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Hydrogen–hydrocarbon turbulent non-premixed flame structure

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ABSTRACT

In this study, the structure of turbulent non-premixed CH_4-H_2/air flames is analyzed with a special emphasis on mixing and air entrainment. The amount of H_2 in the fuel mixture varies under constant volumetric fuel flow. Mixing is described by mixture fraction and its variance while air entrainment is characterized by the ratio of gas mass flow to fuel mass flow at the inlet section. The flow field and the chemistry are coupled by the flamelet assumption. Mixture fraction and its variance are transported by the computational fluid dynamics (CFD) code. The slow chemistry aspect of NO_x is handled by solving an additional transport equation with a source term derived from flamelet library.

The results obtained show an improvement of mixing with hydrogen addition leading to a strong consumption of CH_4 and a high air entrainment into the centerline region. As a global effect of this, the composite fuels burn faster and thereby reduce the residence time which ultimately shortens the flame length and thickness. On the other hand, hydrogen is found to increase NO_x level.

1. Introduction

The attention given to CH_4-H_2 mixtures as a fuel has considerably increased in the last couple of years. This tendency is attested by the considerable number of publications on this subject. These studies among others dealt with the determination of autoignition delay [1], flame stability [2–4], and pollutant emissions [5,6]. The aim of this study is to assess numerically the effect of hydrogen addition on the structure of turbulent non-premixed CH_4/air flame. The prediction analysis is based on the knowledge of mixing and air entrainment. It is of high importance to investigate mixing and air entrainment as they are at the origin of flame stabilization and pollutant formation.

This research is a complementary approach to the previous studies on the subject which were restricted to specific operating conditions (temperature, pressure, H_2 percentage in the mixture, etc.) and limited to global flame parameter measurement or prediction [3,6].

The model adopted here uses the k–ε turbulence closure within SLFM (Steady Laminar Flamelet Model) for combustion.

The flamelet approach allows reducing the computational burden as the flow field and the scalar field are decoupled. In this approach, the mixing process is treated locally as a one-dimensional problem.

The numerical simulations are performed in the configuration of Brookes and Moss [7] in which detailed data sets of mixture fraction and temperature measurements of this

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Nomenclature

T	temperature, K
P	pressure, Pa
Y	mass fraction
Z	mixture fraction
k	turbulent kinetic energy, $m^2\,s^{-2}$
H	enthalpy, $J\,kg^{-1}$
$h°$	enthalpy of formation, $J\,kg^{-1}$
C_P	specific heat coefficient at pressure constant, $J\,kg^{-1}\,K^{-1}$
$\dot{m}$	mass flow, $kg\,s^{-1}$
MW	molecular weight, $g\,mol^{-1}$
x	axial direction, mm
r	radial direction, mm

Greek letters

ε	dissipation rate of turbulent kinetic energy, $m^2\,s^{-3}$
μ	dynamic viscosity
φ	global equivalence ratio
ρ	density, $kg\,m^{-3}$
χ	scalar dissipation rate, s^{-1}

Subscripts

O	oxidizer (air)
F	fuel
g	gas (burnt gas)
0	injection section
st	stoichiometric
n	species
ref	reference
t	turbulent

Superscripts

~	Favre-averaged
–	Reynolds-averaged
″	fluctuations

flame are available at 1 atm in the case of 100% CH_4. These experimental data are used for model validation.

The article consists of five sections. Following a brief explanation of the flame configuration, the combustion model adopted is introduced. A general description of the governing equations and turbulence modelling is then presented. The numerical simulation results are presented with a discussion in the last section. The conclusion summarizes the findings of the presented work.

2. Flame configuration

The flame configuration studied is a confined co-flow axisymmetric turbulent diffusion flame (Fig. 1). The nozzle diameter of the burner is 4.07 mm with an annulus of 0.16 mm width for the premixed pilot flame. The mean inlet velocity of the fuel jet is 20.3 $m\,s^{-1}$ and the jet Reynolds number of the flame is 5000. Experimental data of axial and radial profiles of mean temperature and mean mixture fraction are available in the case of 100% CH_4 [7].

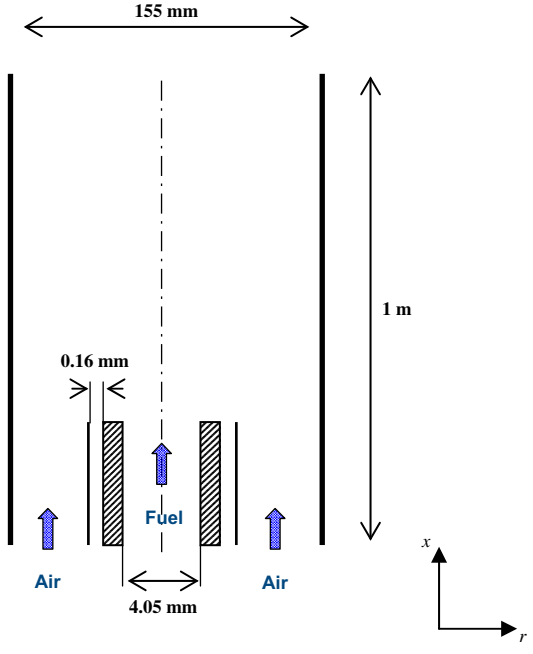

Fig. 1 – Flame configuration.

3. Combustion model

The flamelet model used in this study was developed by Pitsch and Peters [8]. In this formulation mixture fraction variable Z is obtained from the solution of a conservation equation with an arbitrary diffusion coefficient and appropriate boundary conditions. Note that the instantaneous thermochemical state of the fluid is related to a conserved scalar quantity known as the mixture fraction which is defined as [8]

$$Z = \frac{\frac{\phi Y_F}{Y_{F,0}} - \frac{Y_O}{Y_{O,0}} + 1}{\phi + 1} \tag{1}$$

where φ is the equivalence ratio defined by

$$\phi = \frac{Y_{F,0}}{Y_{O,0}} \Big/ \left.\frac{Y_F}{Y_O}\right|_{st} \tag{2}$$

Table 1 – The characteristics of chemical mechanisms used in Davidenko (2005) [11].

Chemical mechanisms	Application	Number of reactions	Number of species
GRI 1-2	Natural gas	177	30
GRI 3.0	Natural gas + NO_x	325	52
Princeton	CH_4–C_3H_8	621	90
Leeds v. 1.5	CH_4–C_2H_6	175	35
CNRS-LCSR	Natural gas + NO_x	689	153