Combined experimental-numerical investigation on the structure of methane/landfill gas flame using PIV

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ABSTRACT

The purpose of this study was to implement particle image velocimetry (PIV) method in a premixed flame, measuring the burning velocity, analyzing the flame front, and evaluating the velocity at different flame zones. Methane and LFG70 (70% CH4 + 30% CO2) were used as the fuel and air as the oxidizer in an axisymmetric burner working in the atmospheric conditions. In the first step, the obtained images were processed by the PIV method, and then the velocity field was determined. By analyzing the streamlines in different areas of the flow field, the boundary of the flame front was identified and the velocity variation inside and outside of the flame front was investigated. The cone angle method was further used to calculate the burning velocity and investigate the flame structure at different equivalence ratios (0.7, 1, 1.1, 1.3, and 1.5) and Reynolds numbers (200, 400, and 600). Finally, the experimental cases were studied numerically, where the effect of initial temperature of the mixture on the burning velocity was also investigated for various CH4/CO2 ratios. The height of the flame front is minimized at the maximum burning velocity. Also, by adding carbon dioxide to the methane gas, the burning velocity of methane decreases and consequently the height of the flame front increases.

1. Introduction

Today, combustion-related researches have got more important in the societies as a result of increasing air pollution, the reduction of fossil fuel resources, and the growing consumption of energy. Generally, burning velocity, flame structure and velocity field of flame are the most important factors in the investigation of combustion processes [1,2]. The burning velocity is, primarily, defined as the velocity of the unburned gases perpendicular to the flame front [3]. There are several methods for measuring burning velocity. The use of the cone angle method, Transparent-Tube method [3], the constant-volume bomb method [4], the constant pressure bomb method [5], heat flux method [6], and particle image velocimetry (PIV) [7,8] are among the most widely used methods.

Methane (CH4), because of its abundance of natural resources, is one of the most commonly used fuels in the industry, and to further increase its stability and reduce the pollution formed during its combustion, other types of gas fuels are mixed with methane in various volumetric percentages [9,10]. Methane is commonly diluted with hydrogen-H2, nitrogen-N2, and carbon dioxide-CO2 [11–13]. Fuel composition has a considerable impact on the burning velocity. Therefore, studies on the burning velocity of methane/diluent mixture are deemed an imperative subject of the combustion research [14], as it can be used to obtain important information on the stability, temperature, and structure of a flame [15].

Previous research has established that a carbon dioxide tank can be placed next to the methane tank in the internal combustion engines [16,17], to mix the two gases before entering the engine in a determined mixing ratio. This change in the composition of the fuel will lead to reduce the NOx formation [18]. The composition of fuel is one of the effective factors in the burning velocity of a laminar flame. However, in internal combustion engines, the turbulent burning velocity of flame is one of the factors affecting the combustion stability [18]. Besides, based on the Flamelet Model, a turbulent flame consists of a set of laminar flames, therefore, to investigate the turbulent flame, it is deemed necessary to evaluate the burning velocity of the laminar flame [19]. This shows the importance of examining and evaluating the burning velocity of laminar flames.

Dilution is one of the important strategies for reducing the temperature of the combustion chamber and, consequently, reducing NOx emissions [20,21]. An inhibitor diluent is a gas with a high thermal capacity, which increases the thermal capacity of the mixture and decreases the emission of NOx by lowering the combustion chamber temperature [9,22]. CO2 and N2 are among the conventional diluents, whose high thermal capacity increase the thermal capacity of the mixture, the absorption of combustion heat and, consequently, reduce...
the flame temperature and the amount of NOx produced [14,23].

