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Controlling Mechanisms of Ignition of Solid Fuel in a Sudden-Expansion Combustor

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Ignition of solid fuel by a hot oxidizing flow in a sudden-expansion combustor was investigated experimentally. The controlled variables of the experiments were concentration of oxygen (12–25%), gas temperature (750–850°C), and flow velocity (19–46 m/s). The step height was 29 mm. The corresponding Reynolds numbers based on the flow velocity and the step heights were 12×10^4–31×10^4. The controlling mechanisms of ignition in the flow with abundant oxygen were distinct from those with little oxygen. The initial flame kernels formed near the reattachment point and adjacent to the surface of solid fuel when the oxygen concentration was large. The process was controlled by diffusion and the ignition delay decreased with increased flow velocity. For the flow containing oxygen at a small concentration, the initial flame kernels formed within the recirculation zone and away from the surface of the solid fuel. The process was then controlled by the chemical kinetics and the ignition delay increased with increased flow velocity.

I. Introduction

IGNITION is generally stated to occur at a time and location at which the rate of reaction reaches an appropriate condition. Kulkarni et al.[1] made an extensive list of ignition criteria. Of the many criteria defined previously, the most popular criterion of ignition for experiment is the first appearance of a flame recorded photographically. Ignition was typically classified in the solid phase, heterogeneous, or in the gaseous phase.[2] It is generally agreed that the ignition of solid fuels takes place in the gaseous phase.[3] Kashiwagi et al.[4] and Kashiwagi and Summerfield[5] found that a theory of ignition in the gaseous phase gave the best fit to their experimental data for ignition of solid fuel under convective heating. For a flat plate of solid fuel burning in a stream of hot oxidizing gas, decreased velocity of the freestream increased the ignition delay because it diminished the rate of convective heating.[6] Niioka et al.[7] reported that the ignition mechanism of a solid fuel in a hot stagnation-point flow depended upon the flow velocity. A regime controlled by pyrolysis corresponded to a small velocity and the ignition delay decreased with increasing velocity. At a large velocity, the ignition process altered to reaction-control region and the ignition delay increased as the flow velocity increased. Investigating the controlling mechanism of a flame spreading over solid fuel surface, Fernandez-Pello and his co-workers[8–11] reported that the rate of flame spread depended on how rapidly the temperature of the solid surface was raised to its pyrolysis or vaporization temperature; that rate depended linearly on the velocity of gaseous flow and approximately on the square power of the concentration of oxygen in the gas.

Those investigations of the ignition of solid fuel and subsequent flame spreading were conducted in a simple flow. In a combustor with sudden expansion, the complicated flowfield contains many characteristic regions: freestream, shear layer, recirculation zone, and redeveloping boundary layer. Current understanding of ignition of solid fuel and subsequent flame spreading in such combustors is not thorough. Major difficulties result in part from the extreme complexity of temporal and spatial domains regarding the related features of turbulent flow and the mixing process. The objective of our work was to investigate the controlling mechanism of ignition in a sudden-expansion combustor and to interpret this phenomenon in terms of heat transfer and the process of mixing between the main flow and fuel vapor.

II. Experimental Design

A. Test Rig and Instrumentation

The experiments were performed in a wind tunnel that supplied a hot oxidizing gas stream under specified conditions. A schematic diagram of the experimental apparatus appears in Fig. 1. The air was blown by a 75-kW Roots blower with speed control provided by a frequency inverter (Hitachi). The blower provided a maximum flow rate of 50 m^3/min with a maximum static pressure of 70 kPa. An acoustic absorber was set behind the Roots blower to minimize pulsation of flow. The hot oxidizing gas at the inlet of the test section was generated by burning liquefied petroleum gas (LPG) with air in a specially designed vitiator. To control the temperature and concentration of oxygen in the hot gas, we adjusted the flow rates of LPG and oxygen gas by needle valves and measured them with rotameters. A divergent section, a settling chamber with stainless-steel honeycomb, and a convergent section with a contraction ratio of 13.6 were set before the test section to reduce the turbulence level of the gas stream.

