Experimental observation on the structure and sooting characteristics of laminar CH4 and C2H4 double diffusion flames

Liu, Fengshan; Smallwood, Gregory

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EXPERIMENTAL OBSERVATION ON THE STRUCTURE AND SOOTING CHARACTERISTICS OF LAMINAR CH_4 AND C_2H_4 DOUBLE DIFFUSION FLAMES

F. LIU, and G. J. SMALLWOOD
Institute for Chemical Process and Environmental Technology
National Research Council, Building M-9, 1200 Montreal Road, Ontario, Canada

ABSTRACT

The conventional Gülder laminar diffusion flame burner was modified by introducing a central air jet inside the fuel tube. The modified burner in general produces a double flame structure: an inner inverse diffusion flame and an outer normal diffusion flame. In this study, the structure and sooting characteristics of double CH_4 and C_2H_4 flames at different central air jet flow rates were investigated.

INTRODUCTION

The structure and soot formation characteristics of laminar normal diffusion flames (NDF) (fuel jet is issued into air) and inverse diffusion flames (IDF) (air is issued into fuel) have been extensively studied both experimentally and numerically. It has been made clear that IDFs exhibit remarkably different soot formation features from those of NDFs due to the very different temperature, chemical environment, and residence time experienced by incepted soot particles [1]. In IDFs, soot particles are formed outside the flame sheet (on the fuel rich side) and subject to increasing mixture fraction and decreasing temperature as they are convected downstream. The soot particles do not go through an oxidizing process. In NDFs, the soot particles formed low in the flame and on the fuel rich side of the flame sheet are 'pulled' towards the flame centerline and go through a fuel rich and high temperature for a relatively long time before finally cross the flame sheet where they are oxidized. As a consequence of these differences, NDFs have a much higher soot loading than IDFs and do not emit soot when operated below smoke point. On the other hand, IDFs emit soot. Several studies have shown that the structure of IDF can be predicted by theories developed for NDF [2,3]. This is because mathematically the NDF and IDF are indistinguishable and the only difference is that fuel and air are interchanged.

In an attempt to extend the operating range of an IDF burner, Sobiesiak and Wenzell [4] examined the effects of air and fuel injector diameters and flow rates on the structure, appearance, and stability of a turbulent natural gas double diffusion flame (DDF). A DDF consists of an inner IDF is enveloped by an outer NDF. A DDF can be generated either by replacing the coflowing inert gas (used to shield an IDF) with air in an IDF setup or introducing an air stream inside the fuel stream of a NDF burner. In the work of Sobiesiak and Wenzell, the outer oxidizer stream is the quiescent air. DDF configuration is closely related to that of staged-air combustion technology for NOx control found in many practical applications. Kwak et al. recently showed experimentally that DDF burner offers several advantages over the NDF burner in a gasification study of municipal solid waste [5]. In another recent numerical and experimental study, Liu et al [6] investigated the structure and sooting characteristics of a laminar methane DDF using a modified Gülder diffusion flame burner by inserting a coaxial air jet of 3 mm i.d.

inside the fuel tube. Under the conditions considered in [6], both numerical modelling and experimental observation showed that the IDF cannot be established, though an inner lifted flame is observed both experimentally and numerically when the central air jet flow rate is sufficiently high.

The present study investigates the structure, appearance, and sooting characteristics of laminar CH_4 and C_2H_4 DDF using a revised design from that used previously in [6] by using a larger coaxial air jet of 6.55 mm i.d.

EXPERIMENT

The burner employed in this study is a modified version of the standard NRC co-annular laminar diffusion flame burner (Gülder burner). A top view of the burner is shown in Fig.1. It consists of a central air jet of 6.55 mm i.d. and 7.94 mm o.d., a coaxial fuel pipe of 10.95 mm i.d. and 12.75 mm o.d., and another coaxial outer air jet of 100 mm i.d. Before exiting their respective nozzles, both air streams and the fuel stream pass through porous metal disks to achieve uniform flows and suppress flow disturbances. The flow rates of all three streams were controlled using mass flow controllers (Aalborg). In the present experiments, the flow rates of fuel and the outer air stream were maintained constant (194 cm^3/min for C_2H_4, 388 cm^3/min for CH_4, and 284 l/min for air) while the central air jet flow rate was varied. The effect of the central air jet flow rate on the flame appearance was recorded using a digital camera. For the C_2H_4 flames, the distributions of soot volume fraction were measured using the 2D line-of-sight attenuation technique [7].

Fig.1. Top view of the double diffusion flame burner.

