Temperature field measurement of an array of laminar premixed slot flame Jets using Mach-Zehnder interferometry

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1. Introduction

Multiple flame jets are used widely for domestic and industrial purposes. In order to augment the heat transfer rate of a large surface area, jets arranged in an array can be manipulated [1]. The slot flame jet comparing to circular flame jet is more capable to produce uniform and high average heat flux [2]. To control the surface temperature distribution, an array of jets can be employed [3]. Parameters such as equivalence ratio and Reynolds number of the mixture, heating height and jet-to-jet spacing affect the jet’s efficiency. These parameters have impacts on flow structure, which cause a change between shapes of the flames [4,5].

Single and multiple slot flame jets have a distinct application. A single jet is usually used for concentrated heating. In some situation, the area which should be heated is quite large, thus multiple flame jets is employed. Due to the strong interaction between the flame jets, information for a single flame jet is not reliable, unless the flame jets are located far enough from each other [6]. Thus, the effects of the interaction between the jets on the flame structure and temperature field of the multiple flame jet systems should be investigated.

In order to understand the flame shape and structure of the multiple slot flame jets, the present work was conducted to investigate the heat transfer characteristics of a single, twin and triple laminar premixed methane/air slot flame jets.

Many experimental methods for temperature measurements have been developed. Most of the practical techniques are conducted by thermocouples and resistance thermometers [7]. 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 [8]. There exists many optical methods such as Interferometry [9–11], Laser speckle technique [12], Schlieren photography [13–15] and Moiré deflec-tometry [16–19] that have been studied to obtain and visualize the temperature field of gaseous flames. All the interferometry methods, including Mach-Zehnder interferometry [20,21], Talbot interferometry [22–25] and Holographic interferometry [26,27] 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 [28,29]. For a premixed flame, the error caused by variation of gas composition is less than 2% for equivalence ratios of φ < 2 [30,31].

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So the refractive index of air can be used instead of gaseous products of combustion [32].

Due to limited information about multiple free flame jets shape and structure, studies of single flame jet and impinging flame jet can help to understand the foundation of the present work. Xiao et al. [33] measured and visualized temperature field in a two-dimensional partially premixed slot jet 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 2.4, the refractive index of air can be used instead of gaseous products of combustion [32].

In the previous works of the authors [39,40], the structure, temperature field and thermal flame height of methane and LFG fuels have been studied in a slot flame jet at different Reynolds numbers and equivalence ratios. In this work visualization of overall flame temperature field of an array of slot flame jets has been investigated by Mach-Zehnder Interferometry. A single, twin and triple slot flame jets are studied to the flame shape, structure and temperature distribution of laminar premixed methane/air flames. All the tests were carried out at the equivalence ratio of unity, because it is more applicable and efficient in heating instruments. The effect of Reynolds number and jet-to-jet spacing on maximum temperature value and its distribution is also investigated. Reynolds number varied from 200 to 400 and S/D<sub>n</sub> ratio was changed in the range of 1.15 to 2.75 to include different jet-to-jet spacing.

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 mirrors and the Beam Splitters are at parallel position to facilitate the infinite fringe mode for isotherm observation.

More details about Mach-Zehnder interferometry technique is presented in the literature [20,41,42]. All the isotherm 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 schematic of the experimental setup is depicted in Fig. 2. Flame were generated using stainless-steel rectangular jets with...
inner cross-section of 60 mm × 6 mm and 250 mm height and wall thickness (t/2) of 3.5 mm. Length to the width ratio of the jets is large enough to neglect the three-dimensional effects of flames in the z-direction.

In order to obtain a uniform exit velocity profile, the inside surfaces of the slot jets are highly polished. Furthermore, 1.5 mm diameter stainless-steel balls and a honeycomb section were used at the mixture entrance to the jets in order to prevent non-uniformity of the flow. As shown in Fig. 3, S is the center-to-center distance between the jets. The geometrical details of the jets are illustrated in this figure.

The slot jets are mounted on a positioner, which can move both horizontally, and vertically to achieve the parallelism of the laser beam with the slot jets length. In order to protect the flame from ambient disturbance, the jets are 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 the visualization of the flames structure. Two 10 cm diameter windows are mounted on the enclosure's walls to 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-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 premix the fuel and air. The enhancement of mixing of the fuel and air is due to the turbulence, which leads to a further complete combustion process. It is worth noting 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 cylinders, 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 mixture.
in the slot jets from infinite fringe analysis. A code has been developed to obtain the temperature field and isotherm patterns at different Reynolds numbers. In the Mach-Zehnder interferometry technique, the relative phase difference, \( \Delta \phi(x,y) \), of the two interfering light waves can be obtained [20] as:

\[
\Delta \phi(x,y) = \frac{1}{\lambda_0} \int_0^L (n_{\text{ref}} - n(x,y,z)) \, dz
\]

(1)

Where \( \lambda_0 \) is the wavelength of the laser beam that equals to 638.2 nm, \( n_{\text{ref}} \) 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 jet along the laser beam.

