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An experimental study on laminar $CH_4/O_2/N_2$ premixed flames under an electric field

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Abstract

This work investigates the electric field effect on gas temperature, radiative heat flux and flame speed of premixed $CH_4/O_2/N_2$ flames in order to gain a better insight into the mechanism of controlling the combustion process by electrophysical means. Experiments were performed on laminar Bunsen flames (Re<2200) of lean to rich mixture composition (ϕ=0.8-1.2) with slight oxygen enrichment (Ω=0.21-0.30). The Schlieren flame angle technique was used to determine the flame speed, and thermocouple measurements at the post flame gas were conducted. The radiative heat flux was measured by using a heat flux meter. At high field strengths, coincident with the appearance and enhancement of flame surface curvatures, an apparent change in flame speed and gas temperature was observed. However, the application of an electric field had no significant effect on flame speed and temperature when the flame geometry was unaltered. This was supported by radiative heat flux showing negligible electric field effects. The modification in flame temperature and flame speed under electric field was attributed to the field-induced flame stretch due to the body forces produced by the ionic winds. This additional flame stretch, coupled with the influence of non-unity Lewis number, accounts for such changes. This reinforces the idea that the action of an electric field on flames with a geometry that remains practically undeformed produces very minimal effect on flame speed, temperature and radiative heat flux. A possible mechanism of combustion control by the application of flame stretch using electric field was introduced.

Keywords: Electric field; Flame speed; Radiative heat flux; Methane; Premixed laminar flame

1. Introduction

In recent years, considerable effort has been directed to the study of flame and field interaction and its influences on the combustion process [1]. Other effects on flame characteristics such as extension of flammability limits, shortening of flame length, increased stability, effect on temperature, heat release rates and sooting characteristics were also observed. With the discovery of these field-induced influences, studies have been directed to investigate the plausibility of utilizing these effects in combustion control.

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It is a well established phenomenon that the interaction between the charged particles (electrons, ions) generated in the flame and the external electric field draws these charged species from the flame and they are acted upon by an electric force. The electric field force, which increases with electric field strength intensity and particle number density, generates the mass transfer of ions in the field direction and produces a wind of neutral molecules with which the ions collide called "ionic winds" [2]. But whether the observed influences are a direct consequence of ionic winds or indirectly by chemical effects brought about by the ionic winds deserves some attention. A number of researchers [2-4] proposed that the observed field effects on flames are mainly due to this ion-molecule collision phenomenon. Because of the relatively small ion concentrations observed in flames (of the order 10^{-7} mole fraction), their modification cannot significantly alter the reaction rates of the branching and decomposition processes needed to support the combustion [5]. It has been shown that the ion driven electro-gas dynamic effects which are present and quantifiable account for the experimental observations in many cases. For most cases, the effects that were observed were on flames geometrically altered by the field.

Although controversies abound in the literature on the influence of electric field on burning velocity, this is one aspect of combustion that has received much attention. Jaggers and Von Engel [6] reported that flame propagation speed can rise well above its value without the field because of the increase in reaction rate brought about by electron collisions. Interestingly, a study by Bowser and Weinberg [2] reported that there is very minimal, almost undetectable effect on burning velocity under saturation conditions and the reported minimal effect is due to positive ions rather than electrons. Workers who studied the use of electric fields to determine the burning velocities of methane and hydrogen flames [5] supposed that an applied electric field has no effect on the burning velocity. Recently, a study on electric field induced flame speed modification by the application of pulsed *DC* electric field [7] reported that the flame speed of premixed propane-air flame could be substantially increased due to the flame front wrinkling and increased reaction area and was ascribed to electric pressure effects.

