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Visualization of Fuel Jet in Conditions of Highly Preheated Air Combustion

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During highly preheated air combustion, fuel and air are introduced separately into a furnace. High-temperature air is injected into the furnace and mixed with the already present combustion products to generate a hot gas with low oxygen concentration into which fuel is supplied directly. The way the fuel and air are injected into the furnace chamber is of primary importance for the distributions of furnace temperature, oxygen, and fuel that thus affects NO_x emission and combustion efficiency. Fuel directly injected into a crossflow of a highly preheated (up to 900°C) oxidizer with variable oxygen content was studied experimentally. For still and high-speed photography, direct and schlieren color visualizations were used to record images of flames. Flame size, visibility, color, liftoff distance, and flow structure were investigated. The oxygen concentration in the highly preheated oxidizer was found to have a substantial effect on flame size, liftoff distance, and flame-base fluctuation. A lower oxygen concentration increases the flame size and the liftoff distance, and for the high-velocity fuel jet it also increases the fluctuation and liftoff distance. Temperature has the opposite effect of decreasing the flame size but not in the same proportions as an increase in oxygen concentration. The flame visibility decreases with decreasing oxygen concentration and increases with temperature. Also, flame color changes from bright white/yellow to blue/green/yellow and is primarily influenced by oxygen concentration.

I. Introduction

PREHEATED combustion air reduces fuel consumption and therefore has an appreciable economic effect.[1,2] One serious problem with a higher preheated air temperature is the high emissions of NO_x. Because the flame temperature increases as the air temperature is increased, higher NO_x emissions are observed in efficient combustion systems. When fuel direct injection was investigated, a crucial breakthrough was made.[3,4] The technique is based on a unique idea to reduce the peak flame temperature and oxygen availability in a flame. Fuel and air are injected, separately, directly into the furnace. The method for fuel and combustion air injection into a furnace is of primary importance. At first, high-temperature air jets create large-scale recirculations of the furnace gases, distributing the oxygen throughout the entire combustion chamber. High-temperature zones with low oxygen content are created. The fuel must be directly injected into this environment. Subsequent mixing between fuel jets and furnace gases regulate combustion rate, in-furnace temperature distribution, and emission of nitrogen oxides. Sugiyama et al.[3] and Matsumoto et al.[5] have shown that the emissions of NO_x can be controlled by the fuel-jet injection velocity and injection angle. They found that the lowest emissions of NO_x could be obtained if air and fuel jets are parallel to each other.

Many researchers have studied the mixing mechanism, flow structure, and properties of turbulent diffusion flames, and results are widely reported in the literature. These investigations cover different flow configurations, but mainly coflow air and fuel were studied. Transverse fuel-jet behavior particularly for a blowing ratio

$$r = \sqrt{\left(\rho_{\text{fuel jet}}\, u^2_{\text{fuel jet}} \big/ \rho_{\text{cross flow}}\, u^2_{\text{cross flow}}\right)} \qquad (1)$$

greater than one and when air and fuel are supplied separately to the furnace, has not been thoroughly investigated.[6] A fuel jet injected into an environment containing high-temperature and low oxygen gas has been investigated even less. The influence of fuel-jet dilution on combustion stability and flame structure has been investigated by, for example, Prasad et al.[7] The results obtained with low-temperature air and coaxial fuel jets, which were highly diluted by nitrogen, show increased flame liftoff distances. On the other hand, propane jet diffusion and premixed flames in a high-temperature pure airstream (over the self-ignition temperature) were investigated by Amagai and Arai.[8] It was confirmed that both the diffusion and the premixed flames were well stabilized by the high-temperature environment. Still photography was used to measure flame length and liftoff for nitrogen-diluted methane flames injected into preheated coflowing air (up to 1400 K) by Fujimori et al.[9] It was found that the flame was stable for dilutions up to 80% in highly preheated air.

Color, size, shape, and global structure of a transverse flame jet in high-temperature (900–1150°C) and low oxygen (as low as 4%) environments was reported by Hasegawa et al.[10] They found that large volume and low luminosity of the flame characterize this new type of combustion. Visible-light intensity profiles of the flames were measured with a charge-coupled-device camera. The color of the flame was found to be bluish-green to green, depending on air-inlet conditions. It was also found that flame stability is significantly affected by oxygen concentrations below 10% if the air temperature is lower than 900°C.