In order to obtain reference refractive index, the ambient temperature, pressure and relative humidity are required to be measured. As mentioned before, the jet’s cross-section dimensions and temperatures of the overall fringes are obtained. Eq. (1) is simplified to:

\[
\Delta \phi(x,y) = \frac{n_{\text{ref}} - n(x,y)}{\lambda_0}
\]

(2)

and the local refractive index is obtained as follows:

\[
n(x,y) = n_{\text{ref}} - \frac{\Delta \phi(x,y) \lambda_0}{2 \pi L}
\]

(3)

By determining the local refractive index from Eq. (3), Gladstone-Dale equation [34] gives the local temperature as:

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

(4)

Where \( T_{\text{ref}} \) is the temperature of the undisturbed region near the flame. Eq. (4) calculates 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 jet-to-jet spacing. The Reynolds number of slot flame jet was measured corresponding to cold fuel/oxidizer mixture gasses and defined as:

\[
Re = \frac{\rho_{\text{mix}} V_{\text{exit}} D_h}{\mu_{\text{mix}}}
\]

(5)

Where \( \rho_{\text{mix}} \) is the density of the gaseous mixture, \( \mu_{\text{mix}} \) is dynamic viscosity of mixture, \( D_h \) is hydraulic diameter and \( V_{\text{exit}} \) is the velocity at exit of slot jet. \( \rho_{\text{mix}}, \mu_{\text{mix}} \) and \( D_h \) are calculated as follows:

\[
\rho_{\text{mix}} = \sum Y_i \rho_i
\]

(6)

\[
\mu_{\text{mix}} = \sum \left( \mu_i Y_i \sqrt{M_i} \right) \left( Y_i \sqrt{M_i} \right)
\]

(7)

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

(8)

Where \( i \) represents the mixture component, \( Y_i \) is mole fraction, \( M_i \) is molecular weight, \( L \) and \( W \) are slot length and width respectively. According to Eqs. (6)-(8), it was found that \( \rho_{\text{mix}} = 0.967 \text{ kg/m}^3, \mu_{\text{mix}} = 1.801 \times 10^{-5} \text{ Pa.s} \) and \( D_h = 0.0109 \text{ m} \) which correspond to stoichiometric condition. For each Reynolds number, the velocity at exit of the slot jets can be determined according to Eq. (5).

3. Reliability of experimental results

3.1. Uncertainty analysis

The uncertainties of the obtained flame temperature field are evaluated from three major sources: the uncertainty of equivalence ratio (\( \phi \)), 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 air. The uncertainty analysis has been carried out for all the cases. The maximum uncertainties for the equivalence ratio and Reynolds number are \( \pm 5.5\% \) and \( \pm 3.46\% \) respectively. Detail information about measurement method of these uncertainties is presented in [43–45].

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 [46] and at the lower equivalence ratios, the error is less than 2% [47].

The second cause for errors in the optical method is changes in the refractive index of air at high temperatures. When the laser beam passes through a premixed slot flame jet, it deviates from its original path. Kharitonov [48] 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% [26].

3.2. Validation

In order to investigate the accuracy of the experimental results and data reduction method, the temperature obtained from the optical method is compared with that of thermocouples at the horizontal line passing through the center of the maximum temperature region. The measured flame temperatures with thermocouples were modified to account for the effect of convection and radiation [49,50]. Fig. 4 (a) shows the comparison of the results obtained from the two experimental methods at \( \phi = 1 \) and Reynolds number of 200. In this figure x is the horizontal distance from the center of the jet (see Fig. 4(b)). Good agreement is obtained between the flame temperature profile 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 combustion (\( \phi = 1 \)) was compared to the experimental results of Hu [35] and a good agreement observed. The maximum discrepancy between the temperature obtained from thermocouples and Mach-Zehnder interferometry technique is 31 °C on the isotherm line of 932 °C for the equivalence ratios of \( \phi = 1 \).

4. Results and discussion

The effects of Reynolds number and jet-to-jet spacing on the flame shape, structure and its temperature field are studied experimentally for the cases of single, twin and triple slot flame jets with the inlet condition of \( T_0=298 \text{ K} \) and \( P_0=0.87 \text{ atm} \). In the present study, the Reynolds number varied in the range of 200 to 400, which is in the laminar flame region, and all the tests performed on the stoichiometric combustion, \( \phi = 1 \). The non-dimensional jet-to-jet spacing varied in the range of 1.15 to 2.75 to investigate the effect of jet-to-jet spacing on heat transfer characteristics of multiple flame jets.
4.1. Flame shape

Photographs of single flame jet at different Reynolds numbers and equivalence ratio of, φ=1, are shown in Fig. 5(a). According to Fig. 5(a), the flame contains three major zones: a blue inner reaction zone of unburned gases, luminous zone of hot radical species with nearly triangular cross-section and blue outer zone, which contains mainly complete combustion products. By increasing the Reynolds number, the height of the inner zone, which is an indicator of thermal flame height [51], augments. Since, Reynolds number is proportional to the inlet average velocity at each equivalence ratio, increasing Reynolds number caused the reaction zone to occur at higher vertical distances. Because of the large concentration of reactive species in the inner reaction zone, the maximum temperature occurs just above of this zone [52].

