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The dilution effect on the extinction of wall diffusion flame

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Abstract The dynamic process of the interaction between a turbulent jet diffusion methane flame and a lateral wall was experimentally studied. The evolution of the flame temperature field with the Nitrogen dilution of the methane jet flame was examined. The interaction between the diffusion flame and the lateral wall was investigated for different distance between the wall and the central axes of the jet flame. The dilution is found to play the central role in the flame extinction process. The flame response as the lateral wall approaches from infinity and the increasing of the dilution rate make the flame extinction more rapid than the flame without dilution, when the nitrogen dilution rate increase the flame temperature decrease.

Keywords: Flame; N_2 Dilution; Wall flame; Infrared thermography; Methane

1 Introduction

Flame extinction is important for both turbulent combustion [1] and fire safety [2]. Based on the mechanism, extinction of nonpremixed flame can be roughly categorized in to four different types, stretching extinction, and dilution extinction, and radiation extinction, and convection extinction [1]. Due to increase of the velocity gradient at the vicinity of the flame surface, the residence time of the reactants is decreased and extinction in this manner induced can be called 'extinction by strain'. In nonpremixed combustion, excessive dilution of one of the reactants can increase the chemical

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reaction time and ultimately lead to extinction, which can be called 'extinction by dilution'. In some cases, where the flame surface is pushed very close to a nonadiabatic wall, heat loss starts to prevail and flame temperature decreases. As a consequence, the chemical reaction time decreases and eventually leads to extinction, which can be called 'extinction by convective heat transfer'. Under certain conditions, e.g. opposed-jet flame at low strain rate and with the absence of buoyancy, the flame thickness becomes large, and radiative heat loss from the large high temperature zone starts to dominate. Similar to that of the convective heat losses, the decrease in flame temperature reduces the chemical reaction time and produces 'extinction by radiation'. The review here is focused on the second and the third combined effects of extinction which are the extinction by convection and radiation and the extinction by stretching and dilution.

Sarnaki *et al.* [3] conducted an experimental and computational investigation to understand and quantify the source of uncertainties associated with such characterization of extinction limits of fuel-air mixtures, ranging from low extinction strain rate methane-air flames to high-extinction strain rate ethylene-air flames. Experiments were conducted at various nozzle separation distances to investigate potential differences in axial velocity profiles along the axial and radial directions and the corresponding local extinction strain rates. The slope of axial velocity in the axial and radial directions at the air outlet boundary was found to increase with decreasing nozzle separation distance. The variation of local extinction strain rate with changes in separation distance was within the uncertainty of experimental data.

An experimental study was conducted to investigate a laminar flame speeds and extinction strain rates of benzene, n-propylbenzene, toluene, o-, m-, and p-xylene, and 1,2,4- and 1,3,5-trimethylbenzene flames in the counter flow configuration under atmospheric pressure [4]. The experimental data revealed that the aromatic fuel structure plays a critical role on flame propagation, with the laminar flame speed decreasing with an increase in methylation of benzene but the extinction data revealed a more discriminative effect arising from the fuel structure differences.

The kinetic effects of low temperature nonequilibrium plasma assisted CH_4 oxidation on the extinction of partially premixed methane flames was studied by Sun *et al.* [5]. The experiments showed that non-equilibrium plasma can dramatically accelerate the CH_4 oxidation at low temperature. The rapid CH_4 oxidation via plasma assisted combustion resulted in fast chemical heat release and extended the extinction limits significantly.

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An experimental study based on high-speed images of OH planar loser induced fluorescence technique of a turbulent diffusion flame of a compressed natural gas (CNG) conducted by Juddoo and Marsi [6] identified three types of structures, common to all studied flames: 'breaks', 'closures' and 'growing kernels'. Events of 'breaks' are counterbalanced by the occurrence of 'closures' which reconnect the flame sheet and maintain stable combustion particularly in the upstream regions of flames.