In addition to the investigation of flame speed, the plausibility of utilizing this field and flame interaction for a number of applications in combustion systems such as reduction of pollutant emission and improvement in heat transfer was studied. A preliminary investigation conducted by Payne and Weinberg [8] on flame and field interaction and its applications asserted that the improvement in heat transfer rates with field application was due to induced gas movement by the fast ion drift. Other researchers [9, 10] reported an increase in heat transfer rates as well. Owing to the potential of using an electric field as an alternative tool for combustion control, investigations on the electric field control of pollutant emissions from flames such as CO_2, CO, NO_x and soot [4, 9-15] have also received much attention. Soot deposition on a charged plate was experimentally observed because the charge of the carbon particles is positive, and thus collected on the negatively biased electrode. Experiments conducted on flame channel flows under the action of weak electric fields [10] showed that the process of enhanced heat and mass transfer in the field produced local disturbances in temperature and mass fraction profiles and resulted in quenching of the reaction zone.

While the bulk of the previous works demonstrate that a field-induced modification in flame characteristics is attainable in flames burning a fuel-air mixture, to the author's knowledge no work has been conducted to study the presence of these effects in oxygen-enriched conditions. The motivation to focus on oxygen enhanced flames is borne from the growing importance of oxygen-enhanced combustion in many applications [16]. It is of interest to investigate if the observed effects of electric fields on characteristics of flames burning in air can be extended to flames that are slightly oxygen-enriched.

The purpose of this study was to investigate experimentally the effect of a radial DC electric field on flame speed, temperature and radiative heat transfer of a premixed laminar flame under slightly oxygen-enriched conditions. In this work, a comparison of the flame characteristics under an undisturbed condition and disturbed condition by electric field is reported.

2. Experimental method

2.1 Nozzle bunsen burner

A schematic diagram of the experimental set-up is shown in Fig. 1. The experimental investigations were performed using a laminar premixed flame burning a mixture of $CH_4/O_2/N_2$. The burner-electrode configuration, which is shown schematically in Fig. 2, consisted of a nozzle tube, axial wire electrode, outer mesh and a gas feeding system. The nozzle burner tube, which enabled the creation of a uniform velocity profile and straight-sided flame cone for the unburned gas, consisted of a 270 mm-long quartz glass with an exit nozzle diameter of 9.0 mm. Gas enters through a feeding system below the burner. An axial wire electrode (d=1 mm) is located at the center of the burner tube and terminates 4 mm below the exit of the nozzle burner. An outer wire mesh (d=115 mm, h=50 mm) is placed concentrically with the burner in such a way that the electric field is directed radially from the central wire electrode to the

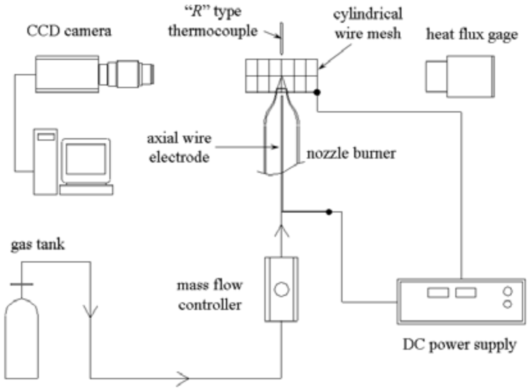


Fig. 1. Schematic diagram of the experimental set-up.

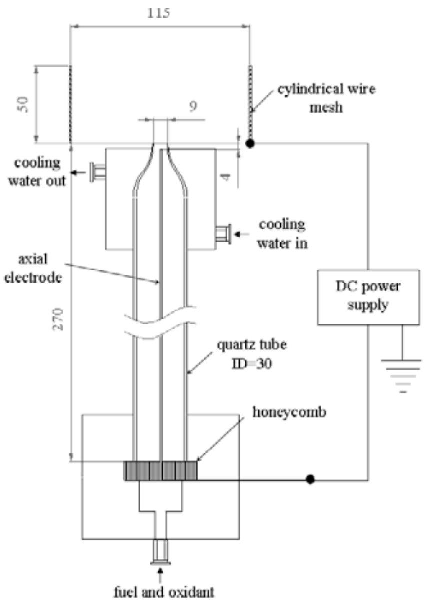


Fig. 2. Nozzle burner and electrode configuration.