Flame shapes of twin slot flame jets at the small, moderate and large non-dimensional jet-to-jet spacing, $S/D_h = 1.15, 1.6$ and 2.06 for Reynolds number of 200 are depicted in Fig. 5(b). At $S/D_h = 1.15$, outer layers of the adjacent flame jets were merged with each other, and a strong interference has occurred. By increasing $S/D_h$ ratio from 1.15 to 2.06, it was evident from Fig. 5(b) that the between-jet interference became weaker.

Photographs of the triple slot flame jets are shown in Fig. 5(c) at Reynolds number of 200 and jet-to-jet spacing of $S/D_h = 1.15, 1.83$ and 2.29, which demonstrate the small, moderate and optimum jet-to-jet distances. At the small and moderate jet-to-jet spacing, due to strong interference between the jets, the side flame jets restricted the flow of the central flame jet and squeezed the side flame jets inwards. Simultaneously, the side jets quenched the central flame jet. So that its inner reaction zone became slightly shorter. Particular characteristic of the multiple slot flame jets are jet-to-jet interference, which leads to a lower heat flux in the interacting zone. At the largest $S/D_h$ ratio of 2.26, the behavior of three single flame jets was distinctly observed, and each of the triple flame jets had enough distance to develop freely and very little effect of jet-to-jet interference could be seen.

It was concluded from Fig. 5 that Reynolds number and $S/D_h$ had a significant effect on the shapes of the multiple slot flame jets. Due to interference between the jets, center and side jets had a different shape. By increasing Reynolds number at the same jet-to-jet spacing, the interference between the jets became stronger and flame jets should be placed at the further distances.

4.2. Temperature field

4.2.1. Single flame jet

The flame structure of the premixed methane/air single flame jet at the equivalence ratio of unity and Reynolds numbers of 200, 300 and 400 is characterized in Fig. 6. 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. By increasing Reynolds number the height of the inner zone augmented and the stability of the flame is decreased. The problem of flame stability is due to air suction from its sides by the flame, which causes unwanted cross flow and flame oscillation.

Flame temperature profile, which is obtained from data reduction along the horizontal line passing through the maximum temperature region (white line shown in Fig. 6) at different Reynolds number and stoichiometric condition, φ = 1, is shown in Fig. 7. By increasing Reynolds number, variation of the maximum flame temperature is negligible (i.e. 7 K) but flame expands and a greater area is affected by heat flux from combustion zone.

Due to the symmetrical geometry at both sides of the centerline of the flame zone, only the temperature distribution on the right-hand side has been displayed in all figures.

4.2.2. Twin flame jets

The isotherm patterns of twin flame jets with small, moderate and large jet-to-jet spacing at different Reynolds numbers are shown in Fig. 8. All the flames under investigation were laminar. Due to the interference between the jets, structures of the isotherm patterns were different. In addition, the isotherm patterns were also affected by the Reynolds number and jet-to-jet spacing. There was a negative pressure at each of the interacting zones, which compelled the flame to move inwards. It is also observed from Fig. 8 that by decreasing the jet-to-jet distance there exists a hot zone in the in-between jet region, and this high temperature in the reaction zone enhanced the heat flux. By increments of jet-to-jet distance, the temperature of this region reduced and the in-between jet interference became weak.

Moreover, greater interference and heat flux were observed by increments of Reynolds number at a particular jet-to-jet distance. Fig. 9 illustrates flame temperature profiles of the premixed methane/air twin flame jets at Re=200 and different jet-to-jet spacing along the white horizontal line which illustrated in Fig. 8. When the S/Dh ratio was increased from 1.15 to 2.06, it was found that all the three curves were of the similar trend except near the centerline. Each of them had one peak and one trough. All the peak values occurred near the centers of the jets. By increasing S/Dh, temperature of the centerline decreased and demonstrated that by reducing jet-to-jet spacing higher heat flux can be obtained.

The temperature distribution of the twin slot flame jet at Re=200, 300 and 400 and small and large jet-to-jet spacing are depicted in Fig. 10. By the increment of Reynolds number at a constant jet-to-jet spacing due to the connection of the cool central core regions, which contained unburned methane/air mixture at the centerline, the temperature values in this area are different as shown in Fig. 10(a). In addition, the location of the maximum flame temperature did not occur at the center of the side jets but a location shifting towards the edges due to the
negative pressure at the interacting zone. When the S/Dh ratio was increased, it was found from Fig. 10(b) that the interference between the jets became weak, and the behavior of the twin jet appears as a single jet.