Landfill gas (LFG) is mainly composed of methane and carbon dioxide and is naturally produced in landfill sites and digestion facilities. LFG is regarded as a renewable energy source that can further be converted to various types of biofuels [24]. Since mixing methane with carbon dioxide produces different combustion properties than the pure methane, its combustion characteristics should be thoroughly investigated [25]. LFG has though some issues while being used in combustion process: lower calorific value compared to hydrocarbon fuels, flame stability, flame burning velocity, and lower temperature range [26]. Therefore, a great deal of previous research has focused on these characteristics of landfill flame and the factors that can improve these parameters [27,28]. Dai et al. [29] examined the stability of flames generated by combustion of biogas in a reference burner. Six mixtures of biogas were selected, with a carbon dioxide content ranging from 30% to 45%. Zhen et al. [30] investigated the effect of blending hydrogen gas on the combustion of landfill with three different types of landfill including LFG60 (60% CH4 + 40% CO2), LFG50 (50% CH4 + 50% CO2), and LFG40 (40% CH4 + 60% CO2), in which the volume fraction of hydrogen varied from 10% to 50%. Adding hydrogen resulted in a clear increase in stability, burning velocity, and flame temperature. Littlegohn et al. [31] studied the dilution of fuels in industrial boilers and its impact on the emission of NOx and CO in laboratory scale. The results showed that addition of a small amount of H2 increases the burning velocity of methane, improves the flame stability, and reduces the target emission. Daily et al. [32] also conducted research on combustion dilution with CO2 and N2. The results of their studies showed that N2/CO2 dilution reduces NOx emission. Halter et al. [19] studied the effect of adding nitrogen and carbon dioxide to methane and measured the burning velocity of the obtained mixtures. In this study, they used the constant-volume bomb method and numerical simulation. Finally, it was observed that nitrogen had a smaller effect than carbon dioxide on the burning velocity, and it was concluded that this phenomenon is directly connected to the higher heat capacity of CO2 [19].

Optical methods for measurement of the flow field are of great importance because of their high accuracy and the ability to simultaneously measure the flame characteristics [33]; in addition, these methods cause less perturbation in the flow than the other methods like hot-wire velocimetry [34]. Therefore, these techniques are particularly appropriate for studying the combustion characteristics and are very much investigated in recent years. The PIV measurement method is, therefore, one of the most practical techniques for recognizing and studying the flame structure accurately. However, to precisely analyze the structure of the flame, measuring the velocity magnitude in different points of the flow field is necessary, which is a basic capability of the PIV method [1]. Lewis and von Elbe [35] used a particle imaging and tracking method for the first time by adding magnesium/titanium dioxide particles to the methane/air mixtures, where by photographing and analyzing the flames using PIV, they could determine the position of the flame front. In another study, Zhao et al. [7] used the PIV method to measure the burning velocity in a premixed flame of dimethyl ether and air as the fuel and oxidizer. Dimethyl ether was also diluted with nitrogen and its effect was investigated. Experiments were carried out in the presence of 15% nitrogen for fuel dilution and finally, the results were compared with previous studies [7]. In a study conducted by Chong and Hochgreb [36], the burning velocity of methane-acetone-air mixtures was investigated using the PIV technique. In this study, acetone was added in the range of 0–20% to the methane/air mixtures and was found that in the equivalence ratios below the stoichiometric limit, the addition of acetone has little effect on the burning velocity of the mixture and only increases by about 0.2 cm/s, whereas, in fuel rich conditions, the addition of acetone to methane increases the burning velocity 3–6 cm/s [36]. Choi and Puri [1] investigated the effect of flame stretching on the flame structure and variations of the burning velocity for a slot burner with methane and air mixture. They also measured flame curvature, using the PIV data to estimate the flame stretching [1].

Laminar burning velocity is the most important flame propagation characteristic in spark ignited premixed combustion. As the fundamental flame propagation characteristic of landfill gas requires further study, this paper looks into this matter with the aim of a better understanding of LFG as a renewable fuel. In general, using the PIV measurement method for studying the phenomena of combustion fields has been widely considered by researchers in recent years. The aims of the current study are to investigate and evaluate the flame structure, velocity field and burning velocity of LFG/methane flame in an axisymmetric burner using the PIV measurement method. To study the target properties, methane and LFG70 were used as the fuel and air as the oxidizer. To be able to use the results of this study to evaluate the combustion properties of landfill gas, methane was diluted with 30 vol % CO2, as a common composition of the landfill. The empirical findings in this study provide a new understanding of measuring the burning velocity of LFG70 in an axisymmetric burner with geometry and operating conditions used in this study by using the PIV method for the first time. In addition, the present study was modeled numerically using CHEMKIN-II package. In the first step, the numerical modeling results were validated with the experimental data. Furthermore, other influencing factors on the burning velocity were studied. For this purpose, methane was diluted into carbon dioxide at various proportions. The effect of initial temperature of the fuel and oxidizer mixture on the burning velocity of methane and LFG70 was also investigated.

