Two-dimensional temperature field measurement of a premixed methane/air flame using Mach–Zehnder interferometry

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Abstract

An optical visualization of laminar premixed methane/air flame is carried out in order to investigate the flame structure and its isotherm pattern in a slot burner. Mach–Zehnder interferometry technique is used to obtain an insight to the overall temperature field. The slot burner with large aspect ratio (L/W), length of L=60 mm and width of W=6 mm was used to eliminate the three-dimensional effect of temperature field. The effects of Reynolds number ranging from 100 to 800 and equivalence ratio ranging from 0.7 to 1.4 on thermal flame height (H), structure and isotherm patterns are investigated. The present measurement reveals that the variation of maximum flame temperature with increment of Reynolds number is mainly due to heat transfer effects and is negligible. While the equivalence ratio has a noticeable effect on flame temperature. In addition, maximum temperature occurs at stoichiometric mixture is higher and the effect of Reynolds number at lean mixtures is almost negligible. The results also show that the effect of Reynolds number is more than the equivalence ratio on the thermal flame height. For validation of experimental results from Mach–Zehnder Interferometry, K-type thermocouples are used at peripherally low and moderate isotherm lines.

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1. Introduction

Many practical combustion chambers, such as internal combustion engines, domestic furnaces and boilers rely on premixed flame propagation. Higher combustion efficiency and lower pollutant production make these types of combustion a suitable choice among all other strategies [1]. Therefore, understanding the fundamental flame characteristics at different inlet conditions is essential for appropriate use of this strategy in industrial applications. Burner-stabilized laminar premixed flames are used to study fuel combustion characteristics and chemical kinetics in a combustion environment. Slot burner utilizing laminar premixed flames are effectively one-dimensional and can be made steady, thus facilitating detailed experimental measurements of temperature, flame speed and species profiles and so, a detail study of fundamental flame characteristics. The slot burners comparing to circular flame burners is more capable to produce uniform and high average heat flux and uses for concentration heating [2]. These burners also, have wide applications in manufacturing of glass products and designing heaters and boilers [3]. Study of the laminar premixed flame structure, leads to the understanding of turbulent flame theories and then, spreads their application to a much broader field than laminar flame [4].

Natural gas, which mainly consists of methane, offers considerable economic and environmental advantages such as improved efficiency, availability, and pollutant emissions and are commonly used in several applications. Methane can reach to high temperatures like other hydrocarbon fuels and produces lesser emissions, which make it a very popular fuel [5,6]. However, information on structure of premixed methane flame is very rare that shows the necessity of further study of two-dimensional flame temperature [7–10].

Many experimental methods for temperature measurements have been developed. Most of the practical techniques are conducted by thermocouples and resistance thermometers [11]. These methods are intrusive, point-wise and disturb the temperature field in the region of interest. On the other hand, optical methods are mainly fast, non-intrusive and accurate [12]. There exists many optical methods such as Interferometry [13–15], Laser speckle technique [16], Schlieren photography [17–19] and Moiré deflectometry [20–23] that have been studied to obtain and visualize the temperature field of gaseous flames. All the interferometry methods, including Mach–Zehnder interferometry [24,25], Talbot interferometry [26–29] and holographic interferometry [30,31] are based on changes in the refractive index of the gaseous products of the flame. By knowing the flame gaseous products and using the
Gladstone–Dale relation the temperature can be calculated \[32,33\]. For a premixed flame, the error caused by variation of gas composition is less than 2% for equivalence ratios of \(\phi < 2 \) \[34,35\]. So the refractive index of air can be used instead of gaseous products of combustion \[36\].