The entrance of the combustor was 50 mm high and 200 mm wide. A polymethylmethacrylate (PMMA) slab, 10 mm

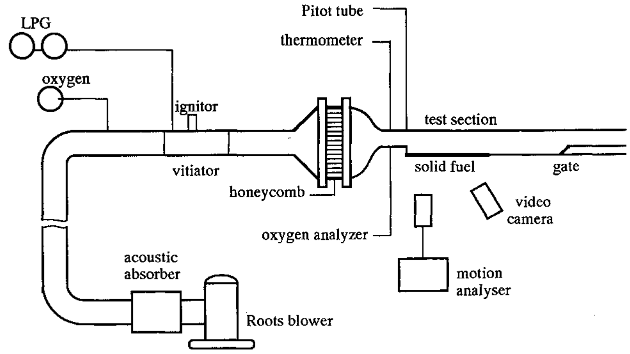

Fig. 1 Schematic diagram of the experimental apparatus.

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thick, 400 mm long, and 110 mm wide, was used as the fuel. Each side of the combustor was fitted with a quartz window to enable visual inspection of the ignition and the process of flame spreading. The fuel slab and its support were slid into the combustion chamber through a gate, which was normally closed, when the inlet conditions of the flow remained stable at the specified experimental conditions.

The inlet velocity was measured with a pitot tube. The temperature of the inlet gas was measured with a K-type thermocouple and a digital thermometer (Fluke 2190A). The concentration of oxygen was measured with an oxygen analyzer (Signal Model 8000). All inlet conditions were monitored just before the inlet of the test section. The ignition delay was recorded by a video camera (Sony CCD-340) with 30 photographs/s, and the ignition process by a motion analyzer (Kodak) with the speed set at 2000 photographs/s. To identify further the ignition transient, photographs of the ignition processes were treated by image processing to enhance the contrast of the gray level.

B. Test Conditions and Data Accuracy

The main parameters of the experiments were the inlet conditions: concentration of oxygen (12–25%), gas temperature (750–850°C) and flow velocity (19–46 m/s). The step height was 29 mm. The corresponding Reynolds numbers based on the inlet velocity and the step height were 1.2×10^4–3.1×10^4. The range of flow velocity in this work was limited by the experimental equipment. It must be large enough to avoid flashback and could not be very large to diminish the combustion instability in the vitiator. The Reynolds number in our experiment is similar to that of 1.5×10^4–3.7×10^4 in the experiment of combustion behind a rearward-facing step conducted by Pitz and Daily.[12] Uncertainties of the experimental data resulted from reproducibility. The maximum uncertainties of the ignition delay and period of flame spreading, determined by five tests of reproducibility, were 7.3 and 12%, respectively.

III. Results and Discussion

A. Flame Kernel Formation

The initial stage of ignition is the formation of the flame kernel. One or several flame kernels formed, then expanded or disappeared, and other individual kernels developed and kept spreading. Finally, all flame kernels joined to form a continuous flame zone. Where and how the initial flame kernels were formed and were capable of developing into a stable flame was our main interest.

The length of the recirculation zone is an important index of the flowfield and was thus identified before detailed interpretation of the results. The length of the recirculation zone observed in all cases of our experiments, estimated according to the flame configuration on the photographs, was about 5–7 step heights, whereas that of the premixed reacting flow measured by LDV was reported to be five step heights.[12] Yang et al.[13] reported that the length of the recirculation zone increased with increasing the bleed of normal mass through the base. Therefore, our data of greater length of the recirculation zone possibly resulted from the effect of gasification of the solid fuel.

Figures 2 and 3 are photographs of the ignition process at 850°C for a large (25%) and a small (15%) concentration of oxygen, respectively. With a greater concentration of oxygen, many flame kernels formed almost simultaneously adjacent to the surface of the solid fuel and near the reattachment point (Fig. 2a). This point divided the flame kernels into two groups: one was located in the recirculation zone and the other in the region of the redeveloping boundary layer. Flame kernels of the former group moved toward the backstep and the latter moved downstream. Later, more flame kernels were generated (Fig. 2b). Most flamelets in the recirculation zone