2. Experimentals

2.1. Experimental setup

An overview of the fuel network system and the PIV setup is presented in Fig. 1. In this investigation, an axisymmetric nozzle burner was used which had an inner diameter of D = 7.62 mm (0.3 in.) and a stainless steel wall with a thickness of 1 mm. The length of the burner, L, was set to 400 mm to satisfy the fully developed condition of L / D > 0.06 × Re [37], where Re is the mixture’s Reynolds number (fuel + oxidizer). The burner is in fact designed according to the mentioned criterion to ensure that parabolic velocity profile is in fully developed regime in the tube even at the worst case, i.e. up to the maximum velocity during the experiments. Flows with three different Reynolds numbers are investigated (Re = 200, 400, and 600) and the flow is considered laminar. In the first step, pure methane was used as the fuel and air as the oxidizer. Thereafter, methane was diluted with 30%carbon dioxide. Mass flows of air, methane, and CO2 were set based on the equivalence ratio and Reynolds number. The flows entered to the burner after crossing the seed. Since CH4 is an explosive gas, a flashback arrestor is installed in the methane line, to stop the flame and avoid the reverse flow of gas.

Fig. 1 also shows a schematic diagram of the PIV setup. To illuminate the flow field, an Argon ion laser (ILT-5500) with 750 mW power output was used, where the generated beam wavelength was between 457 and 514 nm. For capturing the PIV images, a high-speed camera (SONY-NEX-FS700UK) was utilized, which had a resolution of 1920 × 1080 pixels and 1000 fps. The exposure time of the used camera was adjustable from 1.3 s to 1/10,000 s. Different exposure times of the camera were tested to achieve a situation where the emission of the flame became negligible against the illumination through the laser. Also in this process, the quality of photos was an important consideration. Finally, the exposure time was adjusted to 1/4000 s for Re = 200, and 1/5000 s for Re = 400 and Re = 600. During the experiment, the density of particles was controlled to prevent the effect of seeds on the flame. By increasing the seeding density, the flame started to vibrate and the flame front was wrinkled. By comparing the flame structure in presence of seeds and without them (by the direct observation and using the flame photo) the seeding density was...
adjusted and the optimum condition was chosen.

TiO₂ micro powders were used as seeding particles with a diameter of roughly 0.5–5 µm. This choice was due to the high melting point and reflection coefficient of TiO₂. The measurements were conducted with seeding rates relatively low to avoid perturbing the flow. To assure that the seeds track the flow, the Stokes number, defined as the ratio between the response time of particles and a time characteristic of the flow, obtained in the current study is much lower than 1 (St ≪ 1) [38].

The used camera had two manual focus modes and autofocus, where the manual mode was used in this study. Considering the height of the flame, the zoom of the camera was adjusted until fitting the flame on the screen. In addition, the quality of photos was considered to achieve the best outcome for further image processing. According to the height and width of the flame, the PIV measurement window was set at 5 × 8 cm, which corresponds to 360 × 640 pixels. Using a MATLAB code named PIVlab 1.41 [39] for image processing, cross-correlation method was implemented, where for search window 64 × 64 pixel and for interrogation window 32 × 32 pixel was considered and 200 pairs of images were used to determine the velocity from PIV for each case. Also, the correlation coefficient (R) of image processing method (cross-correlation method) always was obtained greater than 0.90. In Fig. 2, two raw photos of the PIV imaging which were used for further processing by the PIV method are presented. These two images are two successive photo where the time difference between them is 1/1000 s.

2.2. Burning velocity measurement

The burning velocity was used for data validation. To achieve this, the burning velocity of methane and LFG70 was measured. For this purpose, after processing each PIV image throughout the flow field, velocity vectors were computed, then by using the velocity field, streamlines were drawn. Thus far, a number of studies have indicated that the velocity suddenly increases on the flame front and its direction changes [1,2]. Considering this phenomenon, magnitude and direction of the velocity at each point of the streamlines were calculated. Afterwards, the boundary of the flame front was determined. Using the flame front coordinates and drawing the crossing curve from these points, the flame inner cone was obtained. To measure the inner cone angle, the calculated curve was fitted to a triangle using linear interpolation and, eventually, the cone angle was obtained. Furthermore, the mean velocity magnitude at the exit of the burner was calculated. Burning velocity was afterward determined using Eq. (1). Fig. 3 presents a schematic summary of the methodology that is used in all experiments. In the linear interpolation of the points, the difference between the actual points and the interpolated ones was measured and the experiments and image processing continued until the difference between the actual and fitted values reached below 5% and the correlation coefficient (R) was always greater than 0.95.

