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Temperature measurement of axisymmetric partially premixed methane/air flame in a co-annular burner using Mach–Zehnder interferometry

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ABSTRACT

In this paper partially premixed laminar methane/air co-flow flame is studied experimentally. Methane–air flame is established on an axisymmetric co-annular burner. The fuel-air jet flows from the central tube while the secondary air flows from the region between the inner and the outer tube. The aim is to investigate the flame characteristics for methane/air axisymmetric partially premixed flame using Mach–Zehnder interferometry. Different equivalence ratios (φ=1.4–2.2) and Reynolds numbers (Re=100–1200) are considered in the study. Flame generic visible appearance and the corresponding fringe map structures are also investigated. It is seen that the fringe maps are poorly influenced by equivalence ratio variations at constant Reynolds number but are significantly affected by Reynolds number variations in constant equivalence ratio. Temperatures obtained from optical techniques are compared with those obtained from thermocouples and good agreement is observed. It is concluded that the effect of Reynolds number increment on maximum flame temperature is negligible while equivalence ratio reduction increases maximum flame temperature substantially.

1. Introduction

Partially premixed flames (PPFs) are formed when a sub-stoichiometric amount of oxidizer is premixed with fuel while additional oxidizer diffuses into the flame to complete combustion [1]. Partially premixed flames have the advantages of both non-premixed and premixed flames. Actually they can enhance flame stability compared to lean premixed flames due to the prevention of flame flashback and decrease pollutant emissions compared to non-premixed flames [2]. In fact, in partially premixed flames pollutant emissions can be controlled by controlling the equivalence ratio. There are many applications for PPFs such as Bunsen burners, gas-turbine, spray flames, gas-fired domestic appliance flames, lifted flames in furnaces, dual fueled internal combustion engines and so on. Although most of the practical combustion processes are happening in the turbulent flow field with higher mixing process [3] but investigation of laminar combustion process is the foundation of combustion science.

Lots of valuable studies on partial premixed flames specify their widespread applications in combustion science. Many numerical and experimental studies have been conducted in laminar partially premixed flames [4–8]. A pioneer work performed by Yamaoka and Tsuji [9] indicated that depending on equivalence ratio of the premixed stream, two separate reaction zone named double flame may be formed in PPFs. Recently the flame structures have been studied by Jeong et. al. [2] in the view of chemiluminescence for methane/air partially premixed co-flow flames. They indicated that at $\Phi \leq 1.36$ the flame has an obvious double flame while as Φ increases from 1.36 to 4.76 its structure changes from a premixed-like to non-premixed-like flame. They also indicated that at higher equivalence ratios the flame structure is like a non-premixed flame with a luminous sooting region tip. One of the primary multidimensional simulations of co-flow laminar flames was conducted by Mitchell et al. [10]. They improved the accuracy of the mathematical modeling which was applied for the simulation. A mathematical and numerical study of co-flow laminar partially premixed methane/air flames has been done by Claramunt et al. [11].They studied the effect of partial premixing level on the main features of co-flow laminar PPFs with an emphasis to the pollutant formation. A comparison of the structures of methane/air and propane/air laminar partial premixed flames was made by Mishra et al. [12] using gas chromatography by measuring the centerline concentration distribution of some selected species. They compared the height of the inner flame for these two fuels. It was indicated that the double flame structure is reported by almost all researches in PPFs when the equivalence ratio of the fuel/air is kept within an optimum limit. This optimum limit varies with fuel type and also the geometry of the burner.

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Nomenclature

D	Diameter(mm)
FN	Fringe number
I	Irradiance(W/m^2)
K	Gladstone-Dale constant(m^3/kg)
L	Tube length(mm)
n	Index of refraction
P	Pressure(Pa)
$\overline{R}$	Universal gas constant(J/mol-K)
Re	Reynolds number
r	Polar coordinate axis, radial direction(m)
T	Temperature(K)
W	Molecular weight(kg/mol)
y	Mass fraction,%
X,Y,Z	Cartesian coordinate axes

Greek symbols

Φ	Equivalence ratio
λ	Wavelength (m)
χ	Mole fraction, %
ρ	Density (kg/m^3)
μ	Viscosity (kg/m-s)