Bechtel et al. \[7\] obtained methane and propane flame temperature and species concentration in the rectangular burner theoretically and experimentally. A model with 13 species and 28 reactions was presented and compared with experimental results. Laser Raman Scattering was used to obtain temperature value at distances above the burner. A good agreement was observed between theoretical and experimental results in three equivalence ratios of 0.84, 1 and 1.25. Coffee \[8\] presented two kinetics mechanisms for 1-D premixed laminar methane/air flame. These two schemes revealed good agreement compared to other kinetic mechanisms and experimental results. The contribution of \(\text{C}_2\) species to methane/air combustion is also examined. It was concluded that the effects of \(\text{C}_2\) chemistry reactions could not be determined quantitatively since the information available is not sufficient. Bradley et al. \[9\] investigated characteristics of premixed methane/air flame such as temperature, height and thickness in an array of slot burners experimentally and numerically. The coherent anti-Stokes Raman spectroscopy technique was used to measure flame temperature. Xiao et al. \[10\] measured and visualized temperature field in a two-dimensional partially premixed slot burner by using laser interferometry holography. The burner constructed of three channels where the rich mixture entered from the inner channel while the air is supplied from the two outer ones. Their investigation showed that when the rich mixture’s equivalence ratio varies from 1.5 to \(\infty\), this technique causes a maximum error of 6%–34% and average error of 2.4%–12.3%, respectively when the refractive index of air is considered as combustion products. Qi et al. \[37\] studied premixed butane/air laminar slot flame jet using Mach–Zehnder interferometry technique. Temperature field is visualized at different Reynolds numbers ranging from 400 to 900 and equivalence ratio of 1–2. Hu et al. \[38\] studied the effect of hydrogen addition on laminar premixed methane/air flat flame. The axial temperature profile of methane/air flame with and without of hydrogen addition is obtained by traveling thermocouple technique. In addition, heat release rate, mass burning rate and flame height based on peak of heat release rate were measured at three equivalence ratios of 0.8, 1, 1.3, and two hydrogen enriching ratios of 20% and 50%.

In order to determine the heat transfer rate of combustion processes, it is necessary to obtain temperature field of the premixed flames \[39\]. Equilibrium concentration, emission characteristic and species reaction rate also, are all affected by local temperature of the flame \[40\]. On the other hand, evaluation of temperature distribution of flame at different conditions is necessary for an efficient burner design \[41\]. As mentioned above, many experimental and numerical studies are performed to obtain the temperature profile in the vertical distance from the burner. In their studies, the overall temperature field at the interaction zone of the flame has not been obtained for methane/air premixed flame by Mach–Zehnder interferometry technique. Also the Reynolds number and the burner geometry not specified clearly. The measurement of thermal flame height for premixed flame has rarely been studied and is limited to partial premixed flames and this parameter is useful for setting burners in the optimum locations \[42\].

In this work, visualization of overall flame temperature field, which is essential for detailed study of combustion phenomena and validation of chemical kinetics, is investigated by Mach–Zehnder Interferometry. Parameters like equivalence ratio, Reynolds number of the mixture and thermal flame height affect the slot burner’s efficiency. These parameters have impacts on flow structure, which cause a change between shapes of the flames. Slot burner is used to study the flame structure, temperature distribution and thermal flame height of laminar premixed methane/air flame. The effect of equivalence ratio and Reynolds number of the unburned combustible mixture on temperature distribution and thermal flame height is also investigated.

2. Experimental procedure

2.1. Interferometer

Flame structure and temperature field of laminar premixed methane/air combustion is captured using Mach–Zehnder interferometry (MZI) which is a nonintrusive method. A schematic of the interferometer setup is shown in Fig. 1. The interferometer consists of a 10 mW helium–neon laser with 632.8 nm wavelength, two doublets, a pinhole, a micro-lens, three flat mirrors (M), two beam splitters (BS) and a CCD camera. The mirror and the beam splitters are at parallel position to facilitate the infinite fringe mode. More details about Mach–Zehnder interferometry technique is presented in the literature \[24,43,44\]. All the isotherm

![Fig. 1. Mach–Zehnder setup.](image-url)
patterns are captured by an “ARTCAM-320p” 30 fps CCD camera with 3.2 M pixels, which is connected to a PC to record the images.

2.2. Experimental setup

The layout of the experimental setup is depicted in Fig. 2. Flames were generated using a stainless-steel rectangular burner with an inner cross-section of 60 mm × 6 mm and 250 mm height and wall thickness of 3.5 mm. Length to the width ratio of the burner is large enough to eliminate the three-dimensional effects of flame in z-direction.

In order to obtain a uniform exit velocity profile, the inside surface of the slot burner is highly polished. Furthermore, 1.5 mm diameter, stainless-steel balls and a honeycomb section were used at the mixture entrance to the burner in order to prevent non-uniformity of the flow. The geometrical details of the burner is illustrated in Fig. 3.