The study [7] of the extinction limits and emission formations of dry syngas (50% H_2 – 50% CO), moist syngas (40% H_2 – 40% CO – 20% H_2O), and impure syngas containing 5% CH_4. A counter flow flame configuration was numerically investigated to understand extinction and emission characteristics at the lean-premixed combustion condition by varying dilution levels (N_2, CO_2 and H_2O) at different pressures and syngas compositions. CO_2 diluted flame has the same extinction limit in moist syngas as in dry syngas but a higher extinction temperature; H_2O presence in the fuel mixture decreases the extinction limit of N_2 diluted flame but still increases the flame extinction temperature; impure syngas with CH_4 extends the flame extinction limit but has no effect on flame temperature in CO_2 diluted flame; for diluted moist syngas, extinction limit is increased at higher pressure with the larger extinction temperature; for different compositions of syngas, higher CO concentration leads to higher NO emission. A numerical investigation was developed to study the interaction between the diffusion flame and a lateral wall and they found that the flame structure is more influenced by the wall [8].

In the paper interaction between a turbulent jet diffusion methane flame and a lateral wall was experimentally studied. The effect of inert gas in the diffusion flame was examined using methane (CH_4) fuel mixed with nitrogen (N_2) gas. The N_2/CH_4 volume ratios were 1/4, 2/3, 3/2, 4/1. The interaction between the diffusion flame and the lateral wall was investigated for different distance between the wall and the central axes of the jet flame.

2 Temperature measurement

In flames, the temperature profile provides very useful information because the flame structure, consisting of species concentrations, density, pressure, and velocity, is associated with temperature. Especially in this study, measuring flame temperature accurately was one of the key issues to estimate the temperature fluctuation and root mean square (RMS) to evaluate the

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flame extinction based on the RMS calculation. There are several techniques available for temperature measurement, namely infrared thermography, sonic thermometry, and laser scattering thermometry. Our experiment is based on the infrared (IR) thermography technique now is the most widely used method because of its accuracy and safety.

3 Experimental apparatus and data reduction

The equipment for our experiments consists of an infrared thermal imaging system, an impinging jet system with diameter $d = 1$ cm, impinging plate of 1 cm in thickness, and a system to measure flow rate and pressure for both of methane and nitrogen gas. The different distances L/d from the wall to the burner axis were under consideration. A schematic diagram appears in Fig. 1. The infrared thermal imaging system (FLIR systems ThermaCAMA40M camera and ThermaCAM research software) has a range of temperature measurement from 300 to 2000 ^{o}C with $\pm 2\%$ accuracy. The IR camera utilizes a 320×240 pixels uncooled focal plane array detector operated over the wavelength range from 7.5 to 13 μm. The field of view is $24^{o} \times 8^{o}$, the instantaneous field of view is 1.3 mrad, and the thermal sensitivity is 0.1 at 30 ^{o}C . Images are transferred to a computer in almost real time and stored therein for further analysis.

4 Results of impinging flame field

4.1 Temperature of impinging flame field

The length of the impinging flame decreases as the N_2/CH_4 mixture ratio is increased. This shows that the nitrogen gas molecules dilute the local methane fuel concentration, which produces better combustion.

When the methane flame mixes with nitrogen gas these flow fields are similar to the cold flow of jet impinging flow [9]. It is evident that the flame stretch might be destroyed by the inert gas, nitrogen. The nitrogen molecules mix with the methane flame and break down the stretch mechanism. In the diffusion flame, a weaker stretch boundary may enhance the mixing rate between the fuel and oxidizer. The fluctuation phenomenon can, therefore, be improved Fig. 2. Unlike the free jet, the wall jet is constantly generating vortices due to the presence of a solid boundary.
Figure 3 illustrates the temperature distribution along the centerline of the