As mentioned, a typical method to measure the burning velocity in a laminar premixed flame is to use the flame internal cone [3].
calculate the burning velocity, first, the entrance velocity to the flame front is considered in the form of two vertical and tangential components \[40\], in which the laminar burning velocity, can be obtained from:

\[
S_l = V_{n,b} = V_u \times \sin \alpha
\]  

(1)

where \(V_u\) denotes the average outlet velocity from the burner and \(\alpha\) indicates half of the formed angle at the peak of the flame internal cone. Also, \(V_{n,b}\) is the vertical component of the average velocity of unburned gases on the flame front, and \(S_l\) is the laminar burning velocity \[40\]. Fig. 4 shows the kinematic equilibrium between the flow velocity and the burning velocity on the flame front for a laminar flame.

The sudden increase in temperature across the passage of the flame front causes a quick expansion of gases in the flame front region \[2\], which implies that the normal velocity component in the burned gas region \(V_{n,b}\) will be greater than that of the unburned zone \(V_{n,u}\). This phenomenon can be deduced by considering the continuity equation on the flame front, and the fact that the density decreases through the flame front \[40\]. The continuity equation on the flame front is:

\[
\rho u \frac{\partial V}{\partial t} = \rho - \frac{\partial V}{\partial t}\frac{\partial \rho}{\partial t}
\]  

(2)

where \(\rho_u\) and \(\rho_b\) denote the density of unburned gases and burned gases, respectively. The tangential component of the velocity on the flame front is not affected by the expansion of the gases, and therefore, its amount will be similar on the two sides of the flame front \[40\]. Changes in the magnitude and direction of the flow velocity vector in the flame front cause divergence of the streamlines in this region \[1\]. In Fig. 5, raw photograph which has been captured in the long exposure time and the processed PIV result of the streamlines divergence in the flame front zone, \(\varphi = 1\) and \(Re = 400\) is shown. Regarding the use of the PIV technique, it should be noted that the main reason is to obtain velocity profiles in different regions of the flame, which cannot be extracted by the other methods. For this reason, the results were first compared with the flame front as seen in conventional photos of the flame, and then the results of the velocity profiles in the transverse and longitudinal axes were extracted.

2.3. Repeatability and uncertainties

Repeatability or test–retest reliability is one of the important issues that should be considered in the PIV experimental studies. For this purpose, in the first step, the repeatability and precision of this study was determined by statistical examination of the test results obtained in 4 separate experiments. During the tests, same experimental and measuring equipment, conditions, and test taker were used. Constant and random errors are errors that may cause unreliability and uncertainty in an experimental measurement. Systematic errors are eliminated by calibrating measurement devices, but random errors should be identified through statistical and analytical methods. As it was mentioned above for each operating condition, the experiments were repeated 4 times, and then the average of the data was calculated and was used as the final test data, then their standard deviation was calculated to obtain the probable errors or unreliabilities and uncertainties of the data. Finally, the total error was measured for each test series, that data were consistent greater than 95% that indicate the reliability and repeatability of the tests. The calculation of the error for methane burning velocity in the Reynolds number of 200 and the different equivalence ratios have been shown in Table 1.

Also, for a more tangible evaluation, the average value of burning velocity for 4 series of measurements of each sample with their standard deviation in different equivalence ratios is shown in Fig. 6.

In addition to the examination mentioned above, flow controller equipment are a source of uncertainty and their error is inevitable. In the current study, for adjusting the flow rate, 3 rotameters (Fischer) were used. The uncertainty of rotameters measurements causes error in the calculation of Reynolds number and equivalence ratio. The presented methods in \[41\] and \[42\] were used to calculate the uncertainty.
of Reynolds number and equivalence ratio, respectively. The maximum uncertainty of Reynolds number and equivalence ratio are 4.2% and 3.9% respectively, for all test in this study.

For the calculation of the burning velocity using angle method, first, the burner outlet velocity and the flame cone angle were calculated from the PIV data. Finally, using the quantitative data ($V_{in}$) and the geometrical data ($\alpha$), the burning velocity was calculated and validated. It can be concluded from the process of burning velocity validation that the PIV results are reliable and accurate. Also, the correlation coefficient ($R$) of image processing method (cross-correlation method) was always greater than 0.90.