RESULTS AND DISCUSSION

Methane double diffusion flames

It was observed that two drastically different flame appearances can be achieved at low central air jet flow rates, depending on the operational conditions. When the methane flame was ignited with the central air jet turned off, a stable NDF with a luminous flame height of 63 mm is generated, Fig.2(a), which is very almost identical to that established with the Gülder burner under the same fuel and outer air flow rates. Without the central air flow, the methane NDF has a blue base about 7 to 8 mm high and the upper part is very yellow-orange in color characteristic of soot radiation. As a small amount of air was added through the central jet (the amount of air delivered through the central air nozzle is represented by the ratio of the central air jet mean velocity to that of the fuel jet $R = U_{air}/U_{fuel}$, where U_{fuel} = 14.47 cm/s for methane and 7.24 cm/s for ethylene), for R less than 1.92, the color of the flame changed significantly from bright yellow-orange (R = 0) to a pale orange structure enveloped by blue (R = 1), then to almost pure light blue ($R \geq 1.5$), indicating the formation of soot is almost completely suppressed. The

variations of the flame color with increasing the central air jet flame rate for $R \leq 1.92$, captured by a digital camera of identical settings, are shown in Fig.2. It is evident from Fig.2 that the IDF is absent when $R < 1.92$ and the central air delivered into the fuel stream is to simply premix with the fuel. As such the resultant flame is likely a partially premixed one. This gesture is supported by the remarkable similarity between the present methane flames and those of partially premixed methane flames reported by Gore and Zhan [8], who found that partial premixing reduces and ultimately eliminates soot particles in methane flames. Although partially premixed methane diffusion flames were also studied by Bennett et al. [9], they did not report how partial premixing affects the sooting behavior of laminar methane diffusion flames. However, they observed a double flame structure (an inner rich premixed flame and an outer diffusion one) when the level of premixing is high enough. It is evident from Fig.2 that dilution (premixing) of CH_4 by air is a very effective way to suppress soot formation in CH_4 diffusion flames.

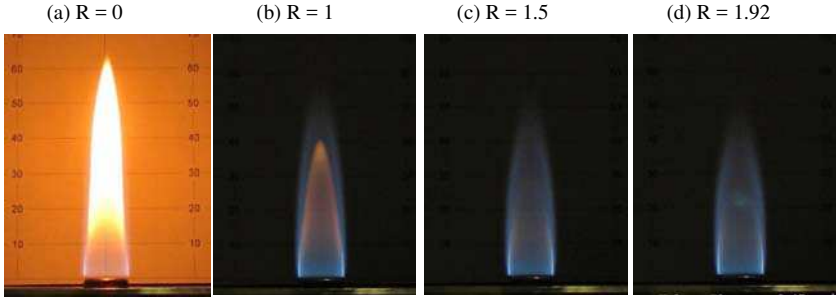

Fig.2 The visible flame appearance of the double CH_4 flame at low central air jet flow rates ($R \leq$ 1.92) when the flame is ignited with the central air jet first turned off and then gradually increased in flow rate. The corresponding equivalence ratios of fuel/central air (if they were fully mixed) are ∞, 12.63, 8.42, and 6.59.

At R =1.92, Fig.2(d), it is interesting to notice that there appears a light blue spot in the flame centerline region at a height of about 2 cm above the burner exit, Fig.2(d). With a further increase in the central air jet flow rate beyond R = 1.92, the blue spot in the flame centerline region moves upstream to form an IDF anchored at the central air nozzle rim and the soot-free blue flame becomes a yellow-orange sooty flame again, Fig.3(c). It is believed that the appearance and upstream motion of the blue spot are associated with the ignition of the partially premixed mixture (between the central air and the fuel) by the outer diffusion flame when such mixture is formed at a location sufficiently close to the outer diffusion flame sheet. Once the mixture is ignited, the flame propagates upstream and stabilizes at the air nozzle rim. After it is formed, the IDF remains anchored over a range of the central air jet flow rate of $R < 3$. The visible flame appearances under conditions of anchored IDF are shown in Fig.3. The inner blue structure of the IDF is clearly visible. The sooting characteristics of the DDF, Figs.3(a) and (b), are strikingly different from those of the partially premixed flame, Figs.2(b) and (c), under conditions of identical air and fuel flow rates. Clearly, the DDF with the establishment of the inner IDF strongly favors soot formation compared to its counterpart without the IDF. The enhancement soot formation with the onset of the IDF can be explained primarily by the flame temperature effect on soot formation in diffusion flames. The IDF significantly increases the temperatures along the flame centerline region, which in turn greatly accelerates the pyrolysis of the fuel, leading to enhanced soot formation. Compared to the case of without central air, R = 0, the luminous flame height of the DDF decreases significantly with the increase in the central air flow rate. This is easy to understand since the fuel requires less oxygen from the outer air stream

to fully react when more air is added from the central air nozzle. As more air is added through the central air nozzle, soot formation is also suppressed, as the luminous zone becomes shorter and fainter. This can be attributed to the dual actions of the central air: suppression of C_2H_2 formation, which reduces the soot surface growth rate, and direct oxidation of soot. It is also interesting to observe that the luminous sooting region always appears at about 8 mm above the burner exit, regardless the central air flow rate.

