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Effect of the mixing fields on the stability and structure of turbulent partially premixed flames in a concentric flow conical nozzle burner

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ABSTRACT

The mixing field is known to be one of the key parameters that affect the stability and structure of partially premixed flames. Data in these flames are now available covering the effects of turbulence, combustion system geometry, level of partially premixing and fuel type. However, quantitative analyses of the flame structure based on the mixing field are not yet available. The aim of this work is to present a comprehensive study of the effects of the mixing fields on the structure and stability of partially premixed methane flames. The mixing field in a concentric flow conical nozzle (CFCN) burner with well-controlled mechanism of the mixing is investigated using Rayleigh scattering technique. The flame stability, structure and flow field of some selected cases are presented using LIF of OH and PIV. The experimental data of the mixing field cover wide ranges of Reynolds number, equivalence ratio and mixing length.

The data show that the mixing field is significantly affected by the mixing length and the ratio of the air-to-fuel velocities. The Reynolds number has a minimum effect on the mixing field in high turbulent flow regime and the stability is significantly affected by the turbulence level. The temporal fluctuations of the range of mixture fraction within the mixing field correlate with the flame stability. The highest point of stability occurs at recess distances where fluid mixtures near the jet exit plane are mostly within the flammability limits. This paper provides some correlations between the stability range in mixture fraction space and the turbulence level for different equivalence ratios.

1. Introduction

Partially premixed combustion is mainly characterized by the non-homogeneous structure of the underlying mixture fraction field [1,2]. Many practical combustion systems operate within this mode due to the method of air and fuel admission into the combustion zone. Even lifted flames created from pure jets of fuel are considered partially premixed at the lift-off height due to the air entrainment into the fuel jet [3,4]. This mode of combustion is also characterized by complex reaction zones which may include edge/triple flames [5,6] and this has led Peters [7,8] to propose the triple flame theory as the key building block for modeling such flows. The structure and stability of partially premixed flames were investigated by many research groups in practical combustion systems [9–13] and in fundamental burners [14–20] and the reader is referred to Masri [1] who recently provided a detailed and comprehensive review of this topic.

In an early study, highly turbulent partially premixed flames were stabilized on a reverse flow reactor similar to the primary zone of gas turbine combustor [14,16], the fuel was delivered into the main air tube through six ports upstream the nozzle exit. The mixing occurs within a mixing length prior to the nozzle exit. Later Lee et al. [15] and Mansour [21] introduced a simple technique with two concentric tubes for creating partially premixed flames where the fuel and air streams are partially premixed within a mixing length in the outer tube. This technique provides precise control of the degree of partial premixing by varying the mixing length. Higher stability of the flames of the concentric

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Nomenclature

A_a	area of the air flow, m^2
A_f	area of the fuel flow, m^2
(A/F)	actual air-to-fuel ratio
$(A/F)_{st}$	stoichiometric air-to-fuel ratio
D	the inner diameter of the outer tube, mm
dZ/dr	radial gradients of the mixture fraction $= \sqrt{(\frac{dZ}{dx})^2 + (\frac{dZ}{dy})^2}$
L	mixing length, mm
$(L/D)_{min}$	minimum limit of stability
$(L/D)_{max}$	maximum limit of stability
$\dot{m}_a$	air flow rate, kg/s
$\dot{m}_f$	fuel flow rate, kg/s
pdf	probability density function
$U_{co\text{-}flow}$	co-flow velocity, m/s
r	coordinate perpendicular to the contours of the mixture fraction, mm
R_Z	the ratio between Z_{mm} and Z_{LR}
R_Δ	the ratio between ΔZ and ΔZ_{LR}
ΔR_Δ	the range of flame stabilization in the normalized R_Δ space.
Re	Reynolds number, based on D and combined mixture flow properties
U_a	air stream velocity, m/s
U_f	fuel stream velocity, m/s
V	axial velocity, m/s
Vrms	root mean square of the velocity, m/s
Z	mixture fraction
Z_L	lean flammability limit
Z_R	rich flammability limit
Z_{min}	minimum value of mixture fraction within the mixing field
Z_{max}	maximum value of mixture fraction within the mixing field
Z_{mm}	mean of Z_{min} and Z_{max}
Z_{LR}	mean of Z_L and Z_R
ΔZ	range of mixture fraction within the mixing field, $= Z_{max} - Z_{min}$
ΔZ_{LR}	range of the flammability limit, $= Z_R - Z_L$
ΔZ_n	normalized range of mixture fraction, Eq. 2