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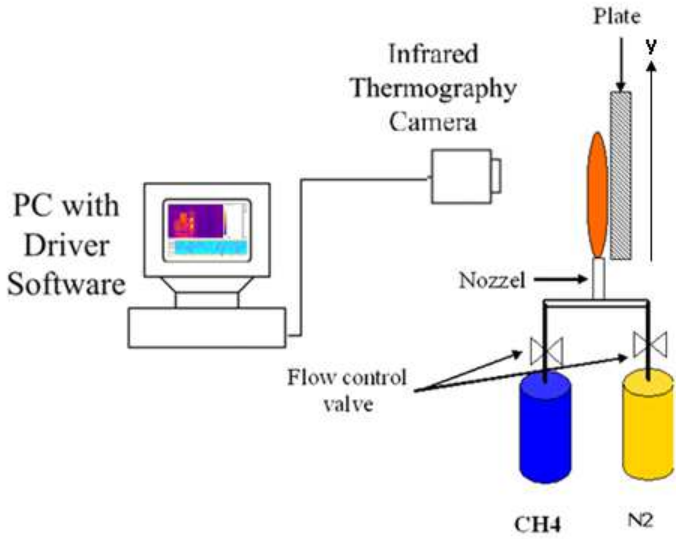


Figure 1: The schematic diagram of the experimental apparatus.

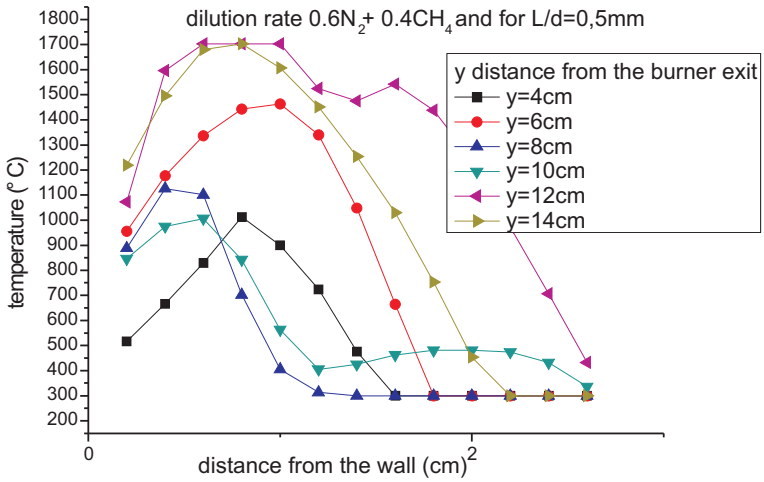


Figure 2: Methane diluted flame for $0.6N_2/0.4CH_4$.

impinging flame mixed with different inert gas ratios and the maximum temperature location for every case in the cross section. The results show that the pure methane impinging flame exhibits a symmetrical conical shape. The flame configuration becomes asymmetrical as the proportion of non-

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reactive gas in the fuel is increased. The stretch force of the flame also becomes weaker when mixed with nitrogen gas.

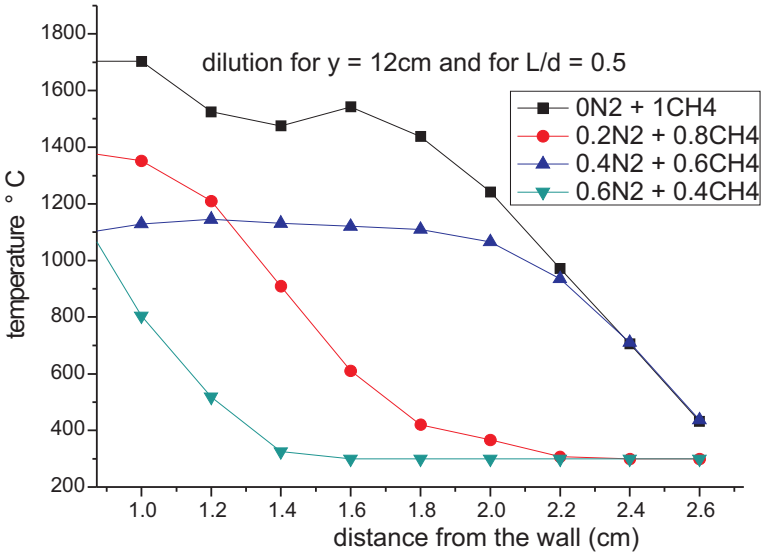


Figure 3: Methane nonpremixed flame for different nitrogen dilution rate.