Subscripts

0	Reference state
G	Global
I	Inner
m	mixture
O	Outer
st	Stoichiometric

Many optical methods have been employed to visualize the flow field in engineering fields such as combustion, convective heat transfer, mixing flows and so on. All optical techniques are non-intrusive, sensitive and full-field which make them more attractive than traditional temperature measuring techniques using thermocouples. On the other hand, thermocouple results are affected by radiation, convection and conduction and they disturb the flow due to their intrusiveness in the flow field. Some of optical techniques used for temperature measurement are spectroscopic methods in which the emitted or absorbed electromagnetic radiation of a gas is measured, spectral radiation methods in which the temperature of an opaque surface is measured by comparison with the Stefan–Boltzmann or Planck radiation laws, a scattered radiation technique in which the Doppler broadening of a light beam is measured to get the temperature level and index of refraction methods in which the index of refraction or spatial derivatives of the index of refraction of a medium is measured and from this temperature field is obtained [13]. Some of the index of refraction methods include Lau phase interferometry [14], Talbot interferometry [15,16], Speckle shearing interferometry [17] and Mach–Zehnder Interferometry (MZI) [18]. These techniques are used to obtain temperature field of transparent fluids by means of index of refraction or its spatial derivatives. Shakher and Nirala [19] reviewed refractive index and temperature profile measurements using laser-based interferometric techniques.

An investigation of temperature profile was conducted by Sharma et al. [20] in axisymmetric butane burner using holographic interferometry. Their results were based on premixed, non-premixed and partially premixed flames. They indicated that when the supply of air is reduced, the temperature decreases while a little increase in flame width is observed. Qi et al. [21] used Mach–Zehnder Interferometry technique to investigate temperature field of a laminar premixed flame. They indicated that the accuracy of results improves by increasing the aspect ratio of the slot burner. It was shown that the inner luminous zone of the flame is heightened by increasing either the equivalence ratio or Reynolds number. It was also concluded that the location of the maximum temperature is just above this luminous zone and the exact location of the maximum temperature depends on the operational condition. It was also inferred that at very high distances from the burner exit the flame is highly influenced by buoyant effect and reaching to accurate temperature fields is difficult. Ahmadi et al. [18] studied temperature measurement of a premixed axisymmetric flame. Mach–Zehnder Interferometry technique was applied to obtain interferograms of the flame. Two oxidizers were chosen: pure oxygen and oxygen-enriched air. They studied the effect of oxygen enrichment and equivalence ratio on temperature field. It was revealed that higher temperature fields are achieved for higher levels of oxygen enrichment. Recently, an experimental investigation of temperature field measurements of a premixed methane–air flame established in a slot burner was conducted using Mach–Zehnder interferometry method [22]. It was concluded that increasing Reynolds number has negligible effect on maximum flame temperature. In a recent work conducted by Kumar et al. [23] the effect of magnetic fields on the temperature and temperature profile of a diffusion flame was investigated experimentally using digital speckle pattern interferometry. The results showed that the maximum temperature of the flame is increased under the influence of an upward-decreasing magnetic gradient and decreased under an upward-increasing magnetic gradient. It was also concluded that a uniform magnetic field has negligible effect on temperature.

As reviewed, some studies have been conducted in partially premixed flames using different methods. For methane/air mixtures, Mach–Zehnder interferometry has rarely been employed to obtain temperature field of an axisymmetric partially premixed flames. The goal of this study is to investigate the flame structure to investigate thermal behavior of methane/air partially premixed flame using Mach–Zehnder interferometry technique for different Reynolds numbers and equivalence ratios in a co-annular burner.

2. Experimental setup and method

2.1. Burner configuration and experimental setup

Methane/air PPF was established on an atmospheric axisymmetric co-annular stainless steel burner. The fuel-air (primary air) jet flows from a tube with inner diameter of $D_I = 10.6$ mm and the secondary air flows from the annular region between the inner tube and a $D_o = 38$ mm diameter concentric tube. The tube length is $L = 210$ mm, Fig. 1.The surfaces of the tubes were polished in order to facilitate a smooth exit velocity profile. In order to homogenate the velocity profiles, the tubes are filled with small stainless steel beads. This also avoids flashing back of the flame. A honeycomb structure is also placed in the tubes to provide a uniform exit velocity.

The experimental setup is illustrated in Fig. 2. Pure methane (99.9% >) is supplied from a high pressure gas container and its