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

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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 ($\Phi = 1.4–2.2$) 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.

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1. Introduction

Partially premixed flames (PPFs) are formed when a 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 $\Phi$ 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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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
pressure is controlled by a regulator. Air is supplied through a compressor which passes through a dryer in order to extract water vapor. Air and fuel are mixed in a mixing chamber filled with stainless steel beads to assure a complete mixing. The distance between mixing chamber and burner is long enough to ensure homogeneity of methane/air mixture [24]. The flow rate for each gas is adjusted using pre-calibrated Dwyer flowmeters and pressure gauges. For temperature measurements, K-type thermocouples are

Fig. 1. Schematic configuration of the burner.

Fig. 2. Configuration of the experimental study.
used. These thermocouples are calibrated in an isothermal bath. All the temperatures are monitored and recorded by “TESTO177” data logger connected to a PC. Relative humidity and the ambient pressure are also measured during the experiments using Samwon SU-503B and TESTO-511, respectively. As illustrated in Fig. 2, two flame arresters are used in the flow path for safety purposes. The combustion chamber which is equipped by two transparent windows for He–Ne laser passage protects the flame from surrounding air disturbances.

2.2. Mach–Zehnder optical setup

A schematic of Mach–Zehnder interferometer setup used in the study is depicted in Fig. 3. All the main components of the setup are a light source, two doublets (D), two beam splitters (BS), three mirrors (M), a charge-coupled-device camera (CCD) and a personal computer (PC). The light source is a 10 mW He–Ne laser with wavelength of 632.8 nm. All the interferograms are recorded by an “ARTCAM 320P” CCD camera which is connected to a PC. In order to lessen the laboratory air motion effect on the experiment, the table is protected with transparent Plexiglas sheets of 1 m height.

2.3. Temperature calculation method

In this part it is aimed to explain the technique used for temperature calculation from the obtained interferograms. Direction of the He–Ne laser beam passing through the flame is parallel to z axis and perpendicular to XY plane, Fig. 1. Since the flame is symmetric at each specific cross section, the index of refraction is assumed to vary in the radial direction. The He–Ne light beam is divided to two separate beams in the first beam splitter (BS1). One of these beams passes through the relative hot medium (medium beam) while the other one has passed through the ambient (reference beam). Phase information in the fringe map is denoted by fringe number, (FN). Fringe number is determined from the irradiance distribution \( I(r) \) using Fringe Counting Technique [25]. Each minimum in an interferogram corresponds to a fringe number such that:

\[
FN = (j - 1)/2, \quad j = 1, 2, 3, \ldots
\]  

Fig. 3. Schematic of the Mach–Zehnder interferometer setup.

A fringe number FN=0 corresponds to the large and bright fringe in the ambient gas. Hence, integer numbers \((FN=1, 2, 3, \ldots)\) are assigned to the centers of all subsequent bright fringes and the centers of all dark fringes are assigned the numbers \(FN=0.5, 1.5, 2.5, \ldots\) in a concurrent pattern. The distribution of the fringe numbers is determined using MATLAB image processing program. Since the position of each minimum in an interferogram is not located orderly, a parabolic spline interpolation routine is used to obtain the fringe number at needed radial locations. The fringe number distribution is related to the refractive index by [26]:

\[
FN = \frac{1}{\lambda} \int (n - n_0) ds
\]  

(2)

Since \( \lambda \), the wavelength of laser beam is known and the fringe number has been measured, the required parameter \((n - n_0)\) can be calculated using numerical form of Abel inversion method [27]. After determining the refractive index distribution in the medium, the Gladstone–Dale equation is applied to relate index of refraction to the density of the gas:

\[
n(r) - 1 = K_{max} \rho(r) = \left( \sum y_i \beta_i \right) \rho(r)
\]  

(3)

where \( y_i \) is the mass fraction of the \( i \)th species, \( \beta_i \) is the Gladstone–Dale constant of that species, \( n_0 \) and \( \rho_0 \) are the index of refraction and density at reference state respectively. Since the combustion is happening in atmospheric pressure and relatively high temperatures, the gas can be assumed to be perfect. Therefore from the equation of state for an ideal gas, temperature is related to density:

\[
T = \frac{P}{\rho R} = \frac{PW_{max}}{\rho R}
\]  

(4)

where \( R \) is the universal gas constant, \( W_{max} \) is the molecular weight of the mixture and \( P \) is the pressure. The mixture molecular weight is expressed as:

\[
W_{mix} = \left( \sum y_i W_i^{-1} \right)^{-1}
\]  

(5)

where \( W_i \) represents the molecular weight of the \( i \)th species. By combining Eqs. (3)–(5) the temperature distribution throughout the flame can be obtained:

\[
T(r) = (n(r) - 1)^{-1} \beta(r)
\]  