4.2 Excitation by dilution and impinging effects

The effects of equivalence ratio, bulk velocity and nozzle to plate separation distance were examined with reference to the nitrogen/methane dilution effects 0.2/0.8; 0.4/0.6; 0.6/0.4; 0.8/0.2; 0/1, for the same methane jet diameter 1 cm, smaller bulk velocities or larger nozzle separations flame to the wall, which eventually extinguished with leaner mixtures between air and methane caused by dilution effect and higher velocities or smaller separations.

Nozzle axis to plate surface distance of $L/d = 1$ or greater had near-uniform profiles of temperature because at this distance the wall has no influence on the flame structure, while smaller values like $L/d = 0.5$ lead to an increase from the axis to a peak at the edge of the impingement region. The amplitude of the peak frequency increased as the separation was reduced. Thus, the flames quenched from large to small radius at the smaller separations. Complete extinction occurred when the mixture between nitrogen and methane is greater than 40%. The dilution rates at

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the impingement plane were at least 40% greater with combustion than with isothermal flow and caused incomplete combustion and extinction, lower temperatures caused by high dilution rates and smaller distance between the flame and the impinging plate Fig. 4.

When the amplitude of temperature fluctuations was further increased by oscillations, the flame detached more rapidly and the flame extinction rate decreased. A reduction in the frequency of oscillations had the same effect and extinction times were greatly reduced by modest increases in bulk velocity or a reduction in nozzle separation distance. Figure 5 shows a temperature signal for a vortex spreading on the wall plate.

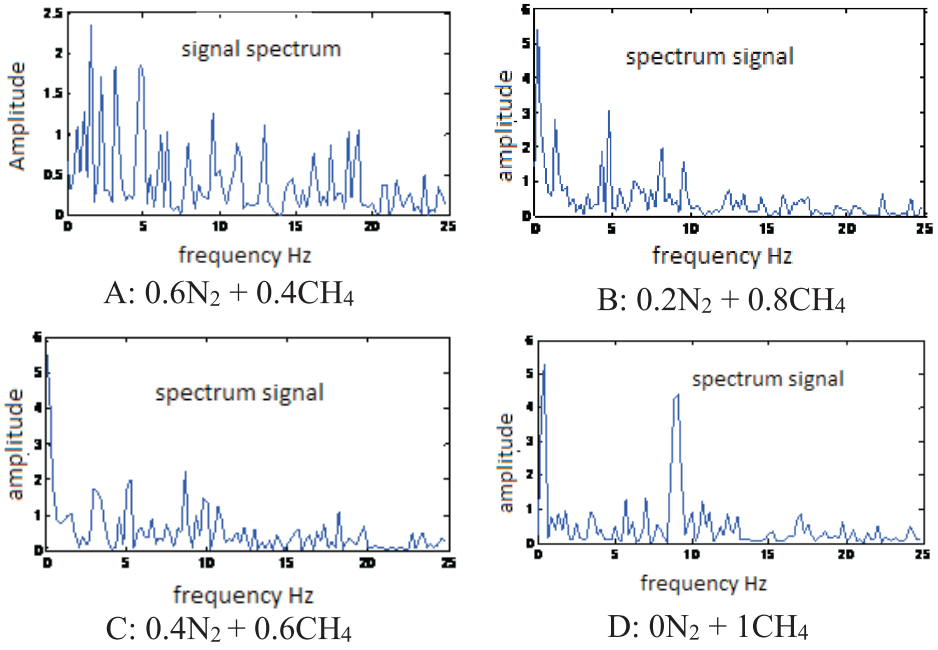


Figure 4: Spectral of temperature fluctuation at the same point for different nitrogen dilution rate for $L/d = 0.5$ (A, B, C, D).