Greek letters

Φ	equivalence ratio
Φ_A	equivalence ratio at point A in Fig. 9a
ρ_a	air density, kg/m^3
ρ_f	fuel density, kg/m^3

tubes burner can be achieved by adding a conical nozzle [20,21] or a pilot flame [17,18] at the exit of the concentric tubes. More investigations of the detailed structure of partially premixed laminar and turbulent flames have been conducted based on advanced laser diagnostics measurements [4,15–19,22–30]. The available data show that multi-reaction zones and triple flames may occur [4,27,31] and the effects of turbulence, equivalence ratio, some mixing parameters and several stabilization mechanisms on partially premixed flames were investigated. However, the effects of the mixing field, as the main parameter, on the flame stability and structure are not yet quantified.

The aim of this work is to study the correlation between the stability and structure of partially premixed flames and the mixing fields for a wide range of conditions. The term partial premixing in this work refers to compositionally inhomogeneous mixture. The degree and nature of inhomogeneity can be described in terms of mixture fraction parameters. Mansour [2] recently provided a simple classification of the mixing field using these quantities and classified the partial premixing environment into sub-regimes. The same parameters were also used by Peters and Trouillet [32] and Gampert et al. [33] to characterize the mixing in turbulent jets. Studying the structure of partially premixed flames requires quantitative data sets of the mixture fraction with well-defined boundary conditions and a precise quantitative description of the mixing field.

The concentric flow with a conical nozzle, CFCN, burner of Mansour [21] is used in the present investigation in order to provide well-defined and well controlled partially premixed flames where the level of partial premixing can vary from non-premixed to fully premixed conditions. Rayleigh scattering technique is employed to provide quantitative measurements of the mixing field in well controlled partially premixed jets spanning wide range of mixing level, turbulence level and equivalence ratios. In addition Particle Imaging Velocimetry, PIV, and Planar Laser Induced Fluorescence, PLIF, of OH radical techniques are employed to study the flame structure of some selected partially premixed flames. The mixing field data are first presented in order to study the effect of the mixing length, the Reynolds number, the equivalence ratio and the relative velocity between the air and fuel streams on the mixing field. Then the stability characteristics of partially premixed flames in the concentric flow burner with and without conical nozzle are presented and discussed. The stability data for the flames without the conical nozzle should provide a map of the stability without any additional stabilization mechanism. This map covers a wide range of flames from near non-premixed conditions to fully premixed conditions. Adding the conical nozzle significantly improves the stability characteristics of the flames [21,22]. In order to study the correlation between the mixing field structure and the stability characteristics of partially premixed flames, the mixing field is further analyzed using the simple classification diagram proposed by Mansour [2] where mixtures can be classified according the range of the mixture fraction fluctuations with respect to the range of flammability limits. Sets of data of the flow field and OH field structure in some selected flames are then presented.

2. The concentric flow conical nozzle burner (CFCN)

An axisymmetric concentric flow conical nozzle burner constructed from two concentric stainless steel tubes and placed in air co-flow is used, as shown in Fig. 1a. The inner diameter of the inner tube, d, is 4 mm and its outer diameter is 6 mm. The inner diameter of the outer tube, D, is 9.7 mm and its outer diameter is 12.7 mm. To adjust the concentricity of the inner tube relative to the outer tube, three pins are attached at the outer surface of the inner tube, as shown in Fig. 1b. The three pins are distributed circumferentially at equal angles of 120° and are located at a distance of 50 mm upstream the exit of the inner tube. The air passes through the inner tube while the fuel passes through the annulus between the inner and the outer tubes. The inner tube can be recessed below the exit of the outer tube in order to control the level of inhomogeneity. The mixing between the air and the fuel starts at the exit of the inner tube and continues downstream through the mixing length, L, as shown in Fig. 1a. L is normalized by the inner diameter of the outer tube, D, to define the level of inhomogeneity at the exit plane such that at $L/D = 0$, the air and fuel streams are separated as is the case for diffusion flames while at larger values of L/D homogenous premixing could be achieved. A divergent aluminum conical nozzle with a cone angle of 52° is attached to the exit of the outer tube. The effect of the cone angle on the stability of the flames was investigated by El-Mahallawy et al. [22] and the data showed that the highest stability occurs at an angle of 52°. The height of the conical nozzle is 65 mm and