(6)

where \( \beta(r) = (P/R)K_{max}W_{mix} \) is assumed to be constant throughout the flame by assuming the local composition to correspond to that of the air [28]. By this assumption, which will be discussed in error analysis section, the local temperature distribution can be obtained [28]:

\[
T(r) = T_0(n_0 - 1)/(n(r) - 1)
\]  

(7)

where \( T_0 \) and \( n_0 \) are the ambient temperature and refractive index not affected by flame. In summary, the fringe counting technique is used to obtain fringe number (FN) from the irradiance of the flame. Abel integral equation is used to relate FN to the refractive index. Gladstone–Dale equation is utilized to obtain density distribution from the refractive index and finally by implementing equation of state for ideal gases, temperature distribution can be obtained.
3. Results and discussion

3.1. Validation of results

Equivalence ratio and Reynolds number based on unburned gas properties at the burner exit range from 1.4 to 2.2 and 100 to 1200 respectively. A constant volumetric flow rate of 11.2 lit/min was maintained for secondary air in all the experiments. The conditions for the inlet mixtures are \( T = 297 \text{ K} \) and \( P = 0.87 \text{ atm} \). Reynolds number and equivalence ratio are respectively defined as Eqs. (8) and (9) in which the mixture viscosity is calculated using Eq. (10) [29]:

\[
Re = \frac{4m_i}{\pi D \mu_{\text{mix}}}
\]

\[
\Phi = \frac{F / A}{(F / A)_{\text{at}}}
\]

\[
\mu_{\text{mix}} = \frac{\sum (H_i X_i \sqrt{W_i})}{\sum (X_i \sqrt{W_i})}
\] (10)

In order to investigate the accuracy of the experimental results, temperatures which are obtained from the interferograms were compared with the thermocouple measurements. Temperatures are obtained at axial locations of 35 mm and 45 mm above the burner exit for \( Re = 1200 \) and \( \Phi = 1.4 \). Convection and radiation effects on thermocouple measurements were taken into consideration and modified [30]. Good agreement is observed between temperatures obtained from the interferograms and thermocouples. The maximum discrepancy between the temperature obtained from thermocouples and MZI technique is 31 K for radial temperature profile at axial location of \( x = 35 \text{ mm} \).

3.2. Flame structure and fringe pattern

In this part the structure of the flame along with fringe patterns are investigated. The effect of Reynolds number and equivalence ratio are both studied by keeping one parameter constant and changing the other one. In Fig. 5, a typical methane/air PPF structure and the corresponding fringe pattern is shown. The flame has an inner blue cone in which the unburned gases exist. As it is obvious, the conical flame front is luminous and the chemical reaction occurs in this finite thickness layer where all of the reactants are readily available. Immediately beneath this luminous zone, the unburned gas is heated to a critical temperature at which chemical reaction happens. The burned gas is expanded and diluted with the surrounding air as it leaves the flame zone. It is worth noting that variation of Reynolds number and equivalence ratio introduce different fringe maps which will be discussed.

In Fig. 6, the flame structure and fringe patterns of partially premixed methane/air flame is illustrated for constant Reynolds number of 1200 and five different equivalence ratios of 1.4, 1.6, 1.8, 2.0 and 2.2. The luminous cone is almost visible for all the flames. It can be seen that increasing equivalence ratio augments both flame visible height and the luminous cone height and consequently thermal flame height. In fact as the mixture becomes fuel rich, more air is needed to diffuse to the mixture to create a stoichiometric mixture at the centerline and consequently it needs more residence time to complete the chemical reaction and the flame is heightened. At different equivalence ratios a similar pattern can be observed for fringe maps except that the height of the unburned gas zone increases in a concurrent pattern with flames structures. But the fringes exhibit rather the same general structure as the equivalence ratio increases.

Similarly in Fig. 7, the flame structure and fringe patterns of partially premixed methane/air flame is illustrated for constant equivalence ratio of 1.4 and seven different Reynolds numbers of 100, 200, 400, 600, 800, 1000 and 1200. Since Reynolds number is proportional to the inlet velocity, its increment leads to an enhancement of the height of the inner zone (unburned gas zone) and the flame visible height at constant equivalence ratio. Despite the previous case of Fig. 6, the fringe maps exhibit totally various structures. It can be seen that the fringes are highly affected by increment of the Reynolds number at constant equivalence ratio. In low Reynolds number of 100, there exist no inner conical zone and increasing Reynolds number causes the flame height to grow.