Figure 6 showed the influence of the reacting flow flame structure by the dilution effect and the wall impinging the RMS of the flame was varied with the distance from the wall when the measurement point is far from the wall the RMS has the great values and when the point is more near the impinging wall the RMS value decrease because just behind the wall more friction produced and the vortex is dissipated. The width of the different impinging gases flame is increased due to the momentum of the nitrogen

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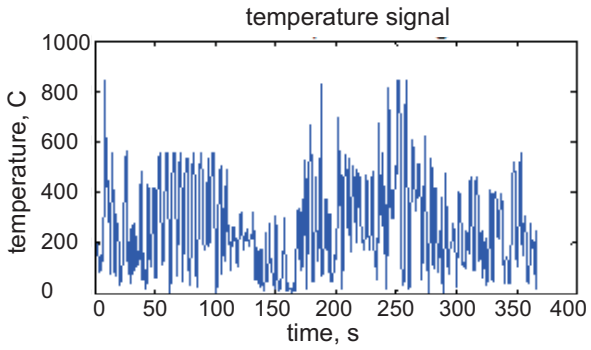


Figure 5: Temperature signal for $0N_2 + 1CH_4$.

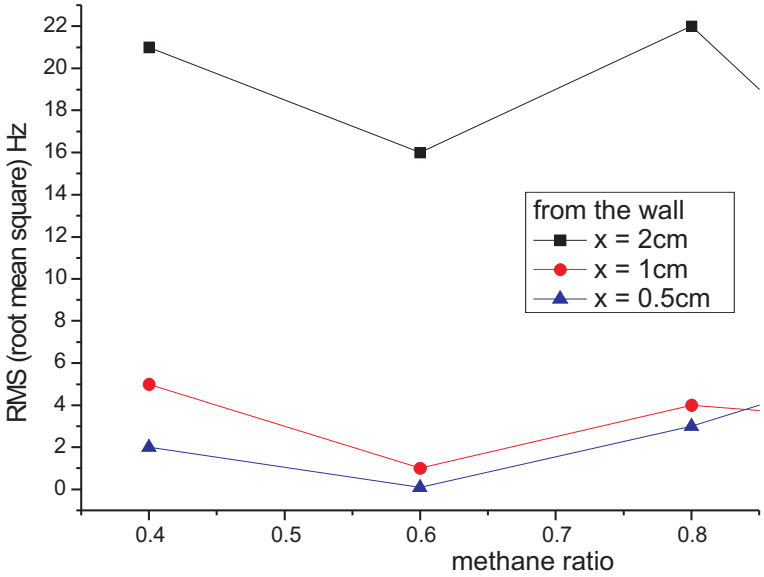


Figure 6: Root mean square RMS value for combined effect of nitrogen dilution rate and the impinging wall.

gas. When the nitrogen fraction rates increase the detached flame length increase is 1 cm for $0.2N_2$ and 4 cm for $0.6N_2$.