The slot burner is fixed on a positioner, which can move both horizontally and vertically to achieve the parallelism of the laser beam with the slot burner length. In order to protect the flame from ambient disturbance, the burner is surrounded by an enclosure with cross-section of 25 cm × 50 cm and height of 150 cm. The enclosure is made up of transparent plexiglas with 5 mm thickness that enables to observe the flame shape. Two windows with 10 cm in diameter are mounted on the enclosure’s walls that let the laser beam pass through the test section.

Methane gas is contained in a high pressure cylinder and has over 99.9% purity. The fuel pressure is controlled by a pressure

Fig. 2. Schematic view of the experimental setup.

Fig. 3. Schematic of the slot burner.
regulating valve. A compressor is used to supply air to the mixer. The flow rates are measured by two rotameters that each are specifically calibrated for methane and air. The calibrated rotameters have an error of 3% of the flow rates at operating conditions. A brass cylindrical mixing chamber filled with stainless-steel balls is utilized to mix the fuel and oxidizer. The enhancement of mixing of the fuel and oxidizer is due to the turbulence, which leads to a further complete combustion process. It is worth nothing that long tubes are used to assure the mixing of gases.

All the temperatures are recorded using K-type thermocouples and a “TESTO 177” four-channel data logger, which is connected to a PC. All the thermocouples were calibrated in an isothermal bath. In order to prevent the flame flashback in the tube and cylinder, two flashback arrestors are utilized. Further details can be found in Fig. 2. The laboratory temperature, pressure and relative humidity are monitored during all the tests.

2.3. Data reduction

The objective of data reduction procedure in this study is to specify the temperature field of the laminar premixed methane/air in a slot burner. A code has been developed to obtain the temperature field of isotherm patterns at different Reynolds numbers and equivalence ratios. When a laser beam crosses through a hot medium, an optical path difference occurs due to the changes of the refractive index of the medium. The optical path difference, ε, of two beams separated by the first beam splitter (BS1) can be obtained as [24]:

\[ ε = \frac{1}{λ_0} \int_0^L (n_{ref} - n(x,y,z))dz \]

(1)

where \( λ_0 \) is the wavelength of the laser beam that equals to 638.2 nm, \( n_{ref} \) is the refractive index of the air at reference state and \( n(x,y,z) \) is the local refractive index of the flame. \( L \) is also the characteristic length of the burner along the light beam. In order to obtain reference refractive index, the ambient temperature, pressure and relative humidity are required to be measured.

As mentioned before, the burner’s cross-section dimensions assure two-dimensional assumption and changes of refractive index in the z-direction is negligible. Therefore, Eq. (1) is simplified to

\[ ε = \frac{n_{ref} - n(x,y)}{λ_0} L \]

(2)

And the local refractive index is obtained as follows:

\[ n = n_{ref} - \frac{ε λ_0}{L} \]

(3)

By determining the local refractive index from Eq. (3), the Gladstone–Dale equation [37] gives the local temperature as

\[ T(x,y) = \left[ \frac{n_{ref} - 1}{n(x,y) - 1} \right] T_{ref} \]

(4)

where \( T_{ref} \) is the temperature of the undisturbed region near the flame. Eq. (4) gives the temperature in a specific point of a fringe field and since each fringe represents an isotherm. The temperatures of the overall fringes are obtained. In this study, twenty photographs were captured to ascertain the reliable isotherm patterns at each specific Reynolds number and equivalence ratio. The Reynolds number of slot flame burner was measured corresponding to cold fuel/oxidizer mixture gasses and defined as

\[ Re = \frac{ρ_{mix} V_{exit} D_h}{μ_{mix}} \]

(5)

where \( ρ_{mix} \) is the density of the gaseous mixture, \( μ_{mix} \) is dynamic viscosity of mixture, \( D_h \) is the hydrodynamic diameter and \( V_{exit} \) is the velocity at exit of slot jet.

\[ μ_{mix} = \sum \left( \frac{n_i M_i}{Y_i} \right) \]

(6)

\[ D_h = \frac{4WL}{2(W + L)} \]

(7)

where \( i \) represents the mixture component, \( Y_i \) is the mole fraction, \( M_i \) is molecular weight, \( L \) and \( W \) are slot length and width, respectively.

