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A parametric study of microjet assisted methane/air turbulent flames

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ABSTRACT

A parametric study of microjet assisted methane/air turbulent flames characteristics is numerically investigated. The Presumed Probability Density Function model and the Discrete Ordinates model are respectively considered for combustion and radiation modeling. The *k-epsilon* Standard model with Pope Correction is adopted as a turbulence closure model. The two step Tesner model is used to quantify the soot particle production in the flame configuration. Comparison with our previous work using the *k-epsilon* Realizable model shows that the *k-epsilon* Standard model with Pope Correction ensures better predictions. The microjet velocity and diameter effects on thermal field, mixing process and soot emission are then discussed. Numerical findings show that the microjet can be used as an efficient tool controlling methane/air turbulent flames. On the one hand, it is shown that the microjet creates an inner flame in the vicinity of the central nozzle exit but does not globally alter the methane/air flame shape. On the other hand, mixing process can be enhanced for high microjet Reynolds number either by increasing the microjet velocity or by decreasing its nozzle diameter for a constant microjet mass flow rate. Soot production can be consequently reduced for low microjet diameter and high velocity values.

1. Introduction

Reactive mixture control constitutes the major objective of researchers and industrials dealing with combustion equipments. Indeed, an efficient mixture guarantees flame stability, ensures better performance and reduces consequently pollutants' emission. Several techniques were applied to control reactive mixing process. Kang et al. [1] have underlined the effect of moderate or intense low-oxygen dilution (MILD) regime in reducing unburned hydrocarbons fraction at the furnace outlet. Pulse combustion has been used as an efficient tool able to maximize thermal efficiency and minimize pollutant emission [2]. Zhuang et al. [3] have controlled the intake air swirl motion in a spark-ignition direct-injection engine in order to improve fuel/air mixing process under low load conditions. Yu et al. [4] have highlighted the repetitive laser-induced plasma efficiency in the stabilization of a premixed methane/air flame. Jeon et al. [5] have presented the homogeneous charge compression ignition method as an effective strategy in controlling combustion performance, flame, and soot in a compression-ignition engine. The use of hydrogen as an alternative to fossil fuels has been elucidated by Nicoletti et al. [6]. By defining a global environmental index for different fuels, the authors have shown that industrial devices performance is the most increased when hydrogen is used [6]. Zhang et al. [7] have proven the effectiveness of hydrogen addition in improving a butanol engine performance and controlling nitric oxides (NOx) for a lean combustion regime. Amrouche et al. [8] have shown that hydrogen enrichment improves combustion process through shortening the flame length. Kashir et al. [9] have studied propane enriched flames developed in a bluff-body burner. Local heat release rate was found to be increased with hydrogen addition due to the inflow carbon atoms decrease [9]. Ilbaş et al. [10] have studied the effect of the swirl number on combustion characteristics and pollutants emission of hydrogen enriched flames developed in a gas-fired combustor. Chouaieb et al. [11] and Tabet et al. [12] have presented hydrogen enrichment as a promising technique able to enhance mixing process. The effect of microjet association to hydrogen enriched flames in reducing soot emission and promoting reactive mixture have been highlighted by Chouaieb et al. [11].

This work constitutes a contribution to underline the microjet technique as a promising tool in controlling turbulent flames. Actually, the concept of microjet in reactive coaxial configurations was introduced by the experimental works of Ganguly et al. [13] and Sinha et al. [14]. Indeed, a microjet can be simply defined as a jet of air or inert species ejected from a low diameter nozzle.

Ganguly et al. [13] have equipped an unconfined coaxial burner by a central air microjet of diameter D_j equal to 1 mm. Their goal was to show experimentally the capacity of the added microjet to control methane/air flame shape, luminosity and emissions for

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Nomenclature

D	diameter, m
D_h	hydraulic diameter, m
D_k	molecular diffusion coefficient, $m^2 \cdot s^{-1}$
E	total mass energy, $J \cdot kg^{-1}$
f	mixture fraction
f′	fluctuation of the mixture fraction
g	gravity acceleration, $m \cdot s^{-2}$
H	enthalpy, J
h	specific enthalpy, $J \cdot kg^{-1}$
k	kinetic energy of turbulence, $m^2 \cdot s^{-2}$
L	length of the cylindrical volume, m
P	static pressure, Pa
T	temperature, K
u_i, u_j	mean velocity components along x and y directions, $m \cdot s^{-1}$
u'_i, v'_j	fluctuating velocity components, $m \cdot s^{-1}$
V	velocity magnitude, $m \cdot s^{-1}$
X	axial position, m
Y	radial position, m
Y_k	mass fraction of species k