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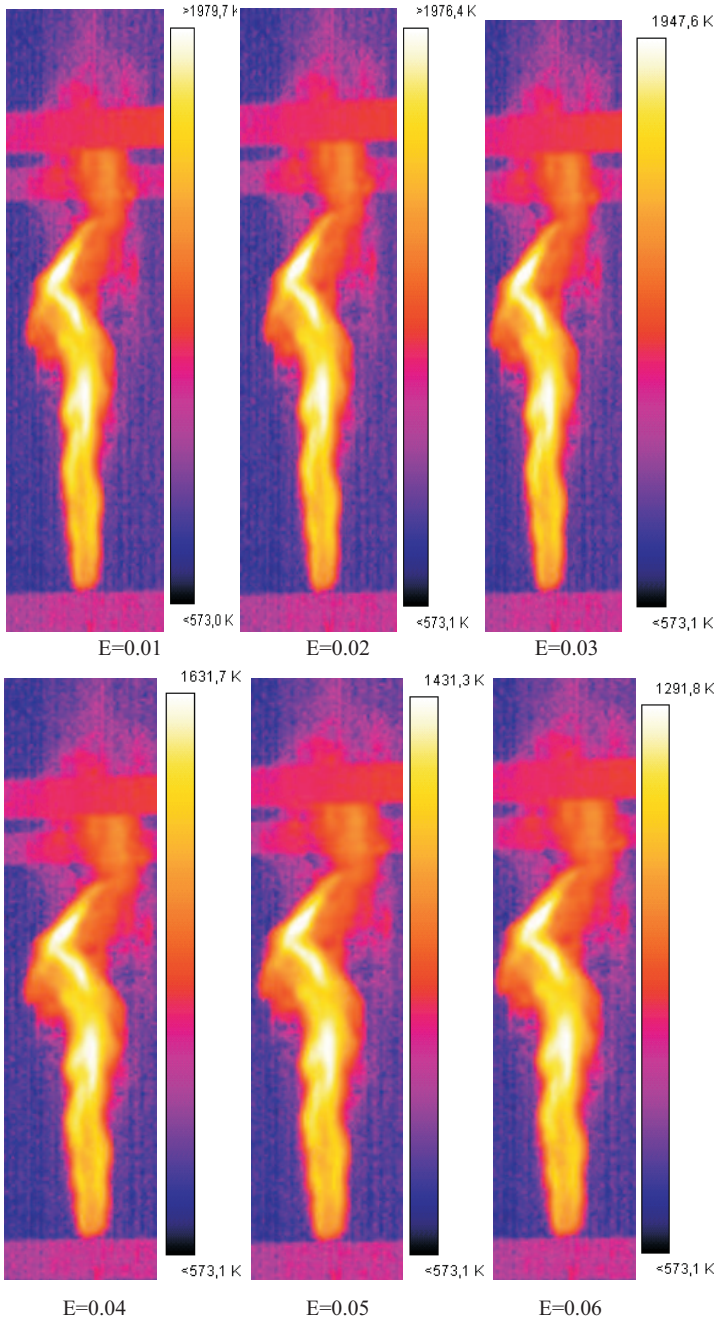


Figure 7: Methane diffusion flame contour for different flame emissivity, E, (thermography results).

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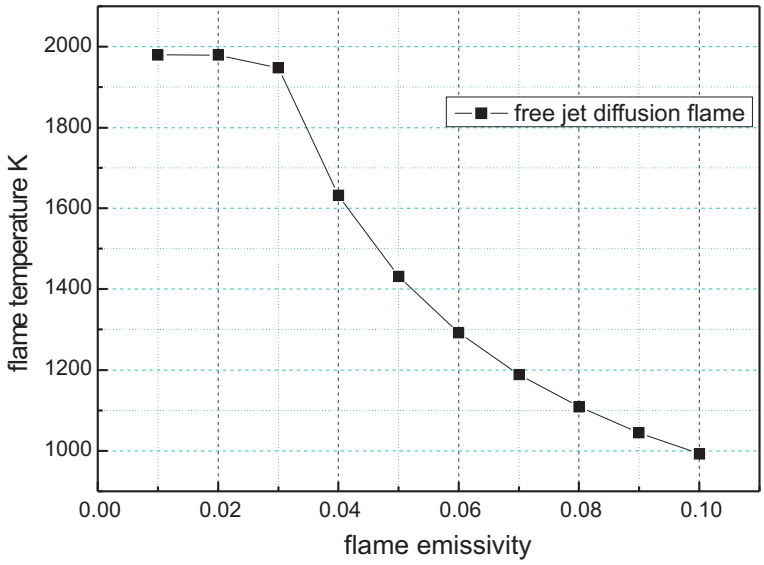


Figure 8: Temperature of methane diffusion turbulent flame as a function of flame emissivity (at Reynolds number of 6000).