3.3. Temperature measurements

The maximum flame temperature, thermal flame height and flame structure based on its maximum temperature locus are investigated from the interferograms. In Fig. 8, the maximum flame temperature is illustrated. Although increasing Reynolds number enhances the heat flux but the maximum flame temperature increment is negligible.
The maximum enhancement in peak temperature for $Re = 100$–1200 was 14 K for constant equivalence ratio of 2. Maximum peak temperature was 2096 K for $\Phi = 1.4$ and $Re = 800$. As the equivalence ratio increases, the maximum flame temperature reduces due to more radiation heat loss which happens as the air supply decreases.

In Fig. 9, thermal flame height which is defined as the axial location ($x$ value) at which the centerline temperature peaks is depicted. Increasing Reynolds number causes the chemical reaction of unburned gas in inner zone to happen at higher axial distances. Besides, as the equivalence ratio decreases, thermal flame height decreases since less air is needed to diffuse to the flame to create a stoichiometric mixture at the centerline and consequently the chemical reaction happens in lower axial distances.

Figs. 10 and 11 illustrate radial locations of peak temperatures for $Re = 1200$ and five different equivalence ratios as a function of dimensional and non-dimensional axial locations respectively. Similarly Figs. 12 and 13 show radial locations of peak temperatures for $\Phi = 1.4$ and seven different Reynolds numbers as a function of dimensional and non-dimensional axial locations respectively. These radial locations are obtained by moving from burner exit to the top to obtain the overall flame shape. Figs. 11 and 12 show the effect of axial non-dimensionalization by $H_f$ (thermal flame height). It is clear that the flames have dissimilar heights but their shapes are all the same (Figs. 10 and 12). It can be seen that the various flame schemes collapse almost on single curves.

4. Uncertainty analysis

As expressed before, the obtained temperature distribution of the flame is based on the assumption that the refractive index of the mixture equals to that of the air. Therefore this can be an error source in the experiment. Qin et al. [28] showed that the refractive index value of a mixture is identical to that of the air for partially premixed flames. Specifically the average error caused by this assumption lies in the range of 1.9–2.3\% for a 2-D axisymmetric flame for equivalence ratios in the range of $1.5 \leq \Phi \leq 2.0$. This error increases by increasing the equivalence ratio of the flame. Therefore the simplified relation obtained for temperature measurement is efficient for relatively fuel-rich partially premixed flames and in this study this constraint was considered for equivalence ratio. The refractive index of air is also dependent on the temperature. Kharitonov et al. [31] concluded that determination of the air temperature by means of the measured refractive index at high temperatures can be done by the Gladstone–Dale constant and the variation of air refractive index is negligible for temperatures up to 6000 K and pressure changes from 0.1 to 10 atm. It was explained by the lack of notable dissociation of nitrogen molecules as nitrogen dissociation develops in 6000–8000 K temperature range. Another source of error is the deflection of the laser beam. When the laser beam passes through the test section it is
slightly deflected within the flame therefore it does not travel along its original path when reflected by mirror. Aebischer and Rechsteiner [32] showed that this divergent angle has no significant impact in Mach–Zehnder interferometer. Another source of error in combustion experiments is due to equivalence ratio. The maximum uncertainty for the equivalence ratio is $\pm 2.3\%$ at $\Phi = 2.1$ for the methane/air mixture. Detailed information about this uncertainty can be found in the literature [33].

5. Conclusion

Methane/air PPF was 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. Mach–Zehnder interferometry technique was utilized in order to obtain the temperature distribution of the flame. This method has the advantages of being non-intrusive, accurate and
also spatially resolved. In order to validate results, thermocouple measurements were compared with the temperatures obtained from the interferometry technique. Relatively good agreement was observed in spite of using the assumption that the refractive index of the mixture equals that of air. In our previous study [22] a premixed flame established in a slot burner was investigated while in the current work an axisymmetric partially premixed flame established in a co-annular burner has been studied. Although the same method of Mach–Zehnder Interferometry was used in both studies, but the techniques of obtaining temperature from the interferograms are different since the burner is axisymmetric in this study and Abel inversion method should be applied. The main findings of the study are:

- At constant Reynolds number increasing equivalence ratio and also at constant equivalence ratio increasing Reynolds number enhances the flame visible height as well as the conical luminous zone of the flame.
- The overall structure of fringe maps is poorly affected by equivalence ratio variations at constant Reynolds number.
- At constant equivalence ratio different fringe maps are exhibited as Reynolds number increases.
- Increasing Reynolds number has negligible effect on maximum flame temperature while reduction in equivalence ratio causes maximum flame temperature to increase considerably.
- Thermal flame height enhances by an increment in Reynolds number and equivalence ratio.
- Radial locations of peak temperature as a function of non-dimensional axial locations revealed that the various flame outlines collapse almost on single curves at constant Reynolds number and different equivalence ratios and vice versa at constant equivalence ratio and different Reynolds numbers. It
helps to determine the flame maximum locus for various Reynolds numbers and equivalence ratios.

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