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Technical Note

Investigation of impinging diffusion flames with inert gas

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Abstract

Experimental investigations on impinging diffusion flames mixing with inert gas were conducted. The combustion results and temperature measurements show that the non-reactive gas might dilute the local fuel concentration in the diffusion process. The shape of the column flame was symmetrical due to the flame stretch force. The results showed that a conical flame was changed by the addition of inert gas to the pure methane fuel. The weakening of the stretch boundary enhanced the mixing rate between the fuel and oxidizer, which would improve the fluctuation phenomenon. The impinging flame became shorter and bluer so the combustor size can be reduced. Nitrogen gas has the advantage that we can visualize the impinging mechanism with different gases in the impinging flame. The color in the mixing plane becomes blue and transparent. The penetration length is about 8 mm near the impinging point for $Re = 145$. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Impinging flame; Diffusion flame

1. Introduction

Investigations of enhanced combustion efficiency have been important for the past decade. Most improvements have concentrated on increasing the turbulent fluctuations and flow intensities. Jet-to-jet impinging is widely used in rocket engines with self-ignition propellants. The purpose of this research is to examine the impinging effect on the jet-impingement diffusion flame.

Two aspects of the impinging flame, jet impingement heating and combustion enhancement have been investigated, Milson and Chigier [1] showed that a cool central core was observed on a plate at the impinging point by the impinging unreacted gas. The cooling area increased with the initial jet velocity. The maximum temperature occurred downstream of the impinging point in wall-impinging flame experiments. Nosseir et al. [2] conducted jet impingement flow field measurements, with the maximum pressure fluctuation occurring next to the impinging point and close to the maximum temperature location. Bain and Smith's [3] results showed that higher pressure and velocity fluctuations may increase the fuel/air mixing rate and the kinetic energy and enhance the reaction rate.

In liquid rocket engines, jet-impinging mechanisms are used to increase the mixing and reaction rates. Experimental results by Witze [4] and Blazowski et al. [5] showed that the flow intensities were proportional to the initial jet velocity. The reaction rate observed by Witze [4] and Holve and Sawyer [6] was shown to be proportional to the square root of the flow intensities. Jet-to-jet impingement has been proven to be useful in the industrial and propulsion fields. One important reason for selecting the jet-to-jet impingement arrangement is to increase the combustion efficiency. The combustor length, therefore, can be shortened and costs can be lowered. Therefore, it is important to study the structures of impinging flames. An experimental investigation is presented in this paper.

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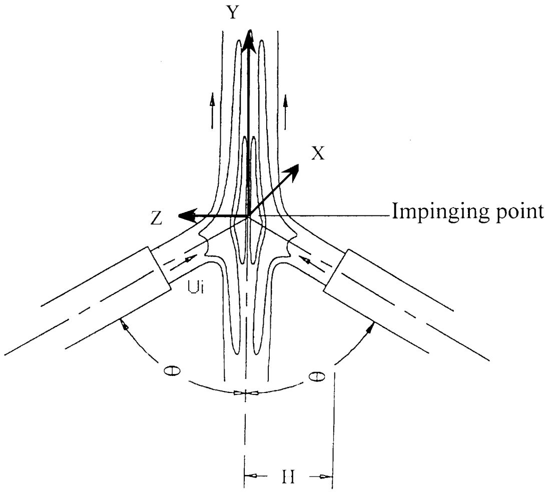

Fig. 1. Configuration of jet-to-jet impingement.

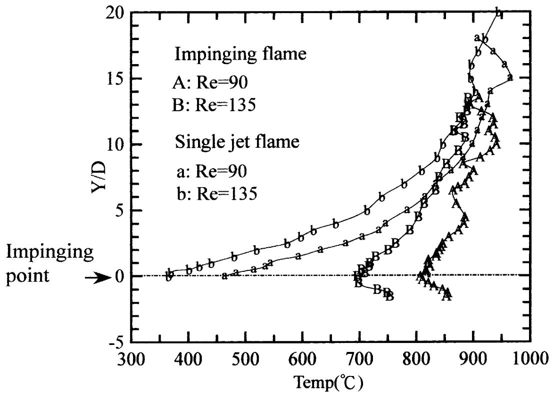

Fig. 2. Development of centerline temperatures of single jet flame and jet-to-jet impinging flame.