4.3 Thermography for free jet turbulent diffusion methane flame

This second part of this study focused on flame emissivity. Experimental investigation was carried out to determine the emissivity of a turbulent diffusion flame generated by a methane jet, Fig. 7. A few studies have used various methods to measure the emissivity of turbulent diffusion flames. Most of the authors have based their work on the assumption that emissivity values can be given for a kind of equivalent medium and have found emissivity values to be related to flame thickness, but there is disagreement on the results of the coefficient relating these two variables, i.e., the extinction coefficient. Furthermore, recent years have seen an increase in the use of IR cameras in applications related to flames studies. Infrared systems behave like a heat flux transducer formed by a two dimensional array of sensors and can transform signals from the sensors into temperatures by specifying the ambient temperature, relative humidity, distance and emissivity of the viewed object. Thus, quantitative thermal measurements made with IR cameras require a good estimate of the emissivity of the object under study. This part of our study takes advantage of the spatial resolution of the IR cameras to compute the emissivity of a methane diffusion flame

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for a free jet and to evaluate the influence of flame emissivity variation on maximum flame temperature. The results obtained with applied image acquisition system demonstrate that the increasing in flame emissivity from 0.01 to 0.1 decrease the maximum flame temperature, Fig. 8.

5 Conclusion

An experimental investigation using an infrared thermography technique on improving the diffusion rate by introducing inert gas into an impinging flame was carried out. The conical shape of the diffusion jet flame was destroyed and the stretch effect was weakened as the methane fuel mixed with the nitrogen gas. The flame structure was that of a plane flame. It is interesting to note that the nonreactive gas, nitrogen gas, spread the flame to a shape similar to that of the cold flow condition. The results show that the inert gas increased the diffusion rate in the reaction process. The flame became bluer and shorter. The fluctuation rate at the tip of the conical flame was also reduced. The blue flame is more stable than the pure diffusion flame. The results suggest that the inert gas does not interact with the reaction flow but does impact the diffusion rate.

It is also interesting to note that the temperature of the impinging flame becomes similar to that of the pure methane flame as the nitrogen gas mixture ratio is increased. The RMS temperature is more influenced with nitrogen addition more dilution we will obtain the flame extinction.

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References

[1] Williams F.A.: *Progress in knowledge of flamelet structure and extinction*. Prog. Energy Combust. Sci. **26**(2000), 657–682.

[2] Williams F.A.: *A Review of flame extinction*. Fire Safety J. **3**(1981), 163–175.

[3] Sarnacki B.G., Esposito G., Krauss R.H., Chelliah H.K.: *Extinction limits and associated uncertainties of nonpremixed counter flow flames of methane, ethylene, propylene and n-butane in air*. Combust. Flame, **159**(2012), 3, 1026–1043.

Unauthenticated
Download Date | 2/20/18 6:59 PM

[4] Ji Ch., Dames E., Wang H., Egolfopoulos F.N.: *Propagation and extinction of benzene and alkylated benzene flames*. Combust. Flame, **159**(2012), 4, 1426–1436.

[5] SunW., Uddi M., Sang Hee Won, Ombrello T., Carter C., Ju Y.: *Kinetic effects of non-equilibrium plasma-assisted methane oxidation on diffusion flame extinction limits*. Combust. Flame, **159**(2012), 1, 221–229.

[6] Juddoo M., Masri A.R.: *High-speed OH-PLIF imaging of extinction and re-ignition in non-premixed flames with various levels of oxygenation*. Combust. Flame, **158**(2011), 5, 902–914.

[7] Ding N., Arora R., Norconk M.,Lee S.Y.: *Numerical investigation of diluent influence on flame extinction limits and emission characteristic of lean-premixed H_2-CO (syngas) flames*. Int. J. Hydrogen Energ. **36**(2011), 3222–3231.

[8] Ghiti N., Bentebiche A.A., Hanchi S.: *Interaction entre une flamme de diffusion et une paroi verticale*. In: Proc. X Colloque Interuniversitaire Franco-québécois sur la Thermique des Systèmes, Saguenay, 20-22 Jun 2011, 239–245.

[9] Witze P.O.: *A study of impinging axisymmetric turbulent flows: The wall jet, the radial jet, and opposing free jets*. SAND74, 8257, 1975.

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