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# 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 ($H_T$), 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 condition. Thermal flame height augments by Reynolds number increase while its increment at rich 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.



## 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

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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 $\varphi < 2$ [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 $C_2$ species to methane/air combustion is also examined. It was concluded that the effects of $C_2$ 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

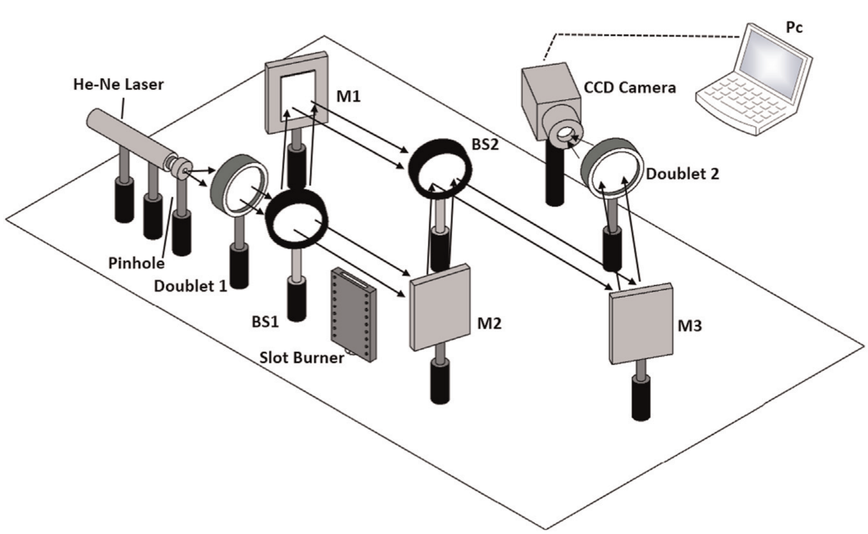


**Fig. 1.** Mach–Zehnder setup.