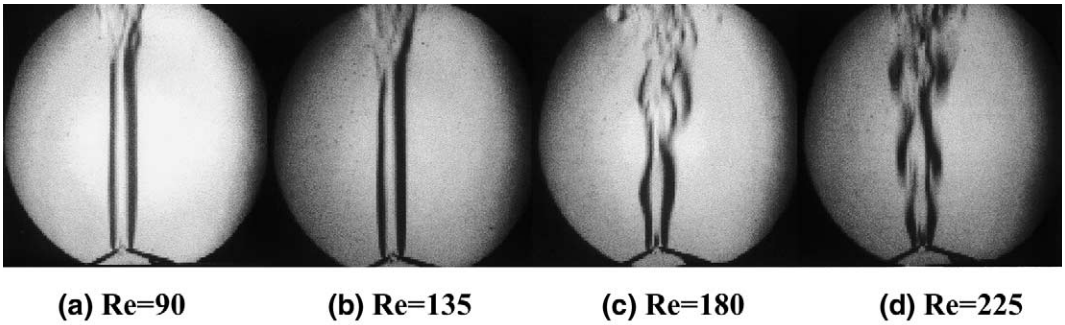

Fig. 3. Evolution of jet-to-jet impinging flames at $\theta = 72°$.

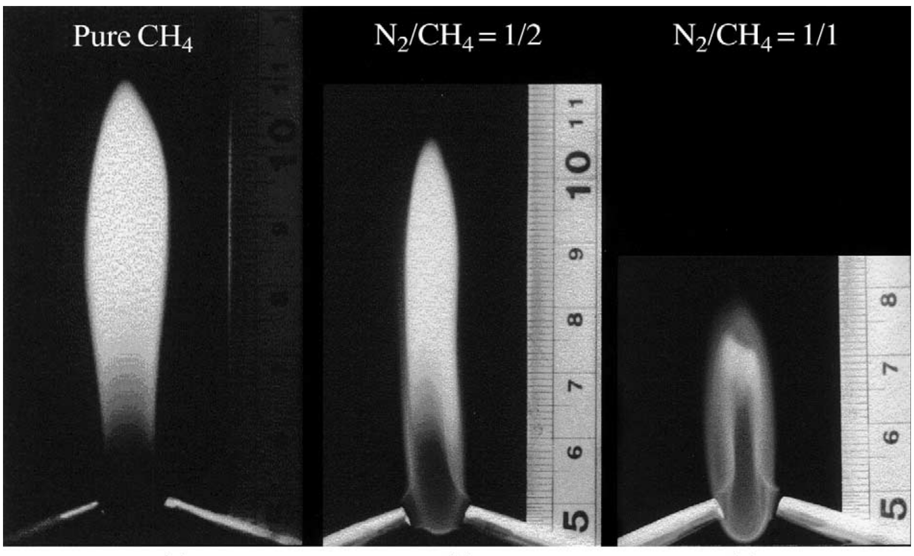

Fig. 4. Impinging-jet diffusion flame in YZ plane at $Re = 225$ and $\theta = 72°$: (a) pure CH_4; (b) $N_2/CH_4 = 1/2$; (c) $N_2/CH_4 = 1/1$.