3. Reliability of experimental results

3.1. Uncertainty analysis

The uncertainties of the obtained flame temperature are evaluated from three major sources: the uncertainty of equivalence ratio (\( φ \)), uncertainty of Reynolds number and the uncertainty of optical method. The uncertainties in equivalence ratio and Reynolds number are mainly due to uncertainties in the volumetric flow meters of fuel and oxidizer. The maximum uncertainty for the equivalence ratio are \( ±7% \) at \( φ = 1.3 \) and \( Re = 800 \). Maximum uncertainty for Reynolds number is \( ±3.46% \). Detail information about measurement of this uncertainties is presented in literatures [45,46].

The other source of uncertainty arises from Mach–Zehnder interferometer. Since the refractive index of air is considered as that of the combustion products, it is one of the error sources. The average error in this case is 2.3% at the equivalence ratio of 2 [47] and at the lower equivalence ratios, the error is less than 2% [48]. The second cause for errors in the optical method is changes in the refractive index of air at high temperatures. When the laser beam crosses through a premixed slot flame burner, the laser beam deviated from its original path. Kharitonove [49] suggested that for temperatures up to 6000 K the variation of air refractive index is negligible and can be considered to that of the air refractive index under normal condition. The last source of error can be due to the constant property assumption for the fuel and air. It was
shown that the maximum error for this consideration is less than 3% [30].

3.2. Validation

In order to investigate the accuracy of the experimental results and data reduction method, the flame temperature at the center of the horizontal line of maximum temperature was studied at two equivalence ratios, \( \phi = 0.7 \) and \( \phi = 1 \) at Reynolds number of 200.

The temperature obtained from the optical method is compared with that of thermocouples. The measured flame temperatures with thermocouples were modified to account for the effect of convection and radiation [50]. Fig. 4 shows the comparison of the results obtained from the two experimental method. In this figure, \( x \) is the horizontal distance from the center of the jet (see Fig. 5(b)). Good agreement is obtained between the flame temperature profiles using interferometry compared with the results of thermocouples. Regarding to the thermocouples kind (K type), the validation for higher temperatures than 1400 K was impossible. Also the peak of gas temperature at stoichiometric and rich combustion \( (\phi = 1, 1.3, \text{respectively}) \) was compared to the experimental results of Hu [38] and a good agreement observed. The maximum discrepancy between the temperature obtained from thermocouples and Mach–Zehnder interferometry technique is 24 °C and 31 °C on the isotherm line of 831 °C and 932 °C for the equivalence ratios of 0.7 and 1, respectively.
4. Results and discussion

The effects of Reynolds number and equivalence ratio on the thermal flame height ($H_T$), flame temperature and its structure are studied experimentally with the inlet condition of $T_0 = 298$ K and $P_0 = 0.87$ atm. In the present study, the effects of Reynolds number ranging from 100 to 800, which is in the laminar flame region, and equivalence ratio ranging from 0.7 to 1.4 are investigated.

4.1. Flame structure

The flame structure of a premixed methane/air at the equivalence ratio of unity and Reynolds number of 300 is characterized in Fig. 5. According to Fig. 5(a), the flame contains three major zones: inner zone of unburned gases, luminous zone of hot radical species and outer zone, which contains mainly complete combustion products. Isotherm lines, corresponding regions in flame zone and their temperature are presented in Fig. 5(b). In this figure, some of the isotherm lines were skipped for clarity. The maximum measured temperature is 2008 K, which is 0.9 methane/air adiabatic flame temperature at this equivalence ratio. This difference is mainly due to heat transfer effects and air suction from the periphery mediums. The figure also points out that there are two regions with great temperature gradient: boundary of the inner zone and outer boundary of the flame. It is also observed that the maximum temperature occurs just above the inner zone. This vertical distance from the burner to end of the inner zone, defined as the thermal flame height ($H_T$), Fig. 5(a).

4.2. Effect of Reynolds number and equivalence ratio

Effect of Reynolds number ranging from 100 to 800 at the different equivalence ratio of 0.7, 1 and 1.3 on the shape and structure of the flame are illustrated in Fig. 6.

By increasing the Reynolds number, the height of the inner zone, which is an indicator of thermal flame height, augments. Since Reynolds number is proportional to the inlet average velocity at each equivalence ratio, increasing Reynolds number cause the reaction zone to occur at higher vertical distances.