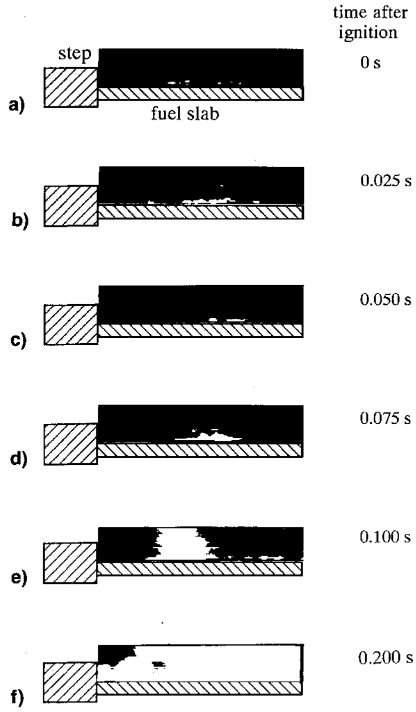

Fig. 2 Photographs of flame kernel formation with oxygen concentration 25% and inlet flow velocity 27 m/s at 850°C; ignition delay was 15 s.

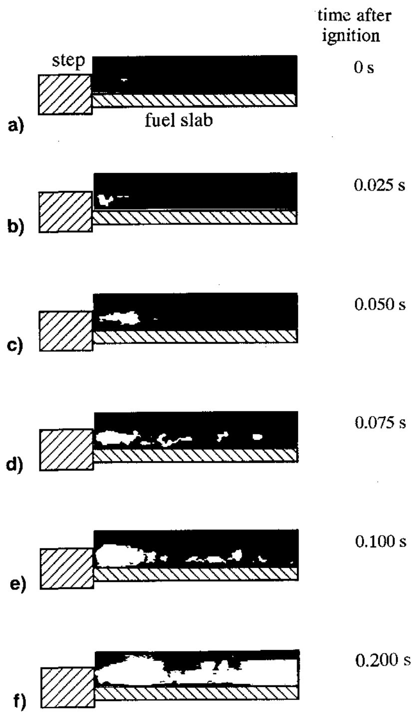

Fig. 3 Photographs of flame kernel formation with oxygen concentration 15% and inlet flow velocity 27 m/s at 850°C; ignition delay was 24 s.

were periodically extinguished (Figs. 2c and 2d) because of its low temperature and the large flame stretch due to vortex shedding. A big flame developed 0.1 s after ignition (Fig. 2e). At 0.2 s after ignition the combustion chamber was filled with the flame (Fig. 2f).

In the case of a small concentration of oxygen, the initial flame kernel formed in the recirculation zone and away from the surface of the solid fuel (Fig. 3a). Then, more flame kernels formed (Fig. 3b) and expanded into a flaming zone (Fig. 3c). As the flames in the recirculation zone grew big enough, they spread toward the region of redeveloping boundary layer (Fig. 3d). Some flame kernels in the region of redeveloping boundary layer disappeared and formed again periodically. About 0.1 s after the first ignition, a well-developed flame zone appeared in the recirculation zone (Fig. 3e); this zone was smaller and dimmer than that at a large concentration of oxygen (Fig. 2e). The flame zone filled most of the combustion chamber at 0.2 s after ignition (Fig. 3f).

We called the flame fully developed when the flame spread over all the surface of the solid fuel. Before the flame was fully developed, a big flame had been developed in the recirculation zone and took a role of holding flame for the aforementioned two cases.

B. Heat Transfer and Mixing

The formation of flame kernels observed in the photographs (Figs. 2 and 3) is interpreted in terms of the characteristics of heat transfer and mixing. Tsai et al.[14] conducted experiments of heat transfer with a hot gas flowing over a backstep in a wind tunnel that was similar to this work. The base wall of the test section was a copper plate with a cooling tank installed beneath it. The temperature of the flow was measured with a thermocouple (0.127 mm, K-type) enclosed in a thin ceramic tube, which was further connected with a stainless steel tube (L-shape, diameter 2.5 mm). The distribution of temperature at the wall behind the backward-facing step was measured through 20 thermocouple wires embedded 1 mm beneath the base wall plate. Experiments on the hot flow were made by varying the temperature of the inlet flow from 200 to 400°C, while the velocity of the inlet flow was varied from 7 to 40 m/s. The range of Reynolds number based on the step height was 3.2×10^3–17.2×10^3. The temperature profiles in Fig. 4 show that the recirculation zone of the combustor was a region of low temperature before ignition. The streamwise distributions of the normalized local Nusselt number with various inlet flow velocities are shown in Fig. 5. Within the recirculation zone, the local heat flux increased in