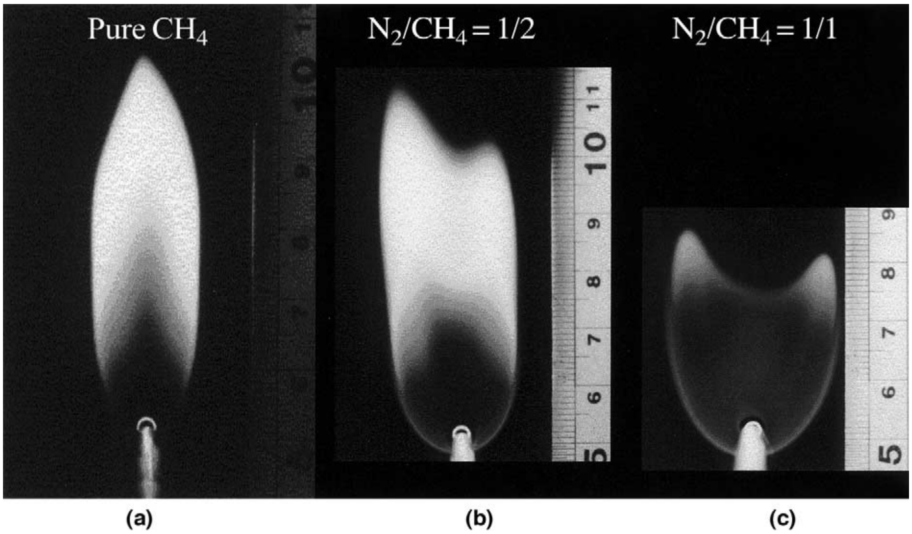

Fig. 5. Impinging-jet diffusion flame in XY plane at $Re = 225$ and $\theta = 72°$: (a) pure CH_4; (b) $N_2/CH_4 = 1/2$; (c) $N_2/CH_4 = 1/1$.

2. Experimental set-up

Fig. 1 illustrates the experimental setup for jet-to-jet flame impingement. The inner diameter of the circular jets was 2 mm. The distance between the two jets was 4 times the inner diameter, $H = 4D$. Half of the intersection angle between the two jets, θ, was adjusted to 72° in this investigation. The geometric co-ordinate system of the impinging jets was defined with plane including both jets set as the XY plane. The YZ plane was then perpendicular to the jets. The origin of the co-ordinate system was located at the center of the impinging point. The combustion results are discussed using observations and temperature measurements. The flame temperatures were obtained using a K-type thermocouple located on a three-dimensional traversing mechanism.

The effect of inert gas in the diffusion flame was studied using methane fuel mixed with nitrogen gas. The N_2/CH_4 volume ratios were 0, 1/2 and 1/1.

3. Results and discussion

Two opposite jets impinge together to form a mixing co-plane. During the impinging process, the jet flow velocities may decrease to a minimum at the impinging point. The momentum energy transfer increases the flow intensities and the mixing rate. Therefore, the combustion rates are accelerated compared with Su and Liu's [7] single jet flame result. Fig. 2 illustrates the development of a single jet flame and a jet-to-jet impinging flame along the centerline plane. The impinging flame shows a faster development rate than the single jet flame. This result may be due to the flow turbulent interaction and mixing during jet impingement. This advantage can shorten the combustion zone. In addition, due to the velocity decrease and higher temperatures near the jet orifices, the blow-off condition limit of the jet-to-jet combustion flame can be extended to a higher range than for a single jet flame.

As with a jet diffusion flame, the buoyancy effect causes the tip of the jet flame to become unstable and fluctuates as the jet flow velocities increase. Fig. 3 shows the evolution of jet-to-jet impinging flames for increasing Re. The fluctuation disturbs the main diffusion flame as the Reynolds number becomes greater than 180 and extends further upstream at $Re = 225$ for $\theta = 72°$.

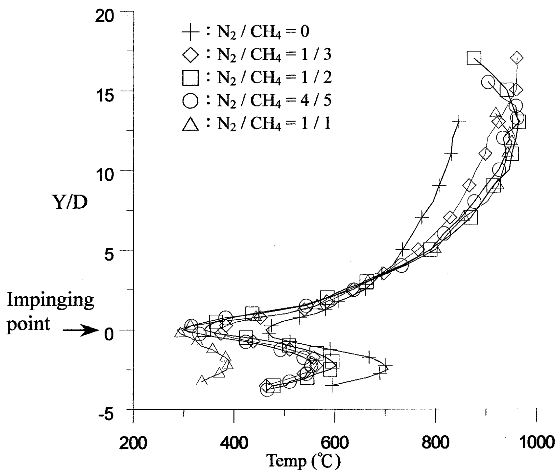

Fig. 6. Temperature distributions along the centerline of a diffusion flame mixing with different ratios of the inert gas at $Re = 225$ and $\theta = 72°$.