At lean combustion due to existence of further air, the burning rate is higher and mixture devours right after escaping from the burner. As air to fuel ratio decreases, mixture will need extra air

![Fig. 7. Isotherm lines of the flame at different equivalence ratios and Re=300.](image-url)
for complete combustion, which leads to flame stretch. Consequently, a longer vertical distance is required for fuel to burn completely, and length of the inner zone will be larger than lean flames. Fig. 6 also demonstrates that the effect of Reynolds number on height of the inner zone is more than the equivalence ratio.

Effect of equivalence ratio ranging from 0.8 to 1.4 on isotherm patterns of premixed laminar methane/air flame at constant Reynolds number of 300 is illustrated in Fig. 7. By shifting from lean to a rich mixture, the inner zone of unburned gas stretches and the maximum flame temperature area is enhanced but stability of the flame is decreased. The problem of flame stability is due to air suction by the flame, which causes unwanted cross flow and flame oscillation.

4.3. Flame temperature

Fig. 8 illustrates flame temperature profiles of the premixed methane/air flame at Re = 400 and three equivalence ratios at a horizontal line which passes through the center of the maximum temperature isotherm. At the same level of x, it is observed that temperature at stoichiometric condition is higher than those of lean, (φ = 0.7) and rich (φ = 1.3) mixtures. However, at lean condition, due to presence of further air, part of combustion energy is used for heating of air and therefore, the flame temperature is decreased.

In Fig. 9 the maximum flame temperature obtaining from data reduction is shown at different Reynolds numbers and equivalence ratios. Although by increasing the Reynolds number, heat flux is enhanced, the peak temperature change is negligible. At the constant equivalence ratio of unity, by increasing the Reynolds number from Re = 100 to 800, the maximum temperature difference of 29 K is observed.

Flame temperature along the horizontal line passing through the maximum temperature region at different Reynolds number at stoichiometric condition is shown in Fig. 10. By increasing Reynolds number flame expands and a greater area is affected by heat.
The thermal flame height is considered as an important parameter in characterizing the structure of premixed flames. Thermal flame height ($H_f$) defined as the vertical distance from the burner at which the temperature is maximized [42], occurs just above the inner zone [10]. Thermal flame height for Reynolds number ranging from 100 to 800 and equivalence ratios of 0.7, 1.0 and 1.3 are illustrated in Fig. 11. It is worth noticing that the flame height enhanced almost linearly with Reynolds number at stoichiometric and rich equivalence ratios. The change in thermal flame height is around 138.1%, 538.7% and 416.6% when Reynolds number is varied from 100 to 800 at the equivalence ratio of 0.7, 1.0 and 1.3 respectively.

The variation of thermal flame height and maximum flame temperature at Reynolds number of 300 and equivalence ratios of 0.8, 1.0, 1.2 and 1.4 are depicted in Fig. 12. The changes in thermal flame height is 152.9% when the equivalence ratio varies from lean combustion, $\phi = 0.8$ to rich combustion, $\phi = 1.4$. By increasing the equivalence ratio, thermal flame height is augmented and the tip of the inner zone moves upwards. Furthermore, the gas temperature is increased up to the equivalence ratio of unity and then decreased. It is simply because relatively more complete combustion occurs at equivalence ratio of, $\phi = 1$, than other equivalence ratios. As the flame becomes richer, incomplete combustion occurs and results is lower temperature.

5. Conclusion

The Mach–Zehnder interferometry technique as an accurate and nonintrusive method to measure and visualize the overall temperature field is utilized to investigate two-dimensional laminar methane/air flame. Good agreement is observed between optical method and thermocouples results, which show its ability to be used instead of other experimental methods. Three major regions are observed in flame, which clearly characterizes its structure, flame height and reaction zone.

The effect of Reynolds number ranging from 100 to 800 and equivalence ratio ranging from 0.7 to 1.4 on thermal flame height ($H_f$), structure, isotherm lines, temperature profiles is studied experimentally. Results indicate that the flame height enhanced almost linearly with Reynolds numbers and equivalence ratios. The effect of Reynolds number on thermal flame height at stoichiometric and rich combustion is more than the lean ones. It is also observed that the maximum temperature occurs at stoichiometric condition. By increasing or decreasing equivalence ratio due to incomplete combustion, the flame temperature and its stability are reduced. The results also show that by increasing Reynolds number, flame expands and a greater area is heated, but variation in maximum flame temperature is negligible.

References