Changes in flame luminescence into greenish with decreased oxygen concentration were also reported by Kishimoto et al.[11] In this work a transverse fuel jet was also investigated and chemiluminescence images were registered by a high-speed camera with an interference filter and UV lens.

In this article, as for still and high-speed photography (HSP), direct and schlieren color visualizations were used to record images of flames. Transverse fuel jets in high temperature (above self-ignition temperature) and in nitrogen-diluted air (as low as 2% oxygen) were investigated. Changes in flame size, visibility, color, liftoff distance, and flow structure were registered.

II. Experimental Setup

The experiments were performed in a high-temperature vertical flow furnace, shown in Fig. 1. A low-velocity vertical flow of diluted oxidizer was obtained by the mixing of air and pure

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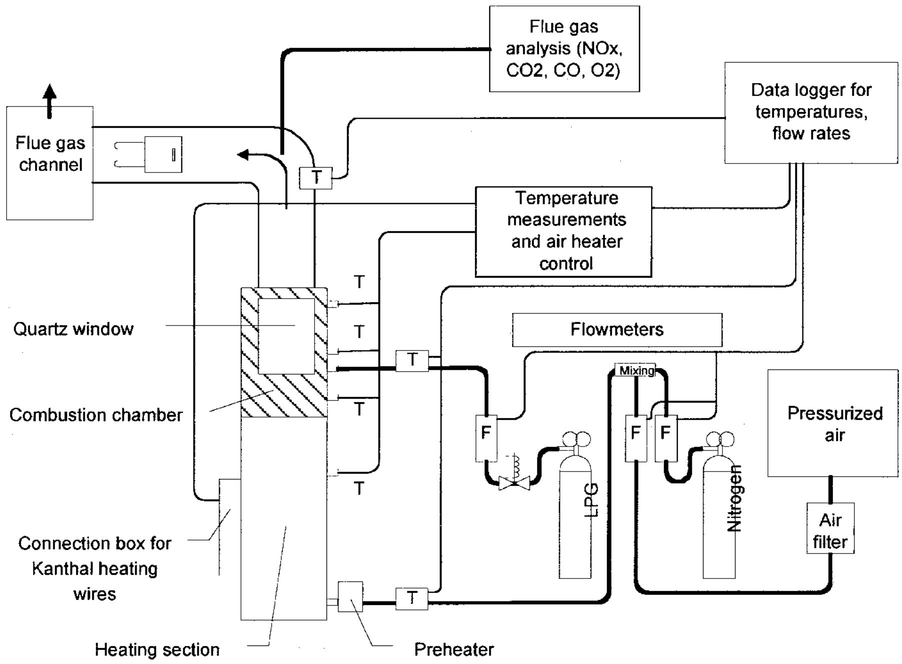


Fig. 1 Schematic of the test furnace.

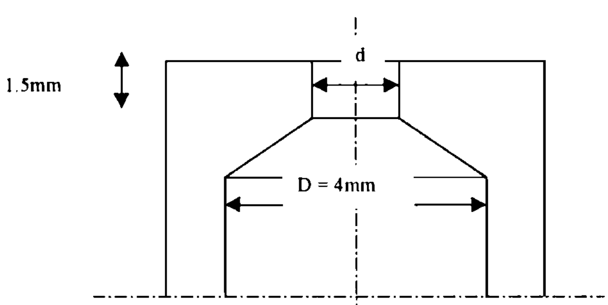


Fig. 2 Design and dimensions of the fuel-jet nozzle.

nitrogen. The oxidizer flow entered the furnace from the bottom through a couple of flow-laminizing devices. Electrical heaters heated up the mixture. The fuel was injected into the laminar vertical diluted oxidizer flowstream by means of a nozzle inserted perpendicularly to the vertical flow, i.e., through the furnace wall and at a level approximately $\frac{1}{3}$ of the combustion chamber height. The fuel used in the experiments was LPG [LPG: C_3H_8 − 75, C_2H_6 − 3, C_3H_6 − 20, C_4H_{10} − 2 (volume per cent)]. Mass flow rates of the oxidizer and the fuel were controlled by flow regulators and logged in a computer. Stable flows of oxidizer and fuel, with a deviation of less than 1%, were achieved with this setup.