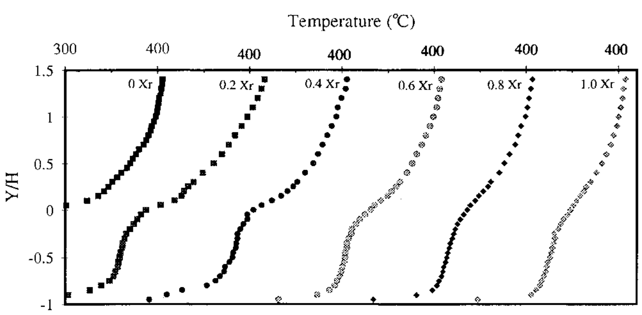

Fig. 4 Distributions of temperature along the horizontal position with inlet velocity 20 m/s and temperature 400°C, at X/Xr = 0, 0.2, 0.4, 0.6, 0.8, and 1.0.

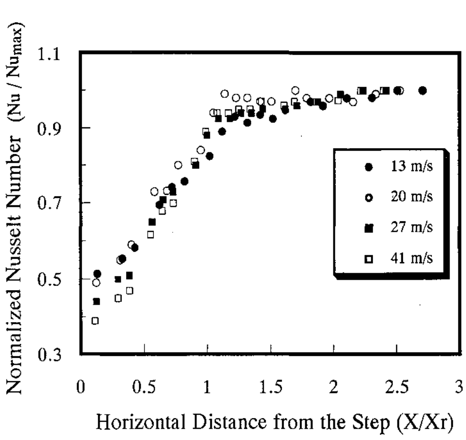

Fig. 5 Distributions of normalized local Nusselt number along the horizontal position at inlet gas temperature 300°C.

proportion to the horizontal distance from the step; its increment decreased and approached a constant value behind the reattachment point, Xr.

The ignition delay includes chemical delay and physical delay. The chemical delay is approximately based on the Arrhenius law and the temperature and the mass concentration of reactants are the main factors that affect the rate of chemical reaction. At the reattachment point, the rate of vaporization of the solid fuel was large due to the large heat flux, the temperature of the gas adjacent to the solid fuel was greater than that in the recirculation zone. All these factors abbreviate the chemical delay. The initial flame kernels formed near the reattachment point as long as the chemical delay was short enough (Fig. 2), although the flow velocity and the velocity gradient were relatively high over there.

When the concentration of oxygen was small, the characteristic time of chemical reaction was long. The recirculation zone provided a greater residence time for the pyrolyzed fuel vapor and oxidant; hence, ignition first occurred in the recirculation zone (Fig. 3). The concentration of fuel vapor was large near the surface of the solid fuel, but the temperature was low and was unsuitable for ignition. The most favorable location of ignition is expected to be associated with the mixing between the pyrolyzed fuel vapor and the main flow. To investigate mixing behind a backstep, Yang et al.[13] adopted two fluids with distinct turbulence intensity; one was the main stream and the other was the normal injection through a porous base with varied rates of injection. Their data of turbulent features (Fig. 6) revealed that mixing occurred in the region between the dividing streamline and the position at which the vertical velocity was zero. The interactions between the two fluids began at 0.4 reattachment length behind the step. In our combustion experiment, ignition occurred first near the area of significant mixing (Fig. 3a).