mesh or vice versa. A varying external DC electric field is applied between the outer wire mesh and the central wire electrode by varying the potential supplied by a DC power source (*Korea Switching Co.).*

2.2 Gas supply system

High purity gas (99.95% CH_4, 99.995% O_2 and 99.9% N_2) was regulated and controlled by digital mass flow controller (*Tylan FC280FA*) and *DasyLab* software. To prevent accidental flashback, two flashback arresters were coupled each with the fuel and oxygen line. Calibration of the gas flows was performed with a *Drycal DC-Lite* portable gas calibrator which has a volumetric accuracy of ±1%.

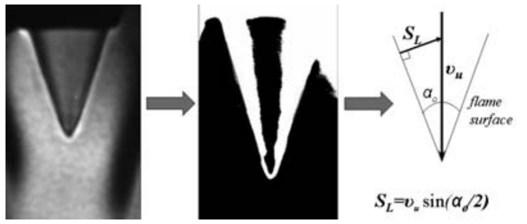


Fig. 3. Processing of the Schlieren image to find the flame speed.

2.3 Measurement of flame speed

Flame speed is an important combustion parameter which depends on a given combustion mixture. For stationary flames with measurable geometry, the gas velocity normal to the flame can be measured either directly or indirectly. An approximate expression to indirectly calculate the flame speed from the flame cone angle, α_o and the unburned gas velocity, u_o [17] is

$$S_L = u_o \sin(\frac{\alpha_o}{2}) \tag{1}$$

Schlieren photography technique, a widely used qualitative optical investigative method, was deemed a simple and convenient way to indirectly measure the laminar flame speed which utilizes the deflection of parallel light rays in the presence of variable density gradients normal to the propagation of the ray. The Schlieren set-up consisted of achromatic type lenses with a diameter of 76 mm and a focal length of 500 mm. The pinhole used was 200 μm in diameter. The image was recorded with a CCD camera (*Roper Scientific, Photometrics Coolsnap-Fx),* saved in a computer and analyzed by using Matlab® to determine the flame angle, α_o. The processing of the raw image to obtain the flame speed is shown in Fig. 3.

2.4 Gas temperature

An "R" type Pt-Pt/13%Rh thermocouple (Omega) with a bead diameter of 0.254 mm and a maximum temperature of 1768°C was used to measure the temperature at the post flame region. The bead was located at a height of 36 mm axially from the burner rim. The signal detected from the flames was acquired and analyzed by Agilent BenchLink Data Logger. The height was selected as close to the flame tip region as possible but within the geometric constraints of the burner and electrode set-up. The measurement point was located coaxially at the center near the flame tip in order to measure detectable changes in temperature associated with shape deformation. The tip is particularly more sensitive to curvature effects and more so with the addition of electric field. No attempt to measure in-flame surface temperature along the sides of the cone was made as there was minimal surface curvature there than at the tip. Another reason for conducting post flame gas measurements rather than in-flame surface measurements was the presence of quasi-instability and fluctuations in flame particularly at higher electric field strengths.

2.5 Radiative heat flux

A heat flux transducer (*Medtherm Corporation)* employing a Schmidt-Boelter thermopile sensor was used to measure the net radiative heat flux from the flame. This sensor is rated to a maximum heat flux of up to 5680 W/m^2, has a nominal absorptance of 0.95 and is able to detect radiation in the range of 0.6 to 15.0 μm. In this type of sensor, there is a transducer that has thermopiles to produce a differential thermoelectric circuit, thus providing a self-generated *emf* of up to 10 mV at full scale. The effective height and length of the viewer with respect to the flame centerline was taken as the setting where the signal-to-noise ratio was maximum and the radiating source was entirely filled within the view restrictor field. The field of view was restricted to an angle of 7° by a view restrictor which was water cooled. The transducer output voltage was measured by a digital voltmeter and recorded in a computer (*Data Bench Logger)*. The transducer output signal, being linearly proportional to the net heat transfer rate absorbed by the sensor, was converted to incident heat flux through the supplied calibration data.