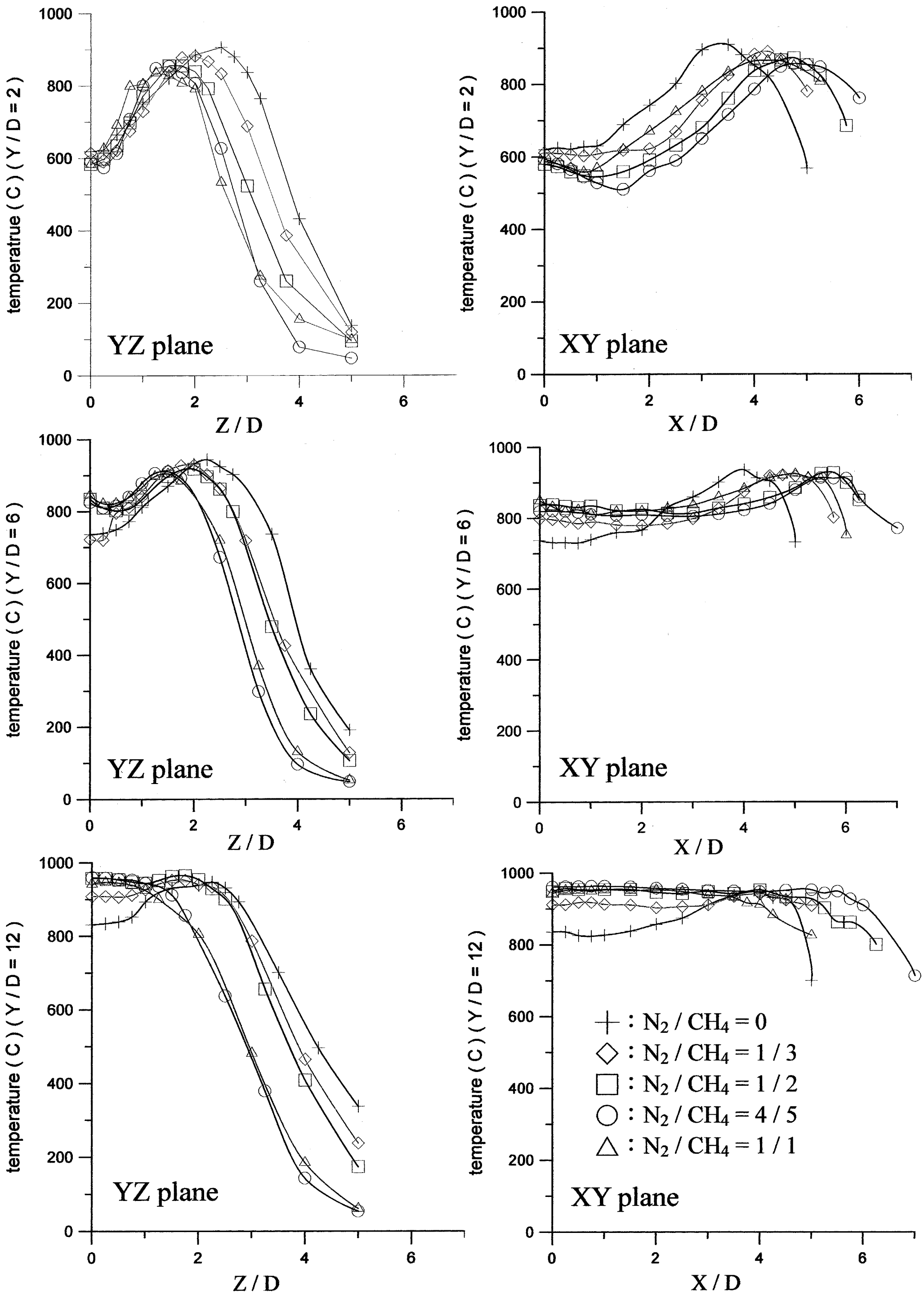

Fig. 7. Temperature distributions in the *XY* and *YZ* planes of the impinging flame mixing with different ratios of the inert gas at $Re = 225$ and $\theta = 72°$.

In a liquid rocket engine, the addition of nitrogen gas may increase the thrust owing to an increase in the mean specific weight. The disadvantage is that the nitrogen reduces the flame temperature. Figs. 4 and 5 illustrate the differences between a pure impinging flame and a flame mixed with nitrogen gas in the *YZ* and *XY* planes.