Variable parameters included air preheat temperature, fuel-injection nozzle diameter, and oxygen concentration (volume percent) in the oxidizer mixture fed to the furnace. However, the total flow of oxidizer mixture (200 Nl/min) and the fuel flow rate (0.3 Nl/min) were kept constant. Data were recorded for nozzle diameters ranging from 0.3 to 0.9 mm, and, for each nozzle size, a set of measurements was obtained for different oxygen concentrations (21–5 vol %). The nozzles shown in Fig. 2 were designed in a previous project to produce a uniform velocity profile in the cross section of the jet.[12]

The combustion chamber was 155 × 200 × 400 mm and was lined with a flexible insulation of fiber alumina. It was equipped with two sets of windows for flow visualization by direct flame photography and by the schlieren technique.

The flue gas was sucked from the flue gas channel in Teflon tubes and conditioned in a dryer/filter unit. The flue gas composition was then analyzed by a flue gas analyzer with electrochemical cells and the data were stored in the computer.

The temperature was regulated by changing the current supplied to the heaters. The pictures were taken after a constant temperature was reached.

III. Experimental Methods

Photography

Two cameras were used for the ordinary photography and the schlieren color visualization. The still pictures were taken by a 60 × 60 mm Hasselblad camera. The flame propagation and the jet of gases were registered with a Hatland high-speed camera. A 16-mm high-speed film, with a sensitivity of 400 ASA, was used for speeds up to 8000 pictures per second.

Schlieren System

The schlieren flow-visualization technique was used to observe flow patterns and instability phenomena in the fuel jet. The schlieren system has 150-mm-diam mirrors and can be used for visualization in black and white or in color. The schlieren color flow-visualization system was designed with a continuously dispersed prism, which has approximately four times higher sensitivity than the black and white system. As shown in experiments on cold jets, the nozzle used in this work is able to create a stable jet in the initial area behind the nozzle orifice. This was also proved with schlieren HSP. The high-speed camera, which can sample over 8000 pictures per second, was used to record the flow patterns.[12]

The flow visualization was done with a special color schlieren method. The combustion chamber was equipped with two windows placed on opposite walls of the combustion chamber. The windows were made of quartz glass with a fine surface, less than $\frac{2}{10}$ wavelength, and were highly parallel. The high quality of the windows was required for obtaining a high resolution of the jets. The diameter of the windows was 150 mm and the thickness was 30 mm. A prism in the optical system just behind the slit made color visualization possible. The prism created a continuous spectrum of light.

The layout of the prism and the full optical system is shown in Fig. 3. The direct-vision prism was made up of three cemented prisms, with the central one consisting of dense flint, and the outer ones being identical and made from cron optical glass. This construction of prisms permits the yellow ray, i.e., the *D* Fraunhofer line, to pass through the prism without any deviation. Other spectral components are slightly deviated. The maximum angle between the

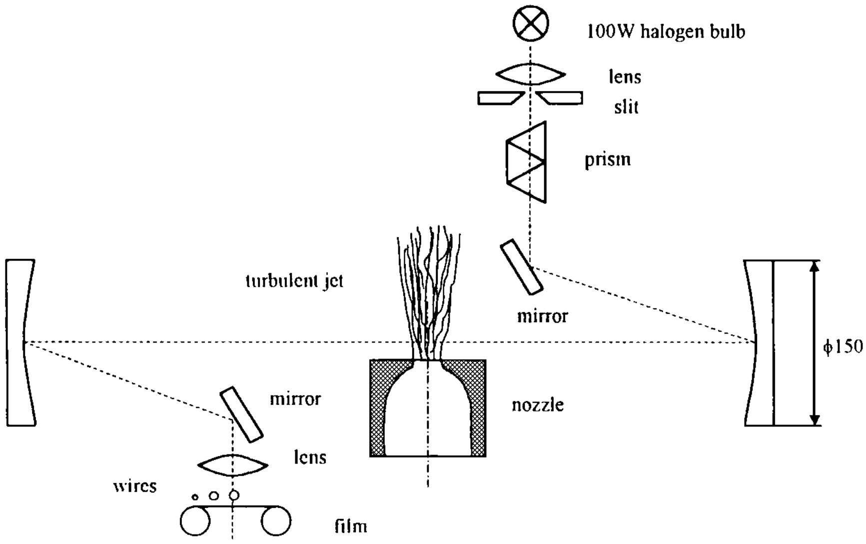


Fig. 3 Layout for the optical color visualization system with direct-vision prisms.