2.6 Flame condition

The over-all reaction for the combustion of methane is given by

$$CH_4 + \frac{2}{\phi}\left[O_2 + \frac{1-\Omega}{\Omega}N_2\right] \rightarrow [H_2O,\ CO_2,\ N_2,\ CO\ etc.] \tag{2}$$

where ϕ is equivalence ratio; Ω is the oxygen enrichment, $\frac{X_{O_2}}{X_{N_2}+X_{O_2}}$; and X_i is the mole fractions of species in the mixture.

In this study, the influence of a varying DC electric field on flame speed, gas temperature and radiative heat flux is reported under conditions of varying equivalence ratio, and oxygen enrichment. The field effect on laminar flame was studied under two different burner-electrode configurations. In the first arrangement the central wire electrode is connected to the negative terminal of the power source while the outer wire mesh is connected to ground and is referred to as mesh (*g)*. For the second configuration the outer wire mesh is connected to the negative terminal of the power source and the central electrode to the ground and is referred to as mesh *(-)*. The equivalence ratio of the fuel-oxidant mixture was varied in the range of 0.8-1.2 and the oxygen enrichment level from 0.21-0.30. The gas flow velocity at the exit of the nozzle burner ranged from 80-310 cm/s.

3. Results and discussion

3.1 Field-induced deformation

As the potential was increased, there was a magnitude of the voltage where the flame started to deform. The effect of the applied electric field on flame shape is shown in Fig. 4 when the mesh was biased negatively, referred to as mesh (*-)*. The deformation was such that bulges appeared near the tip of the flame as the voltage was increased. The greater the applied voltage, the more the flame was deformed. The change in flame shape under the action of electric field is due to the volume force generated by the ion-molecule collisions in the field direction. It is considered that the positive ions such as $C_2H_4^+$, H_3O^+, HCO^+ formed in the flame contributed much to the ion-molecule collision because of their abundance and greater mass compared with electrons. The appearance of bulges in the flame under mesh (*-)* can be explained by the induced drift velocity on the positive ions directed outward to the mesh and its corresponding volume force on the flame in the same direction. For a flame under the action of an electric field in the reverse direction, that is, when the central electrode is biased negatively and the mesh is grounded, referred to as mesh (*g*), a slight narrowing of the flame is observed as shown. In this case, the ions are directed towards the central electrode, hence giving the narrowed shape.

It was further observed in this study that the flame under mesh (*g)* was more likely to start to deform at a

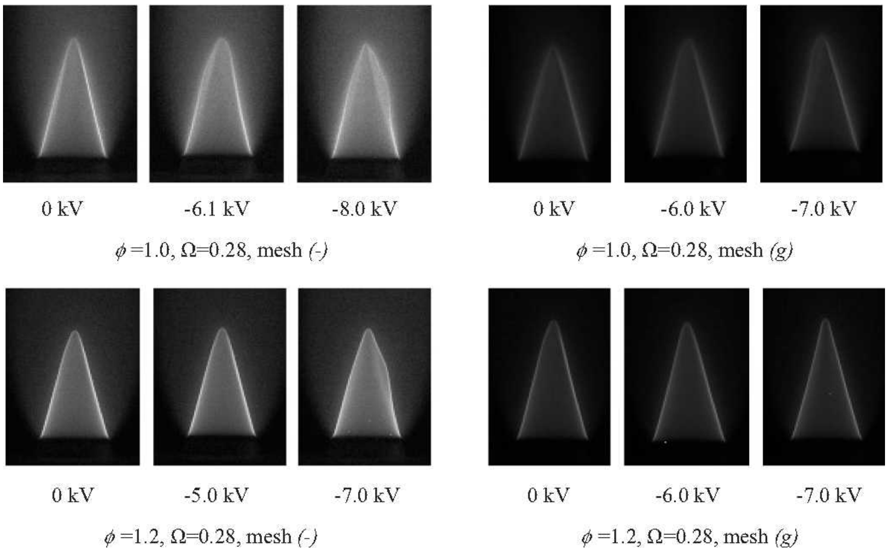


Fig. 4. Deformation of flame with increasing applied voltage for mesh *(-)* and mesh *(g)*.