3. Results and discussion

3.1. Validation of burning velocity

The burning velocity of the flame is calculated at equivalence ratios of 0.7, 1, 1.1, 1.3, and 1.5. Standard pressure and room temperature has been considered as the operating condition. The PIV technique was initially applied to a non-combusting flow where a normal jet profile was attained.

For a closer investigation on this phenomenon, the burning velocity was calculated at similar conditions. As Fig. 8 illustrates, burning velocity and flame front height have inverse trend while changing the equivalence ratio, so that, maximum burning velocity occurs at minimum height. This is due to the fact that by reducing the burning velocity, the flame front achieves a dynamic equilibrium with the speed of the unburned gases by increasing its height, reducing the angle of the flame internal cone, and thus, according to Eq. (1) reaches the equilibrium. The obtained results from the calculations of burning velocity in this study were compared with the results of other researches [5, 43–47], and the results were satisfactory; this comparison is shown in Fig. 9.

3.2. Local burning velocity

The flame front triangle was primarily determined using linear interpolation, which was afterward superposed on the streamlines. At the interaction between the determined triangle and the calculated stream lines, the angle between stream lines and tangential line of triangle, and the local magnitude velocity at the preheating interaction zone was calculated; then local burning velocity was determined using the following equation:

$$S_L = V_L \times \sin \alpha$$

At the burner exit, burning velocity decreases as result of heat loss from the flame to the burner wall. At the flame tip, the burning velocity increases because of the effect of flame stretch [2]. However, it is generally unchanged between the flame base and the flame tip, consequently, the local burning velocity was measured in the latter constant zone. Local burning velocity is an indicative factor of the flame stretch, since small deviations form mean burning velocity would mean the flame stretch has an insignificant effect [2].

In the present study, 10 points were chosen at the flame front to calculate the local burning velocity. The results of these calculations for various equivalence ratios at $Re = 200$ are shown in Fig. 10. After calculating the local burning velocity at the selected points, their mean values were measured and the results were compared with the measured burning velocity in the previous section. The results of this comparison are presented in Fig. 11. The maximum difference between the measured burning velocities by the two methods is 1.5 cm/s at the equivalence ratio of 1.1.

3.3. Effect of Reynolds number

In Fig. 12 the predicted flame front by PIV and the flame direct
Since the burner exit diameter and unburned mixture are constant, by changing the burner outlet velocity only the Reynolds number changes. Therefore, it is deemed that the effect of burner outlet velocity corresponds to the Reynolds number effects on the flame structure.

By changing the outlet velocity, the location of flame front changes too, and its height increases accordingly. But in this case, the important point which was considered is the burning velocity variations. For this purpose, at various Reynolds numbers, burning velocity and flame front height were calculated. It was observed that, in constant equivalence ratio, with increasing Re the flame front height increases as well, but laminar burning velocity remains constant. As can be seen in Fig. 13, the mean laminar burning velocity for φ = 1.1 is 0.36 m/s. Now if in a certain burner, the outlet velocity is increased, the flame is forced to lower the internal cone angle to balance the terms in Eq. (1); hence the height of the flame front is increased.

### 3.4. Effect of equivalence ratio

Fig. 14 presents the measured velocity magnitude at the flame centerline (X-X') for different equivalence ratios at Re = 200. What stands out in the figure is that at the burner exit, the velocity approximately remains constant; then it starts to increase with a gentle slope which can be attributed to heat transfer from the flame front to
the inner zone [48]. According to the thermal flame theory of Mallard and Le Chatelier [49] that is based on heat diffusion from the combustion zone (flame front) to the layers of unburned gas, at the inner zone, several layers of unburned gas are formed which have different temperature; and along the flame centerline the temperature increases gradually, until reaching the maximum temperature and complete combustion conditions. Besides, the pressure is constant in the current study during the combustion process; consequently, the density of gas decreases, and therefore the velocity increases [40].

The most interesting aspect of this graph is the point with an abrupt increase in the velocity. A careful investigation of the location of this point reveals that the point is located in the flame front zone. Fig. 15 presents the calculated height of the flame front by checking the measured velocity at the centerline and the flame internal cone angle. At the flame front, flame reaches the maximum temperature and suddenly expands and because of constant pressure and decreasing of density in the remaining zone, the velocity increases.