4.2.3. Triple flame jets

Effects of Reynolds Number ranging from 200 to 400 and different jet-to-jet spacing at stoichiometric combustion on structure of the triple slot flame jets are illustrated in Fig. 11. At the small jet-to-jet spacing, S/Dh = 1.15, the flame jets collided with each other, and the central jet was quenched but the side jets deflect inwards as explained before. Merging of the outer layers at the interacting zone exhibiting a “w-shape” for the entire flame zone. For small and moderate S/Dh ratios, the temperature value in the center jet region was relatively low. This low temperature due to the cold unreacted mixture in the mid-point of the center jet. It was also found that the center jet had lost the features of a single jet. When the S/Dh ratio was increased to its optimum value, i.e. 2.29, 2.52 and 2.75 for Re = 200, 300 and 400 respectively, the impact of the interference between the jets on the isotherm patterns of the flame could no longer be observed and the three flame jets revealed to be three free single jets. It can be concluded from Fig. 11 that the interference between the jets of the multiple flame jets increased with reducing S/Dh ratio. This interference for twin jets augments the heat flux but for the triple flame jets was found to reduce the heat flux in the interacting region of center jet due to incomplete combustion.

Temperature profile of triple slot flame jets at small and optimum jet-to-jet spacing for Re = 200 is shown in Fig. 12. At the small jet-to-jet spacing due to the negative pressure at the interacting zone, incomplete combustion has occurred in the center jet, and the result is lower temperature value at the centerline of the triple flame jets. When the S/Dh ratio was increased to 2.29, it was evident from Fig. 12 that the temperature of the center and side jets reaches to its maximum value and the in-between jet interference does not affect the burner efficiency.

Fig. 13 shows the temperature distribution in the reaction zone for triple slot flame jets at small and optimum jet-to-jet spacing. The Reynolds number varied from 200 to 400. The effect of Reynolds number on the temperature values is negligible while jet-to-jet spacing has a significant effect on the temperature of center jet. As shown in Fig. 13(a), the cool middle core of low temperature values is formed in the centerline of the multiple
flame jets at a small S/Dk. This cool middle core reduces the heat flux in the interacting region. This heat flux reduction effect becomes stronger when the Reynolds number is increased at a specific jet-to-jet spacing. If the S/Dk ratio was further increased to its optimum values at each Reynolds number, no obvious interference of the flame jets was found, and the result is higher temperature at the center as shown in Fig. 13(b).

5. Conclusion

Experiments were conducted to investigate the heat transfer characteristics of a single, twin and triple slot flame jets. The Mach-Zehnder interferometry technique as an accurate and non-intrusive method is utilized to measure and visualize the two-dimensional laminar methane/air flame temperature field. Good agreement is observed between optical method and thermocouple 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 effects of Reynolds number ranging from 200 to 400 and jet-to-jet spacing at the equivalence ratio of unity on shape, isothen lines and temperature profile is studied experimentally and the results of the present investigation are summarized as follows:

- The results show that by increasing Reynolds number, the height of the inner zone is augmented and the peak of the flame temperature occurs at a higher vertical distance. In addition, by increments of Reynolds number flame expands and a greater area is heated, but variation in maximum flame temperature is negligible.
- With increment of jet-to-jet distance the between jet interference reduced. At the small jet-to-jet spacing strong interference has occurred and this interference increased with increment of Reynolds number at a specific S/Dk. By reducing S/Dk, the two free flame jets unify into one enlarged single flame jet, and this phenomenon did not observed at the large jet-to-jet distance.
- For the triple slot flame jets by reducing jet-to-jet spacing, the central jet was quenched while the neighboring jets deflected towards the center jet. The optimum jet-to-jet distance was obtained at S/Dk = 2.29, 2.52 and 2.75 for Re = 200, 300 and 400 respectively.
- At the small jet-to-jet spacing due to the negative pressure at the between jet interacting region, the location of the maximum flame temperature did not obtain at the center of the side jets but a location shifting towards the edges.
- At a small S/Dk, the cool middle core of low temperature values in the centerline of the multiple flame jets is formed. This cool middle core reduces the heat flux in the interacting region. This heat flux reduction impact becomes more when the Reynolds number is increased at a specific jet-to-jet spacing.
- For the twin slot flame jets by decreasing the jet-to-jet distance there exist a hot zone in the in-between jet region, and this high temperature in the reaction zone enhanced the heat flux while for the triple slot flame jets by reducing jet-to-jet spacing the central jet was suppressed and the heat flux is decreased in this area.

References