lower potential than mesh (*-*). This can be explained by the difference in the field intensity distribution developed by the two electrode arrangements and its relationship with the field-induced volume force. Due to the large area of the mesh electrode and its distance from the flame region, the field gradient developed by mesh (*-*) can be considered less intense. With mesh (*g*), the field developed in the region between the electrodes was highly non-homogeneous. Owing to the small tip area of the charged electrode, the field intensity near the tip was considered much greater anywhere away from it. And because of the proximity of the charged electrode tip to the flame front, the field intensity was considerably greater in the flame region also. Because the volume force is proportional to the strength of the electric field neglecting discharge effects [8], the greater sensitivity to flame distortion of mesh (*g*) as compared with mesh (*-*) was due to the greater field intensity near the tip of the biased central electrode.

3.2 Effect on flame speed

Fig. 5 shows the flame speed as a function of the applied potential. Analogous to the observed effect on flame shape, there was a range of supplied potential where the flame speed essentially remained constant. Noticeably, the flame speed remained constant with the application of electric field up to around-4.0 kV mesh (*g*), indicating that there was no considerable modification of flame geometry up to this potential.

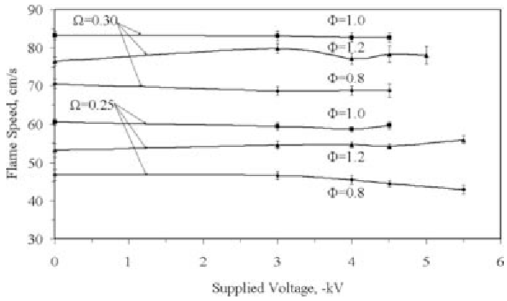


Fig. 5. Flame speed of oxygen enriched flame (Ω=0.25 and 0.30) as a function of supplied voltage.

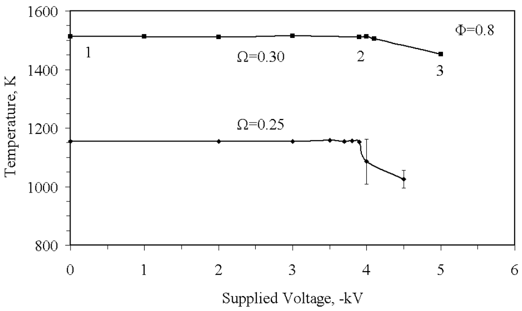
This steadiness of flame speed was expected since the basis for flame speed was the flame cone angle which effectively remained constant. At a higher potential, however, with the appearance of notable flame deformities, an apparent change in flame speed, although small, was observed. This marginal alteration in flame speed was due to the limit that no excessive deformation is effected such that the generally conical flame shape should be preserved in all measurement cases. This change in flame speed was naturally due to the presence of flame surface curvatures associated with higher field intensity as described in the previous section. Interestingly, for lean flames, the flame speed slightly increased. This is shown for Ω=0.25 at Φ=0.8. For rich flame, however, there was a slight increase in flame speed as shown for Ω=0.25 and Φ=0.8.

This can be explained with regards to the effect of the field-induced stretch on flames with non-unity Lewis number and, consequently, to the modification of the burning intensity. For a negatively stretched lean flame with Le<1, the burning intensity weakens and the lean mixture burns leaner, and at Le>1 the burning intensifies and the rich mixture becomes more stoichiometric. This accounts for the minimal, although detectable, effects on flame speed. The modification in flame speed correlates well with the measured change in temperature as will be introduced later.