3.5. Velocity profiles

In this section, velocity in the different equivalence ratios and cross sections of the flame are discussed. Different cross sections across the flame were chosen at different distances from the burner exit. The sections A-A' and B-B' are located inside the inner cone and the C-C' section is located outside the inner cone (see Fig. 16). Fig. 17 shows the magnitude of velocity at different cross sections, equivalence ratios at a fixed Reynolds number of Re = 200 for methane. The velocity profile of landfill was similar to methane, therefore it is not presented here. Since the $\varphi = 1$ case has a short flame front, only one section is considered for this zone (middle graph).

In the inner section of the cone, by moving from the center of the flame to the outer zone, the velocity decreases first, and then at a certain point the velocity suddenly increases. In fact, this point lies on the frontier of the flame front, and the velocity increases abruptly because of the expansion of gases and temperature increase, which in turn reduces the density. This increase continues, and by reaching to the flame edges, in addition to the decreased flame temperature, velocity decreases too. It is observed at the outside of the inner cone of the flame that the velocity in the centerline of the flame is less than the surrounding area and, therefore, by moving from the centerline to the outer zone, the velocity increases slightly with a specific gradient until reaching its maximum value. Then at the edges of the flame, the velocity drops to zero. This phenomenon can be examined in two respects. Firstly, in the outer zone of the inner cone of the flame, which is also known as the secondary combustion zone, the flame forms with a
diffusion combustion process, i.e. air diffuses from outside and fuel from inside of the flame [50]. In this zone, the equivalence ratio changes from zero to infinity, and rich combustion occurs on the center of the secondary combustion zone, while lean combustion happens on the outer side. Between these two zones, stoichiometric combustion is usually formed, that often has the highest temperature [51]. The presented descriptions are illustrated in Fig. 18. Also, the reason for the
lower velocity in the center of the flame compared to the surrounding area is the increase in velocity and acceleration of the velocity component perpendicular to the flame front, due to the reduction of the effects of flame stretch and curvature on the relatively straight edges of the flame front. At the peak of the flame front, the effects of flame stretch and curvature can reduce the acceleration and velocity of the particles. As a result, there is a sharper decrease in velocity over the peak of the flame front and in the central part compared to the surroundings.

3.6. Comparison of CH₄ and LFG70 flame structure

The burning velocity of LFG70 was measured at various Reynolds numbers and equivalence ratios of 0.7, 1, 1.1, and 1.5. Fig. 19 shows comparison and validation of the results in the current study with prior work [43].

As shown in Fig. 20 (lower part), in the landfill flame, the height of the flame front is higher than the case with pure methane. This phenomenon occurs as result of reduced burning velocity at the diluted condition. Reduction of the burning velocity by diluting with carbon dioxide has two reasons. First, carbon dioxide is an inhibitor gas, which means its decomposition process is an endothermic reaction; therefore, adding it to methane absorbs some of the heat which is produced during the combustion process. Consequently, the flame temperature is reduced which in turn leads to a decreased rate of intermediate reactions and reduce the burning velocity. Secondly, dilution of methane by carbon dioxide reduces the concentration of active species in the chemical process; this reduces the reaction rate in the fuel oxidation process. The upper part of Fig. 20 presents the comparison of methane and LFG70 burning velocity.

The flame front is formed where a dynamic balance is established between the burning velocity and the flow velocity, which satisfies Eq. (1). For that reason, the vertical component of the velocity of unburned gases to the flame front should be equal to the burning velocity. Accordingly, with decreasing the burning velocity, for diminishing the peak angle, the height of the flame front is increased. Thus, according to Eq. (1), the vertical component of the entering velocity of unburned gases to flame front and burning velocity are equilibrated.

3.7. Numerical results

The purpose of the numerical simulations in this study was to investigate those factors affecting the flame characteristics, which were not possible to analyze experimentally because of the hardware/software limitations in the lab. First, the burning velocity of methane and LFG70 was calculated numerically and compared with current PIV results and the available literature data. The adiabatic flame temperature and its burning velocity were then measured at different equivalence ratios. In addition, the effect of the initial temperature of the fuel/oxydizer mixture on the burning velocity was examined. For numerical calculations, CHEMKIN-II package was used. From the flame simulators section, the premixed laminar flame-speed calculation was chosen, and the GRI-Mech 3.0 mechanism (325 reactions and 53 species) was used to provide the gas-phase kinetics, the thermodynamic data, and the gas transport properties.

