration (EIA) predicts that the annual primary energy consumption in the U.S. will increase from 101.9 quadrillion Btu to 113.6 quadrillion Btu between the years 2007 and 2030. This requires developing new burners and new technics to ameliorate the structure of the flame, such as the separated-jets burner concept whose emission reduction capacity is very promising [1]. This type of burner consists in separating the injection of gas and oxygen to dilute methane with hydrogen and the oxygen with air. In recent years, stability of a turbulent diffusion flame has received renewed attention due to its varied practical applications. It is used in many systems, such as production of heat (boilers and industrial furnaces), electricity (thermal power plant) and transportation (automotive and aircraft engines, rocket engines ...).

A new generation of burner with separated injections of fuel and oxide presents attractive perspectives in term of limitation

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http://dx.doi.org/10.1016/j.applthermaleng.2016.10.194
1359-4311/

Nomenclature

Cp	heat capacity (kJ/kg k)
D	diffusion coefficient (m^2/s)
E	specific enthalpy (kJ/kg)
f	body force
Ji	diffusion flux (mol/m^2 s)
LCV	lower calorific value (kJ/kg)
M	molecular weight (kg/mol)
$\dot{m}$	mass flow (kg/s)
P	power of the burner (kW)
p	absolute pressure (Pa)
Q	volume flow (l/s)
q	thermal heat (J)
Ri	rate of production
T	temperature (K)
u, U	velocity vector (m/s)
Yi	mass fraction of species i
q_r	radiative flux (W/m^2)
a	absorption coefficient
G	incident radiation

Greek letters

ϑ'	stoichiometric coefficient for reactant in reaction
ϑ''	stoichiometric coefficient for product in reaction
ρ	density (kg/m^3)
τ	stress tensor
μ	dynamic viscosity (kg/m s)
σ_S	scattering coefficient

of nitrogen oxide emissions. Several studies have studied the structure of diffusion flame and non-reacting multiple jets [2–6], they were interested in the mixing of the jets, their dynamics and the pollutant emissions. All these studies confirm that the use of multiple jets rather than a single jet leads to better flame stability and lower productions of NO. The separation of jets allows the dilution of each region of diffusion flame by the combustion products. This dilution homogenizes the temperature in the physical space and decreases the maximum temperature reached in the flame. As a result, a decreasing of pollutants production is registered [7–9]. Weifeng et al. [10] studied numerically the stagnation point offset of opposed jets at various exit velocity ratios and nozzle separations using the Reynolds stress turbulence model. They found that the impingement plane deviates from the midpoint and the flow field becomes stable wile reaching a small difference between the exit velocities of the opposed jets. However, the studies on reacting multiple jets in combustion are mostly limited. Sautet et al. [11] investigated the oxy-combustion, they found that the use of oxygen in separated-jet burners opens interesting possibilities in pollutant and flame control, and has important impacts on flame stability. In fact, the increase of distance between the jets and the central jet velocity makes possible to reduce appreciably the NOx emission. Menon and Gollahalli have studied the interaction between multiple-jet flames of propane [12]. They observed that Carbon monoxide concentration and flame radiation are maximum at moderate values of separation distance and NO concentration decreases monotonically with it. Leite et al. [13] studied the influence of the spacing between the jets, jet number and their diameters on the length of the acetylene flame, their results showed that the flame length of multiple jets increases when flame separation distance decreases and the number of jets increases. The numerical study of Mergheni et al. [14] have studied numerically the effects of the equivalence ratio decrease on characteristics of a burner with three jets, focusing on the mixing of the jets, their dynamics and the pollutant emissions. We have proved the efficiency of oxy-burners in separated nozzles with lean equivalence ratio. Three turbulent aligned jets are experimentally investigated by Boushaki [1]. He showed that the distance at which the jets will interfere depends on the spacing between them, and when this distance decreases, the flame becomes increasingly stable. They also demonstrated that increasing both the central jet velocity and the separation distance between the jets, makes it possible to reduce appreciably the production of pollutants such as nitrogen oxides. The numerical study of Riahi et al. [15] on the non-premixed combustion with k-epsilon model allowed to see very significant results on the flow dynamics and the pollutant emissions. He concluded that the change in the overall equivalence ratio made a change on the structure and the temperature distribution. Indeed, the increase in the air-flow increases the temperature, and pollutant emissions decrease with using the oxygen in place of the air.

Many researchers [16–21] performed experimentally and numerically the effect of hydrogen jet on stability and distribution of temperature. Sébastien et al. [16] investigated the hythane in oxy-combustion in a burner with separated jets and they noted that addition of hydrogen permit to reduce its fluctuations and to decrease the flame lift-off height. The results of El-Ghafour et al. [17] on turbulent naturel gas-hydrogen jet diffusion flame showed that the addition of hydrogen undergoes a gradual improvement of the flame stability and reduces the flame length with high concentrations of hydrogen. The increase in the OH radical that is accompanied with the addition of hydrogen improves the combustion rate and reduces the flame length. Ilbas et al. [18] have studied experimentally spherical flames and they showed that the speed of flame grows exponentially when hydrogen is added to natural gas. The addition of hydrogen to natural gas has a large influence on the evolution of the flame velocity. They stated that increasing the hydrogen percentage in mixture causes an increase in the resultant burning velocity and widening the flammability limits. Several studies have shown a growth rate of the flame when the concentrations of hydrogen increase. Briones et al. [19] have shown, that an increase of 75% hydrogen concentration allows to increase the velocity of the flame more than 60%. This increase in velocity is due to the increase of chemical reactivity between fuel and oxygen. The flames with oxygen have greater stability than those with the air because the use of the oxygen accelerates the reaction rate. These features have the advantage of reducing the convection time and have better resistance to external interference. Mishra and Kumar [20,21] investigated the effect of hydrogen addition on the flame length, radiant fraction, soot free length fraction, gas temperature and emission NO_x for the Liquefied Petroleum Gas composed of 30% C_4H_{10} and 69% C_3H_8 jet diffusion flame.

In this context, the present work provides a numerical investigation of the turbulent methane-oxygen jet with the addition of hydrogen in a burner with three separated jets. This study aims to improve combustion in furnaces. The objective of this work is to examine the effects of hydrogen addition to methane-oxygen mixtures combustion on the flame stability, distribution of temperature, exhaust emissions and radiative heat flux.