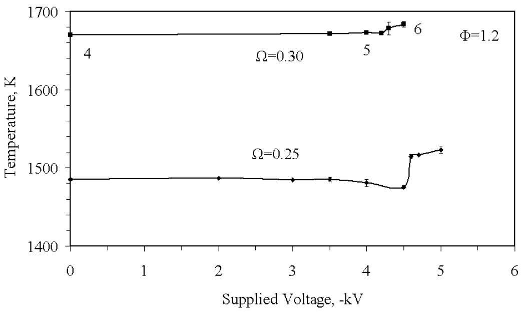
3.3 Gas temperature

The effect on post flame gas temperature with increasing supplied voltage is illustrated in Fig. 6. In the range of low electric field intensity, characterized by the absence of any field-induced flame surface curvature, the temperature essentially remained constant. At potential approximately higher than –4 kV, concomitant with the appearance of flame shape modification, the temperature changed drastically. Of interest was the drop in temperature at ϕ =0.8 as shown in Fig. 6(a). On the contrary, there was an increase in temperature at ϕ =1.2 as illustrated in Fig. 6(b). It is worth mentioning that the modification in temperature was for flames with field-enhanced surface curvatures. This relation is well depicted in Fig. 7 which shows images corresponding to the numbered data points in Fig. 6.

This modification in temperature can be explained by the influence of the non-unity Lewis numbers (Le) in the burning intensity of stretched flames. Specifically for a stretched flame (1) if the heat and mass diffusion are equal (Le=1), then the diffusion is balanced such that the flame temperature is equal to the adiabatic temperature, (2) if thermal diffusion exceeds mass diffusion (Le>1), then there will be more intensified burning in the stretched surface such that the flame temperature is greater than the adiabatic temperature, and (3) if mass diffusion exceeds thermal diffusion (Le<1), then a diminished burning results such that the flame temperature is lower than the adiabatic flame temperature. For lean mixtures, the effective Lewis number is less than unity, while for rich mixture, Le is greater than unity. Studies conducted [18] on methane-air flames with negatively

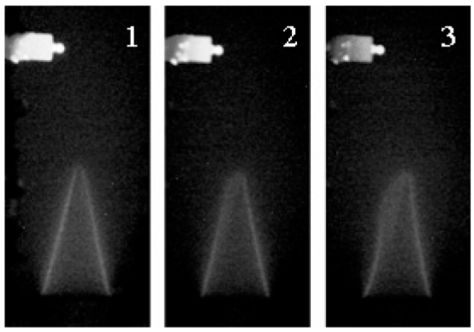


(a)

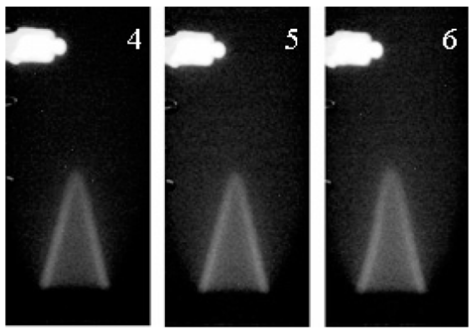


(b)

Fig. 6. Gas temperature with the application of electric field for Ω=0.25 and 0.30. a) ϕ =0.8 and b) ϕ =1.2.



(a)



(b)

Fig. 7. Field-induced deformities in flame shape during thermocouple measurement. The numbered images correspond to the numbered data points in Fig. 6.

stretched tip demonstrated that at Le<1, the focusing effect of thermal diffusion due to compression is less than the defocusing effect of diffusion of the deficient reactant, and the reaction being less intense reduced the flame temperature. This similar mechanism accounts for the reduction in temperature for the lean mixture (Φ=0.8). Noticeable also was the flame tip opening phenomena at this mixture condition with field-induced stretch. The opposite holds for Le>1. The mixture being rich (Φ=1.2) and Le>1 results in the excess diffusion of heat that the reactant diffusion can balance resulting in an increase in temperature.