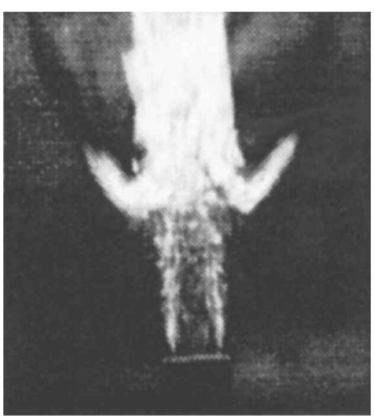
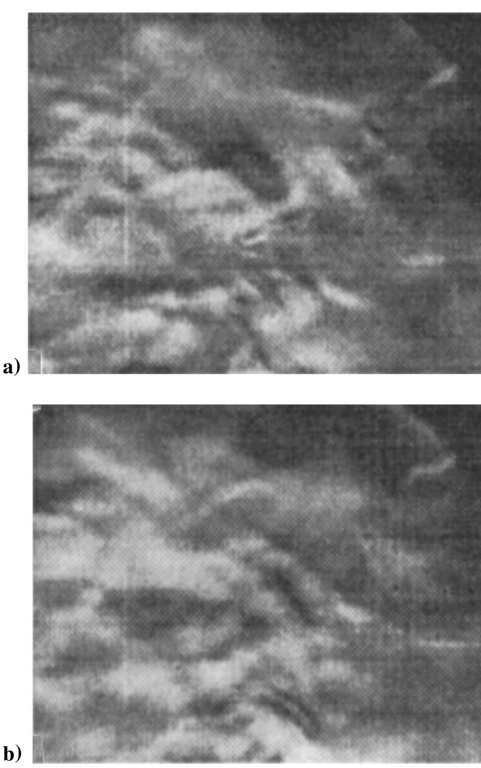


Fig. 4 Schlieren visualization of lifted propane flame in open surroundings. $Re = 10{,}070$, $d = 4$ mm, density ratio DR = 1.54; the wire is placed perpendicular to the propane flow.

Fig. 5 Flame visualization by the Schlieren system: 620°C; $d = 0.7$ mm; fuel, LPG.



a)

b)

Fig. 6 a) 0.4-mm nozzle, 10% O_2; b) 0.4-mm nozzle, 5% O_2. T = 774°C; fuel, LPG.

red and violet rays was not greater than 1°30′. A complete spectrum of white light from a light 100-W halogen bulb with a color temperature of 2900 K was used. Spherical mirrors with a focus length of 1450 mm were used to create the schlieren picture. The height of the slit was constant and 8 mm, whereas its width was varied from 0.5 to 1.5 mm. The white light was split into colors by the constant-deviation prism and focused on a point with the same diameter as the width of the slit.

A more detailed analysis of the optical system provides a correlation between the density gradient ρ and axial coordinate y:

$$\frac{\mathrm{d}\rho}{\mathrm{d}y} = \frac{a}{KLf} \tag{2}$$

where $K = 0.226$ cm^3/g is the constant in Gladston–Dale law, L is the axial dimension of the visualized jet, and f is the length of focus for the collimating mirror. The distance a is the sensitivity of the presented method in the film plane.

To estimate the value of a, a number of measurements were performed with a mechanical shifter in the knife edge. Instead of the knife edge used in a classical schlieren system, a set of wires of different diameters was used. The final result was $a = 0.04$ mm for color schlieren images. Compared with results obtained from experiments in which the white-light technique in the results of the color system showed that this system is at least four times more sensitive.

The schlieren color visualization of combustion seems to be more useful in comparison with the black and white system, if the image analysis is made by red–green–blue (RGB) methods. These methods can distinguish only boundaries between different colors in the object, so it is currently difficult to analyze details of the flow or the flame.