In Fig. 21, the obtained burning velocity from the simulations and the PIV method for methane and LFG70 are presented, and the results are compared with [44,23], and [43]. As can be observed, the numerical results are slightly higher than the experimental values. This discrepancy could be attributed to the fact that the numerical studies are calculated in a completely adiabatic environment. This causes the flame temperature to rise and subsequently, the rate of reaction will increase, while in the laboratory methods, the combustion process has minor heat exchange with the environment and the body of the burner, which in turn lowers the flame temperature, reaction rate, and burning velocity.

In the simulations, methane was diluted by carbon dioxide at various ratios. In Fig. 22, the burning velocity of the CH₄-CO₂ mixture is presented at various equivalence ratios. As can be observed, burning velocity decreases in general by increasing the percentage of carbon dioxide.

The burning velocity is directly related to the flame adiabatic temperature. To better observe this phenomenon, the flame adiabatic temperature for various mixtures was simulated and the results are shown in Fig. 23. Optical interferometry should be used in future works to experimentally validate these results.

3.8. Effect of the mixture’s initial temperature

The burning velocity is a chemical quantity, which depends on various parameters for every fuel, among them, is the initial
temperature of the fuel-oxidizer mixture. From a practical point of view, one of the negative properties of landfill gas is the low flame temperature and burning velocity. These factors affect the flame stability and hence the overall combustion efficiency. A practical technique to increase the burning velocity of a particular fuel is to preheat it. When the fuel-oxidizer mixture is preheated to a specific temperature before entering the burner, during the combustion process the reaction rate increases. When the mixture temperature is high, the species that decompose in the combustion process and their reaction is endothermic, will need less heat to react and thus less heat will be absorbed. Therefore, with a constant amount of heat, more reaction will occur, and hence the reaction rate and burning velocity will increase. Although the preheating process increases the burning velocity and the flame temperature, it may lead to increased NO\textsubscript{x} as well. For this reason, it is recommended that the produced NO\textsubscript{x} of the methane and LFG be measured to find the optimum preheating temperature.

Fig. 21. Validation and comparison of numerical and experimental results of methane and LFG70.

Fig. 22. Effect of CH\textsubscript{4} dilution by CO\textsubscript{2} on the burning velocity.

Fig. 23. Effect of CH\textsubscript{4} dilution by CO\textsubscript{2} on the adiabatic flame temperature.

Fig. 24. Effect of the initial temperature of the mixture of methane/LFG70 and air on the burning velocity.

4. Conclusion

In the present paper, the PIV method was implemented to an axisymmetric burner with a premixed flame of pure methane and landfill gas (LFG70). The flame structure, burning velocity, and flame front were analyzed. The effects of equivalence ratio and Reynolds number were investigated experimentally. Further numerical simulations were performed for various CH\textsubscript{4}/CO\textsubscript{2} dilution ratios and different initial temperature of the mixture. The burning velocity of methane and LFG70 was measured using the PIV technique, and the results were in agreement with the findings from other methods. The results of this investigation may be summarized as:
• The height of the flame front and burning velocity have a reverse relation at a given Reynolds number, i.e., the height is minimized at the maximum burning velocity.

• The flame stretch effect has an insignificant effect on the landfill gas flame structure; while the velocity variation inside and outside of the flame front zone have completely different trends.

• With increasing Reynolds number for a given equivalence ratio, the height of the flame front increases, while the burning velocity remains constant.

• By adding more CO2 (higher dilution ratios in the landfill gas), the burning velocity decreases, and consequently, the height of the flame front increases, e.g., at the stoichiometric condition it diminishes by 0.06 m/s.

The results obtained from the numerical analysis suggest that the burning velocity could be increased by preheating the mixture. This technique can be used to rectify the low burning velocity of the landfill gas.

The PIV technique investigated in this study can be further applied in monitoring of landfill gas combustion in industrial process. It is, therefore, proposed that the future work focus on the application of the proposed scheme in a large scale landfill energy recovery plant.

Notes

The authors declare no competing financial interest.

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