Greek symbols

ρ	density, $kg \cdot m^{-3}$
μ	dynamic molecular viscosity, $kg \cdot s^{-1} \cdot m^{-1}$
ν	kinematic viscosity, $m^2 \cdot s^{-1}$
ε	dissipation rate of the turbulent kinetic energy, $m^2 \cdot s^{-3}$
$\varnothing_i$	thermo-chemical scalar (mass fraction, density and temperature)
τ_{ij}	stress tensor, $kg \cdot s^{-2} \cdot m^{-1}$

Subscript

a	air
g	fuel (methane)
j	microjet
t	turbulent

different microjet rates. Experimental results demonstrate the microjet ability in reducing flame's length. It was also found that the microjet assisted flames were characterized by a lower brightness reflecting less soot production.

The experiments of Ganguly et al. [13] have been prosecuted by those of Sinha et al. [14]. These authors have been interested in microjet assisted methane/air flames developed in a confined volume. The microjet has been presented as a hydrodynamic tool to control methane/air flames by improving the air training in the near field of the central nozzle exit area [14].

Another experimental study was conducted by Yuchun et al. [15] using several lateral microjets of diameters equal to 1 mm. In their work, the authors have been interested in jet flames issued from a burner equipped with six lateral microjets. This study has shown that, for the same air and fuel rates, the lateral microjets were able to modify flames structure and reduce their lengths by improving mixture.

Certainly, the above studies reflect the interest of the microjet technique and its efficiency in controlling methane/air diffusion flames characteristics and pollutants especially because a microjet can be easily handled in industrial combustion engines.

Nevertheless, the number of researches dealing with this axis is limited and few numerical studies are carried out. Kanchi et al. [16] has explored, numerically, the feasibility of microjets' addition to improve round and flat burner performance. Using the *k-epsilon* Standard model, simulations showed that the presence of microjets with a flow rate not exceeding 1% of the main flow rate implies an increase in heat release by 22% and 140% respectively for round and flat burners.

A more recent numerical study was conducted by Chouaieb et al. [11]. In this work, hydrogen enrichment was applied to reduce soot emission and enhance mixing process in methane/air confined flames under the addition of an air microjet. Numerical findings have shown that the use of a central microjet associated to hydrogen enriched flames succeeds in ensuring better mixing process and less soot production.

Certainly, hydrogen enrichment can be judged as a promising technique in improving reactive mixture and decreasing pollutants emissions [17]. Nevertheless, the use of hydrogen in industrial devices is limited by the high cost related to its storage and production.

In this context, contrary to our previous work [11], our objective is to underline, presently, the microjet efficiency in controlling methane/air flames characteristics without implying a composite fuel (methane-hydrogen mixture). A parametric study is then carried out to optimize mixing process and soot emission for microjet assisted methane/air flames developed in the Brookes and Moss confined coaxial configuration [18].

Particularly, in the first part of this paper, previous numerical validation is enhanced in terms of temperature, mixture fraction and soot profiles. The use of the *k-epsilon* Standard turbulence model with Pope Correction instead of the Realizable model [11] shows better agreement with the experimental data of Brookes and Moss [18]. In the second part, the effect of the microjet velocity and diameter on methane/air flames characteristics is investigated.

2. Presentation of the computational domain

The Brookes and Moss configuration [18] is used to study numerically a confined turbulent reactive flow issuing from two coaxial jets. These authors have studied experimentally [18] then numerically [19] the development of a turbulent methane/air diffusion flame in a confined volume.

Given the availability of several measurements in terms of temperature, mixture fraction and soot particles in both axial and radial positions, this configuration was previously studied by many authors. Kronenburg et al. [20] were the first who have studied numerically this configuration. The importance of soot particles' differential diffusion in predicting soot profiles has been demonstrated by Kronenburg et al. [20] and Navarro-Martinez et al. [21] for methane/air flames. The same aspect has been discussed by Wolley et al. [22] for both methane/air and propane/air flames. Tabet et al. [12] have shown the efficiency of hydrogen addition to methane/air flames in enhancing mixing process. Saqr et al. [23] have proven that pollutants production can be reduced by increasing the air free stream turbulence intensity. The effect of turbulence model and radiation model in capturing thermal and dynamic fields has been studied respectively by Saqr et al. [24] and Kassem et al. [25]. Furthermore, Kassem et al. [26] have shown the capacity of the Eddy Dissipation model implementation in OpenFoam code in capturing thermal and species fields.

It should be noted that the Brookes and Moss configuration is equipped with an internal nozzle, of diameter D_g equal to 4 mm ejecting methane. An annular nozzle of diameter D_a equal to 155 mm is used to hold the external air jet. The resulting turbulent