IV. Results and Discussion

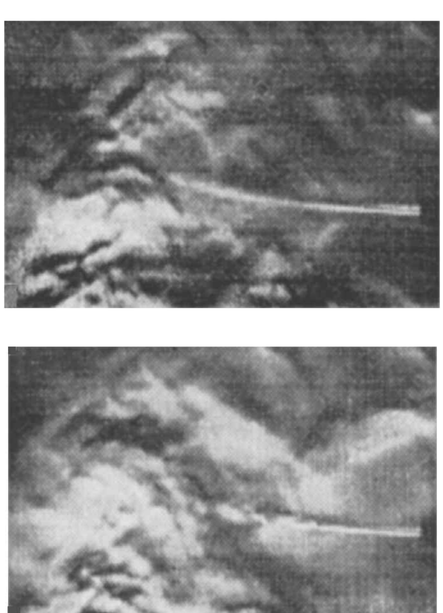
The visualization techniques used in this article are efficient tools to study flow structure in conditions of highly preheated air combustion (HPAC). However, the classical use of the schlieren technique as shown in Fig. 4 is more perceptible compared with the circumstance in which the difference in density between flame and environment is substantially lower. The density ratio DR is defined as

$$DR = \frac{\rho_{\text{oxidizer}, T_{O_x}}}{\rho_{\text{fuel}, T_{\text{fuel}}}} \tag{3}$$

that, calculated for this example, gives $DR = 1.54$.

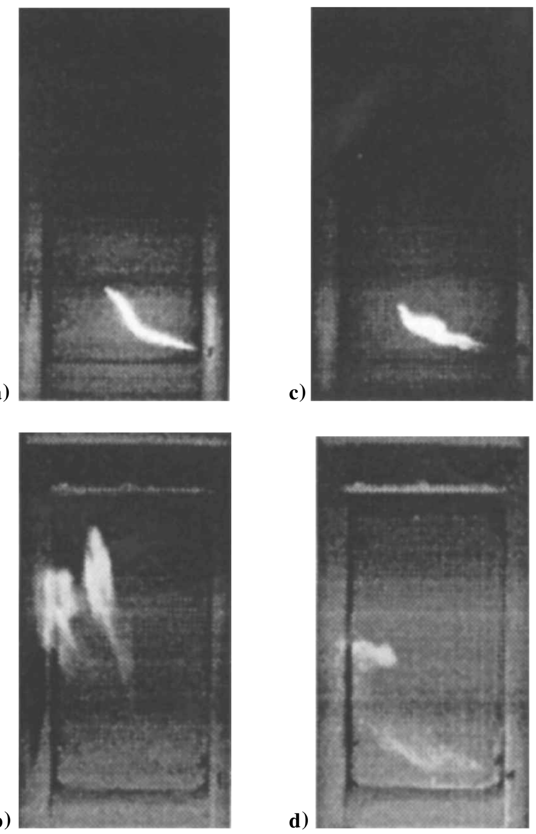
A practical problem that occurred came from the convective flow of air along the outside of the schlieren windows. However, even with this difficulty, the schlieren technique can be used to visualize small gradients in density between the flame and the surrounding gases, particularly in the case of a high molar fraction of oxygen. When the fuel is injected with low velocity (large nozzle), the fuel jet is exposed inside the flame. With higher velocity (small nozzle) the entrainment of the surrounding oxidizer is so strong that the visualization of the jet is much weaker. A typical example of schlieren flame visualization in HPAC is presented in Fig. 5. The fuel jet, flame base, and boundary between flame and oxidizer are clearly seen for the color schlieren system compared with the typical white-light schlieren.