C. Ignition Mechanism

According to the distinct characteristics of ignition under large and small concentrations of oxygen, we observed two control mechanisms of ignition of solid fuel in a sudden-expansion combustor. Figure 7 illustrates two ignition patterns; control was either by diffusion or by chemical kinetics, depending on the concentration of oxygen in the inlet flow. When the concentration of oxygen exceeded 20%, the characteristic time of chemical reaction was brief; hence, the ignition was dominated by the diffusion of fuel and oxygen. The initial flame kernels formed where the abundant fuel vapor diffused into the main flow that contained oxidant (Fig. 7a). When the concentration of oxygen was less than 15%, the period of chemical reaction was relatively long, and the residence time of the mixture of fuel and air was more important. The first flame kernels were thus formed in the recirculation zone, where the fuel vapor was well mixed with the oxidant (Fig. 7b). Under those conditions, the ignition initiated in the region of premixed mixture and was controlled by the chemical kinetics. In both cases, the main flames were all initiated in the recirculation zone.

Figure 8 shows the ignition delay vs the oxygen concentration on logarithmic scales at various temperatures of the inlet gas. The slopes of the ignition delay curves are -2.04 and -2.21 for the temperatures 850 and 800°C, respectively, when oxygen concentration exceeds 20%; whereas the slope is -1.85 for the temperature 750°C, and oxygen concentration exceeds or equals to 22%. The slopes of the curves with oxygen concentration greater than 20% are all about -2; hence, the ignition delay in the region of diffusion control depends upon the inverse square of the oxygen concentration, which is characteristic of ignition in the gaseous phase, consistent with the theoretical prediction of Hermance and Kumar.[15] The transition region was located where the oxygen concentration was between 15–20%. The ignition delay decreased with increasing concentration of oxygen in most experiments. However,

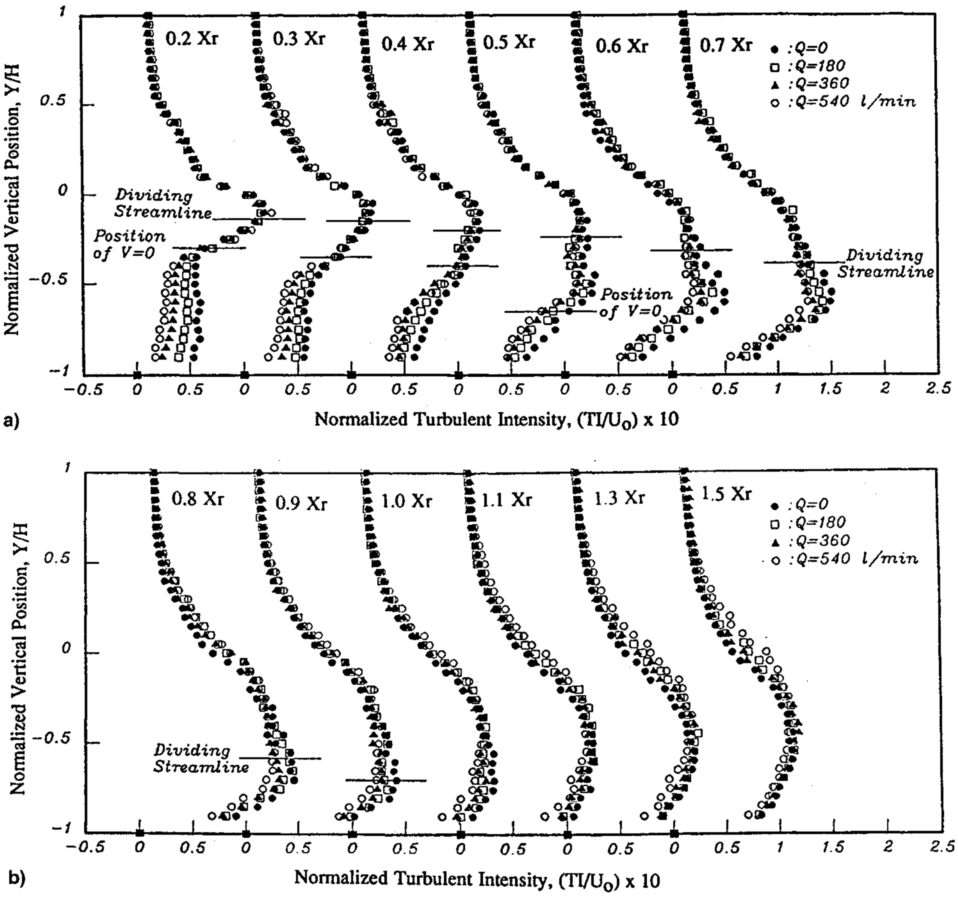

Fig. 6 Effects of normal injection rate on profiles of turbulence intensity with inlet flow velocity 20 m/s at ambient temperature. Cross sections at X/Xr = a) 0.2, 0.3, 0.4, 0.5, 0.6, and 0.7 and b) 0.8, 0.9, 1.0, 1.1, 1.3, and 1.5.