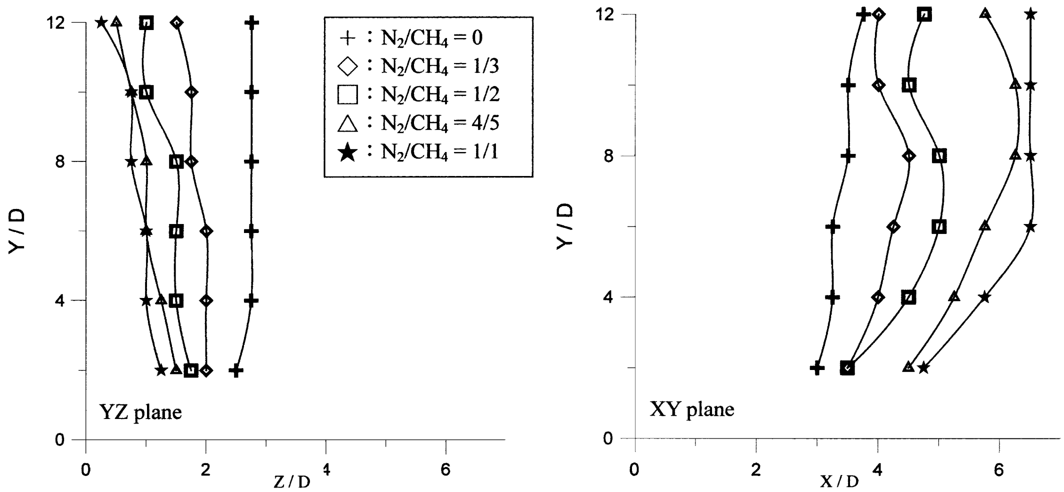

Fig. 8. Location of flame sheet in YZ and XY planes mixing with different ratios of inert gas at $Re = 225$ and $\theta = 72°$.

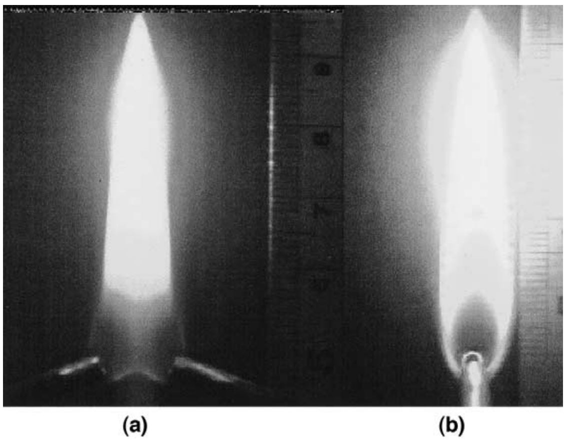

Fig. 9. Configurations of like impinging flames at $\theta = 72°$, $Re = 115$.

The length of the impinging flame decreases as the N_2/CH_4 mixture ratio is increased. The blue area occupies nearly the entire impinging flame for a mixture ratio of 1. This shows that the nitrogen gas molecules dilute the local methane fuel concentration, which produces better combustion.

Because of the flame stretch effect, the pure diffusion flame grows and assumes an axially symmetrical conical shape. When the methane flame mixes with nitrogen gas, the flame shape tends to flatten in the XY plane. These flow fields are similar to the cold flow of jet impinging flow [4]. 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

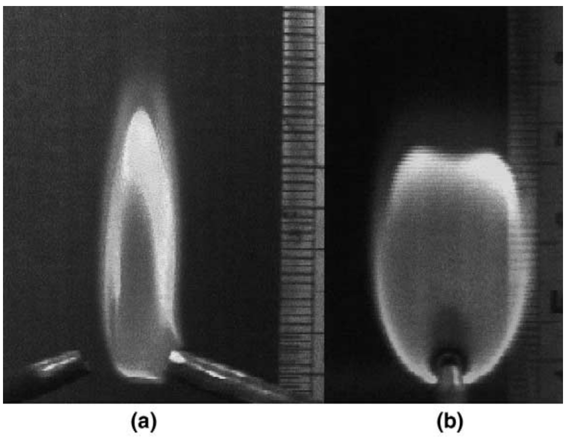

Fig. 10. Configurations of different impinging gases flames at $\theta = 72°$, $Re = 115$ (CH_4) and $Re = 90$ (N_2).