When properly used, the visualization technique can obtain information about the flame base, and thus liftoff distance, and flame shape. By the registration of the flame with a high-speed camera, it is possible to distinguish the flow structure, even inside the flame. For higher temperatures, $T > 750°C$, the liftoff distance was difficult to ascertain, particularly when the oxygen molar fraction was below 8%. The flame liftoff measurements for these low oxygen concentrations were hampered because of a lack of clear contrast between the flame luminosity and the hot chamber walls. Additionally the flame was unstable under the aforementioned conditions. The observations above were made after the analysis of the HSP. The time of exposition for the HSP was four times shorter than the number of expositions per second. The short exposure time increases the sharpness of the photos. The examples of HSP made with schlieren visualization can be seen in Figs. 6 and 7. The fuel jet is clearly seen in all images, but the flame is much better presented with a large nozzle in which the fuel-jet velocity is lower.



a) b)

Fig. 7 a) 0.8-mm nozzle, 10% O_2; b) 0.8-mm nozzle, 5% O_2. 774°C; fuel, LPG.



a) b) c) d)

Fig. 8 a) 0.7-mm nozzle, 21% O_2; b) 0.7-mm nozzle, 2% O_2; c) 0.5-mm nozzle, 21% O_2; d) 0.5-mm nozzle 2% O_2. T = 768°C; fuel, LPG.

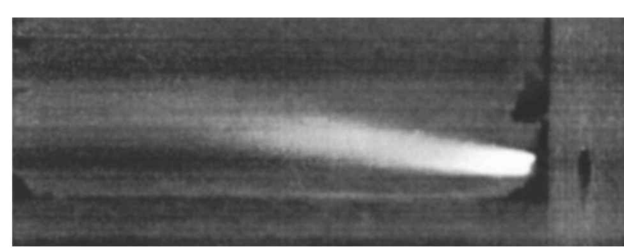


Fig. 9 Ordinary photograph of a flame with 21% Oxygen in the oxidizer, 0.3-mm fuel nozzle, and a preheat temperature of 768°C. Fuel, LPG.

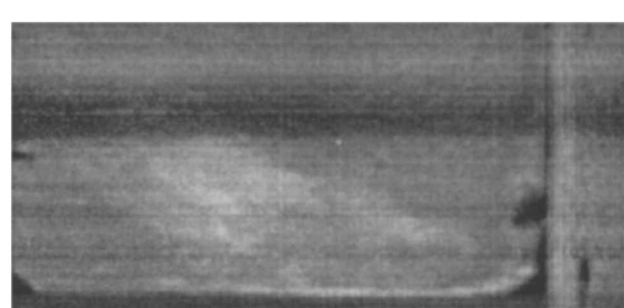


Fig. 10 Ordinary photograph of a flame with 2% oxygen in the oxidizer, 0.3-mm fuel nozzle, and a preheat temperature of 768°C. Fuel, LPG.

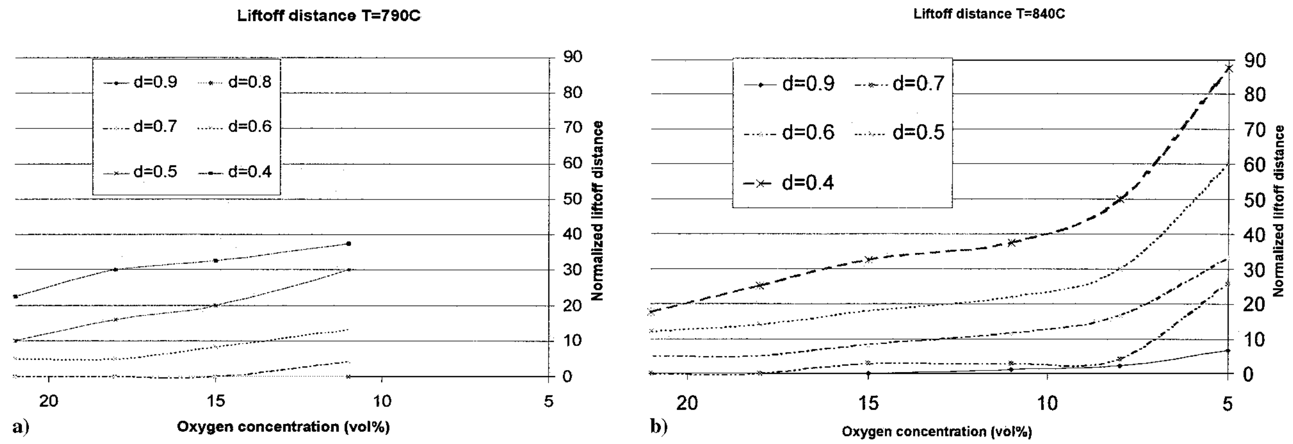


Fig. 11 Liftoff distance normalized with the diameter of the nozzle length/diameter.