The mechanism by which the electric field enhances the flame stretch can be attributed to the modification of the flow field by the body forces brought about by ion-molecule collisions. The application of electric field, sufficient to result in the appearance and enhancement of flame surface curvature, augments the already present flame stretch mainly in the flame tip, and modifies the originally straight-sided cone. This is manifested in the negative curving of the cone surface and a modified curvature at the tip as described in Fig. 4. The electric field provided the additional flame stretch, which was otherwise not present without an electric field.

It is not discounted however that the field application may also affect the global Lewis number by increasing the mass diffusivity of the ionic species under the influence of an electric field. This aspect has to be investigated in more detail considering that the concentration of ions in hydrocarbon flames is very small.

3.4 Radiative heat flux

The measurement of radiative heat flux for undeformed flames under subject to electric field was also conducted. Fig. 8 shows the intensity of radiative heat flux as a function of equivalence ratio both for flames without an electric field and under an electric field. For the in-field condition, the voltage applied was -4 kV, limited to the intensity where the characteristic conical flame shape was preserved. This was to distinguish any field effect as being due to chemical effects or simply to flame deformation. For all mixture conditions, no significant difference was measured for the heat flux of a laminar flame with no field application and a flame under electric field. With this observation, it is expected that no sensible change in gas temperature can be detected. This result is consistent with the temperature measurement showing no variation of temperature with the application of a field for flames that are geometrically unaltered.

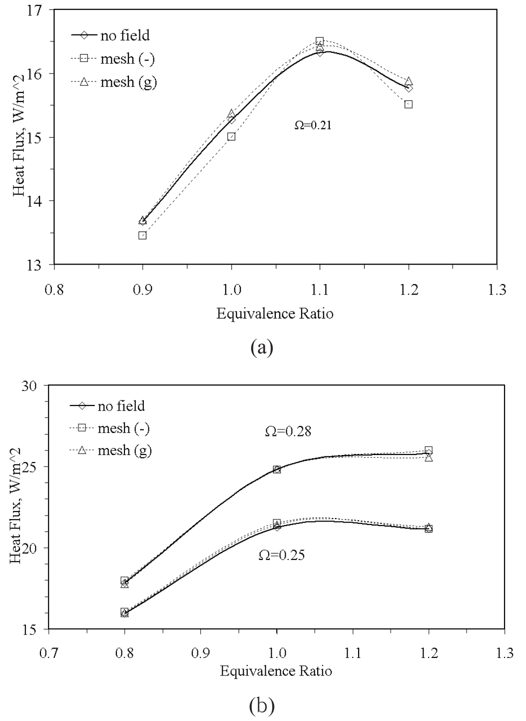


Fig. 8. Radiant heat flux as a function of equivalence ratio. a) Ω=0.21, b) Ω=0.25 and 0.30.

4. Conclusion

The effects of a DC electric field on flame speed, gas temperature and heat flux of $CH_4/O_2/N_2$ premixed flames were studied experimentally. From this study the following conclusions can be drawn:

(1) In the measurement of laminar flame speed using the Schlieren technique, it was demonstrated that there is a range of potential in which the flame speed is unchanged. At high electric field strengths, coincident with the appearance of flame surface curvatures, a modification in flame speed was observed. The change in flame shape correlated well with the modification in temperature and is attributed to the non-unity Lewis number influence on flames stretched by the electric field.

(2) Accompanied by the appearance and enhancement of flame surface curvatures, there was an apparent change in gas temperature. The effect on temperature is ascribed to the influence of non-unity Lewis

number of flames subjected to stretching. The role of the electric field is that it augments the existing stretch at the flame tip and in the flame surface through the body forces brought about by ionic winds. For this reason, no significant effect on the temperature of the post flame gas was detected for flames with unaltered geometry. This was well supported by the heat flux measurements showing minimal effects.

This work provides an insight into the role played by field induced-deformation in flame shape. This reinforces the idea that the action of an electric field on a flame with a geometry that remains practically unaltered produces a very minimal effect on temperature, radiative heat and flux flame speed. A possible mechanism of combustion control by the application of flame stretch using electric field is introduced.

Acknowledgment

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