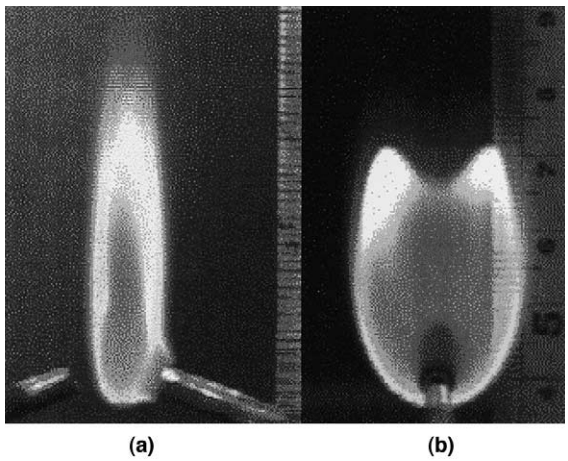

Fig. 11. Configurations of different impinging gases flames at $\theta = 72°$, $Re = 145$ (CH_4) and $Re = 115$ (N_2).

Table 1
Physical properties of the impinging flame

Methane flow rate (ml/min)	Condition					
	Flame height (mm)	Flame width (mm)	Temp. of impinging point (°C)	Penetration (mm)	Tf_{max} (°C)	Tf_{ave} (°C)
350 ($Re = 115$)	36	44	453	6	961	748
450 ($Re = 145$)	28	48	280	8	982	746
350 (Pure)	66	24	593	–	1001	854

stretch boundary may enhance the mixing rate between the fuel and oxidizer. The fluctuation phenomenon can, therefore, be improved.

Fig. 6 illustrates the temperature distribution along the centerline of the impinging flame mixed with different inert gas ratios. The pure methane flame shows slower combustion development. The lowest temperature in every distribution is located at the impinging point of the two jets. Because the non-reactive gas, the temperature at the impinging point decreases as the mixing ratio increases. A $N_2/CH_4 = 1/1$ diffusion flame has a shorter flame length and less flash back upstream of the impinging point. This is consistent with the photos in Figs. 4 and 5. The temperature distributions in the XY and YZ planes shown in Fig. 7 indicate that the diffusion flame with inert gas is extended and flattened. The ratio of the thickness (YZ plane) to the width (XY plane) of the symmetrical conical shape of the pure methane flame is about 4/5. However, the thickness ratio of the $N_2/CH_4 = 1/1$ flame is about 1/3. Obviously, the pure diffusion flame is still not fully developed at $Y/D = 12$. The combustion flame with inert gas has greater efficiency and a shorter reaction zone.

Fig. 8 illustrates the maximum temperature location for every case in the cross section. The location of the flame sheet is also shown. The results show that the pure methane impinging flame exhibits a symmetrical conical shape. The flame configuration becomes asymmetrical as the proportion of non-reactive gas in the fuel is increased. The stretch force of the flame also becomes weaker when mixed with nitrogen gas.

In order to investigate the impinging effect of the two jets, one of the jets was fed with pure methane fuel while the other was supplied with either methane or pure nitrogen gas. The impinging flame from the two pure methane jets in Fig. 9 shows a long conical shape, as was seen with the pure diffusion flame. The reaction zone extended to almost 5 cm. The configuration with different impinging gases, one of the jets supplied with pure nitrogen, is shown in Fig. 10. The flame is bluer and shorter. The combustion length is almost half that in the pure methane jets case. In Figs. 10 and 11, the left side of the different impinging gases flame does not interact with the methane flame. The co-plane of the different impinging gases flame is very different from the pure impinging flame. The color in the co-plane becomes blue and transparent. This transparent region with blue emissions might be described as the mixing zone of the impinging flame. The physical properties of this impinging flame are listed in Table 1. The temperature at the impinging point decreases as the nitrogen flow rate is increased. The maximum and average flame temperatures exhibit the same tendency. The penetration depths along the centerline are 6 and 8 mm when Re is equal to 115 and 145, respectively. The width of the different impinging gases flame is increased due to the momentum of the nitrogen gas. The penetration of the impinging mechanism can be illustrated using the different gases.

4. Conclusions

An experimental investigation on improving the diffusion rate by introducing inert gas into an impinging flame was executed. 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 non-reactive 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 mixing will shorten the combustion zone which will reduce the combustor size. The nitrogen gas also allows visualization of the impinging mechanism as the color in the mixing plane becomes blue and transparent. The penetration length is about 8 mm near the impinging point for $Re = 145$.

Acknowledgements

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