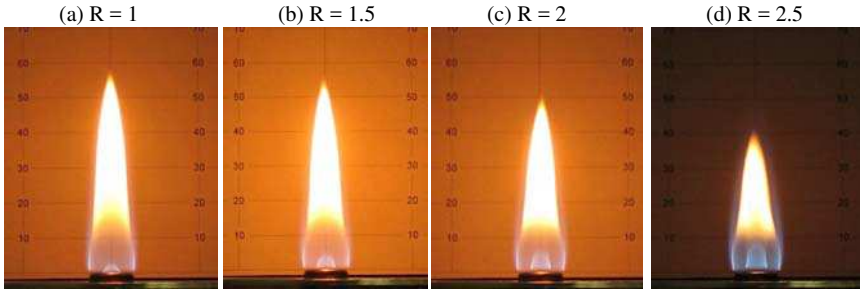

Fig.3 The visible flame appearance of the double CH_4 flame at central air jet flow rates between R = 1 and 2.5 with the onset of the inner IDF. The corresponding equivalence ratios of fuel/central air (if they were fully mixed) are 12.63, 8.42, 6.32, and 5.05.

The visible flame appearances at even higher central air flow rates, $R \geq 3$, are shown in Fig.4. At these higher central air flow rates, the inner flame becomes lifted and the luminous zone is further reduced to a very small region, Figs.4(a)-4(c), and eventually almost disappears, Figs.4(d)-4(e). The lift-off height of the IDF first increases with the air flow rate, Figs.4(a)-4(d), and then remains constant over the range of $5 < R < 6.5$. Further increase in the central air flow rate was not attempted in this study due to the limitation of the mass flow controller.

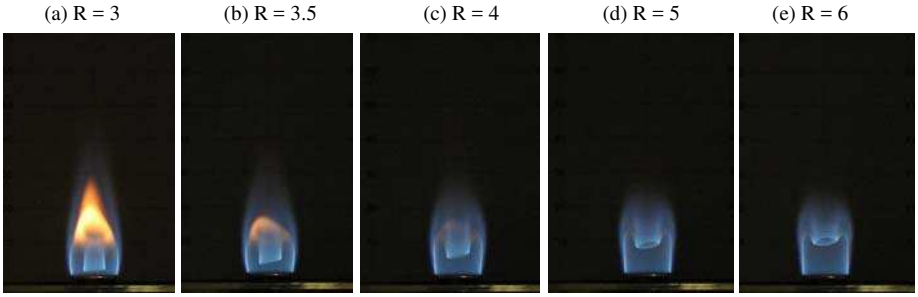

Fig.4 The visible flame appearance of the double CH_4 flame at central air jet flow rates between R = 3 and 6. The corresponding equivalence ratios of fuel/central air (if they were fully mixed) are 4.21, 3.61, 3.16, 2.53, and 2.11.

Unlike the anchored IDFs at low central air flow rates, $R \leq 2.5$, shown in Fig.3 where the tip of the IDF is closed, the lifted IDFs at higher central air flow rates shown in Fig.4 are open-tipped and display a strong interaction with the outer NDF as indicated by the branching of the inner blue ring (the base of the IDF) and the outer blue shell, Figs.4(c)-4(e). The lifted inner flame should be more adequately classified as a triple flame than an IDF.

Ethylene Double Diffusion Flame

Unlike the methane flames, the transition from partially premixed to DDF (with the onset of the inner IDF) does not display a significant change in the flame visible appearance when ethylene is