The base of the lifted flame is seen in most cases and is most clear where there is a high molar fraction of oxygen in the crossflow. An increase of preheat temperature will decrease the temperature difference between the flame and the crossflow; this will make schlieren color visualization difficult to analyze because of the decreased density difference.

With ordinary photography it can be seen that the flame extends over a large part of the combustion chamber. This occurs when the fuel is injected into an oxidizer flow that contains a low molar fraction of oxygen. The liftoff distance and shape of the flame are highly affected by the velocity of the fuel and of the oxygen molar fraction in the oxidizer; this can be registered with a photograph with a long exposure time ($\frac{1}{5}$–$\frac{1}{20}$ s). The long exposure time will of course give an average liftoff distance and size. From direct photography it is seen that the increase of the velocity and the decrease of the oxygen molar fraction give a longer liftoff distance and a larger flame; see Fig. 8. Temperature, oxygen concentration, and nozzle size affect the color and the general visibility of the flame, which presents a problem when one is comparing pictures of different conditions. Intense flames will require a change in exposure times or aperture; if this is not done, the pictures of intense flames will be white and correspondingly, for low-visibility flames, the pictures will be black. This is not the case for schlieren pictures, because in schlieren the light for visualization is supplied by an external lamp.

The size and the liftoff distance of the flame increase with decreasing oxygen concentration in the oxidizer. The visibility decreases and the color changes from bright yellow/white, Figs. 8a and 8c, to a blue/green/yellow flame when the oxygen concentration decreased, Figs. 8b and 8d. These changes are clear to see, but the color change is difficult to register by direct photography, as stated previously. The low-intensity blue/green/yellow flames require a large aperture for collecting more light and will thereby get more interference from the background radiation from the walls of the furnace chamber.

The flame is highly affected by the nozzle size, i.e., the velocity of fuel (mixing of fuel and oxidizer). A large nozzle size will create a bright and intense flame compared with that of a small nozzle. But a larger nozzle will also decrease fluctuations and decrease liftoff distance. This is clear from the photographs. The color will not be highly affected by the change in nozzle size with constant oxygen fraction, except for the smallest nozzle size ($d = 0.3$ mm), which has large fluctuations; see Figs. 9 and 10. An increase in temperature will decrease the size and the liftoff distance of the flame. It will also decrease the fluctuations.

The flame liftoff distance, defined as the distance between the nozzle exit and the base of the luminous flame, was measured as a function of jet velocity, molar fraction of oxygen, and preheat temperature. The values were normalized when written into Fig. 11.

V. Conclusions

The schlieren and the still photographs are used to observe the qualitative futures of the flame in conditions of HPAC, such as flame size, color, and visibility. Moreover, measurements of liftoff distance were performed. The measured liftoff distance decreased with increasing oxygen content and decreased with increasing temperature of the oxidizer. Visual observations done during the measurement of liftoff distances suggest that the oscillations of the flame are connected to the length of the liftoff distance, i.e., a longer liftoff distance will give an unstable flame. The increment of oxidizer temperature seems to have a stabilizing effect on the flame.

The volume of the flame increases as the oxygen molar fraction decreases; when the temperature of the oxidizer is increased the flame volume will become smaller. The velocity of the jet affects the size of the flame, but not as much as the molar fraction of oxygen does.

The color of the flame changes rapidly when the oxygen molar fraction changes from 21% to a lower fraction in the oxidizer. First, the flame has a highly luminous yellow color, almost without any blue flame base. But as the oxygen fraction decreases the blue area expands and the yellow area decreases in luminosity. The exception is when a high fuel-jet velocity (smallest nozzle diameter) is used. Then the blue area does not appear, and instead the yellow area just becomes less luminous.

The schlieren technique is clearly a good method to get information about the flame structure and shape when the temperature difference between the combustion air and the flame is high. In the case of highly preheated combustion, the temperature difference is not large and therefore the density difference is low. The color range is small, which makes analysis of the flames difficult because the borders between colors are very diffuse. Also fluctuations in the preheated air stream will be registered when the flame temperature and the oxidizer temperature are close.

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