used as the fuel. The visible appearances of the ethylene flame (acquired by a digital camera with identical settings) without and with small amounts of central air are shown in Fig.5 for $R \leq 2$. Note that in the case of ethylene the mean fuel flow velocity (U_{fuel} = 7.24 cm/s) is half of that of methane. Again the ethylene NDF without the central air, Fig.5(a), is almost identical to that generated with the Gülder burner and the identical fuel and outer air flow rates. The flame is very luminous and has a luminous height of about 64 mm. With a small amount of central air of R = 1, Fig.5(b), the visible flame height decreases from 64 mm to about 57 mm. At a slightly higher central air flow rate of R = 1.5, Fig.5(c), the visible flame height actually increases slightly from 57 mm to 60 mm. A minor change in the appearance of the ethylene flame was observed as the central air flow rate passed through R = 1.5. The flame suddenly and for a short period of time increases in height and then decreases. This transition is believed to be caused by the onset of the inner IDF discussed earlier for the methane flame. At R = 2, Fig.5(d), the visible flame height decreases to about 57 mm. The addition of air through the central nozzle has a different effect on the visible height of the ethylene flame than that in partially premixed ethylene flames experimentally investigated by Mitrovic and Lee [10], who observed that a small of amount of air premixing (up to φ = 20) does not reduce or even slightly increases the visible flame height, compared to the case of the pure ethylene flame.

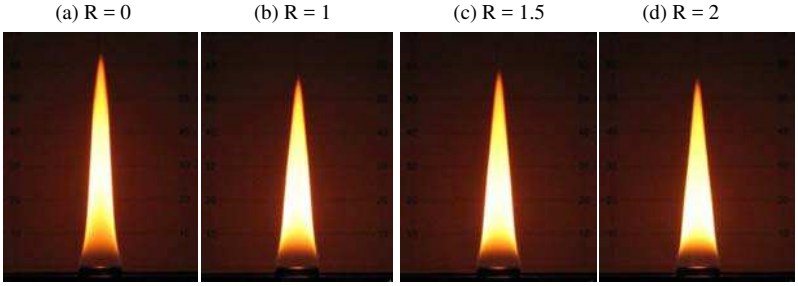

Fig.5 The visible flame appearance of the double C_2H_4 flame at low central air jet flow rates ($R \leq$ 2). The corresponding equivalence ratios of fuel/central air (if they were fully mixed) are ∞, 18.95, 12.64, and 9.47.

The visible flame height continues to decrease and the sooting zone becomes increasingly brighter as more air is added through the central nozzle, as shown in Fig.6. It is also interesting to observe that the flame tip also becomes less pointed, blunt, and finally clipped as the central air flow rate is increased. Such variation in the visible flame appearance reflects that the fact the soot in the centerline region is suppressed and eventually completely eliminated with the increase in the strength of the inner IDF and soot is increasingly confined to the annular region just above the fuel stream. These results are also very different from those observed by Mitrovic and Lee [10] for partially premixed ethylene flames where even at φ = 2.5, corresponding to conditions of Fig.6(d), the partially premixed ethylene flame has a similar visible flame shape as the pure ethylene case albeit the visible flame height is about half of the pure ethylene case. At φ = 2.37 in the present study, Fig.6(d), the visible flame height is only about 15 mm, only about 23% of that without central air. The inner IDF is never lifted under the conditions of this study.

2D LOSA technique was used to measure the soot volume fraction in the ethylene DDF at several central air flow rates. The measurements show that the soot volume fractions decrease with increasing the central air flow rate. At R = 8, the peak soot volume fraction is only 1.5 ppm. Numerical results are in qualitative agreement with the experimental findings and reveal that the

flame temperature increases with increasing the central air flow rate. These lead to the conclusion that the increased brightness of the ethylene DDF is caused by the incandescence of hotter soot particles.

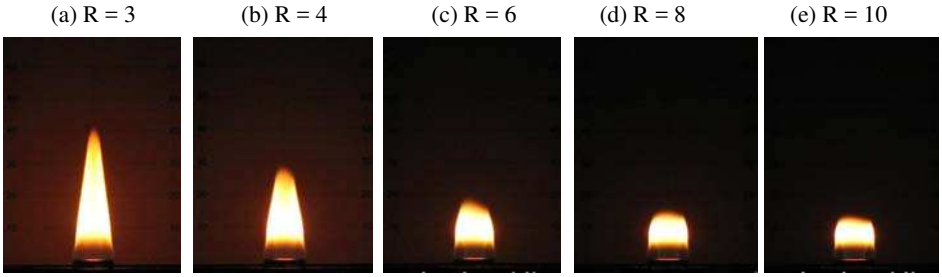

Fig.6 The visible flame appearance of the double C_2H_4 flame at central air jet flow rates $R \geq 3$. The corresponding equivalence ratios of fuel/central air (if they were fully mixed) are 6.32, 4.74, 3.16, 2.37, 1.89.

CONCLUSIONS

A preliminary experimental study using a revised double diffusion flame burner was conducted for methane and ethylene flames. The central air jet has a strikingly different effect on the structure and soot formation characteristics of methane and ethylene flames. The double diffusion flame show different features from the corresponding partially premixed flame and is an interesting flame configuration to gain further insights into soot formation and flame interactions.

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