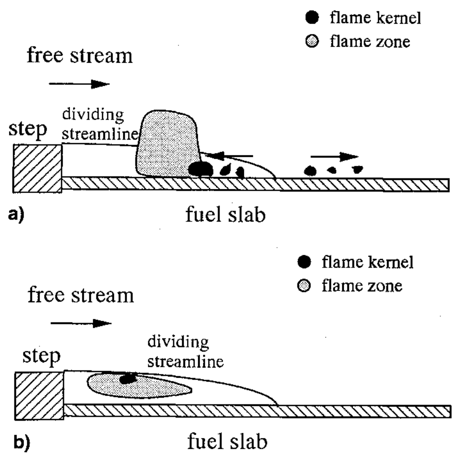

Fig. 7 Schematic diagrams of the controlling mechanisms of ignition with inlet velocity 27 m/s and temperature 850°C. Ignition controlled by a) diffusion, at oxygen concentration 25% and b) chemical kinetics, at oxygen concentration 15%.

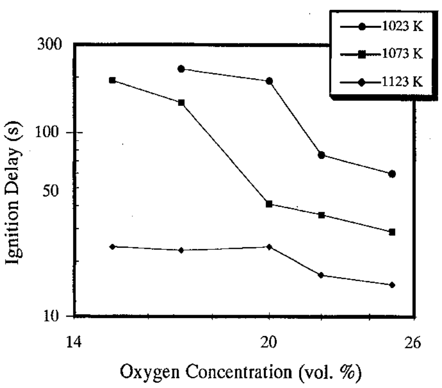

Fig. 8 Ignition delay with inlet flow velocity 27 m/s at various temperatures of inlet gas and concentrations of oxygen.

this concentration had no significant effect on the ignition delay when it was less than 20% at 850°C.

Figures 9 and 10 show the effect of the flow velocity on ignition delay in regions of diffusion and chemical kinetics control, respectively. In the former region, decreasing the velocity of flow increased the ignition delay (Fig. 9) because it diminished the rate of convective heating, and consequently, decreased the rate of production of pyrolyzed fuel vapor. In contrast, decreasing the velocity of flow abbreviated the ignition delay (Fig. 10) in the region controlled by chemical kinetics because it increased the residence time of fuel vapor.

The variation of ignition delay with flow temperature for two concentrations of oxygen is shown in Fig. 11. The ignition delay decreased with increasing flow temperature, but the effect of flow temperature on ignition delay was small at higher temperature. No ignition was observed when the oxygen concentration was less than 17% at 750°C. At 800 and 850°C, ignition occurred even when the oxygen concentration was only 12%.

The effect of oxygen concentration on the controlling mechanism of ignition was more important than that of the temperature in our experiment. The reason might be that the temperature was fairly high and the effectiveness of temperature on the ignition delay decreased as the temperature increased (Fig. 11). However, the influence of temperature can still be identified in Fig. 8. At the oxygen concentration of 20%, the ignition mechanism was chemical kinetics control for the temperature of 750°C, and that was diffusion control for the temperatures of 800 and 850°C.

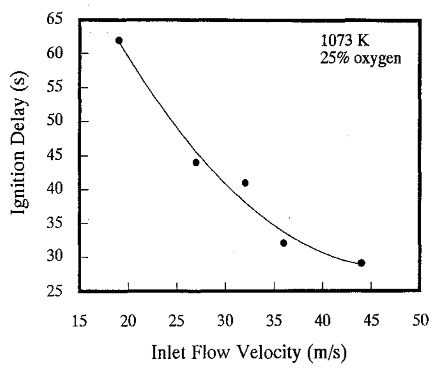

Fig. 9 Effect of flow velocity on ignition delay in the region of diffusional control.

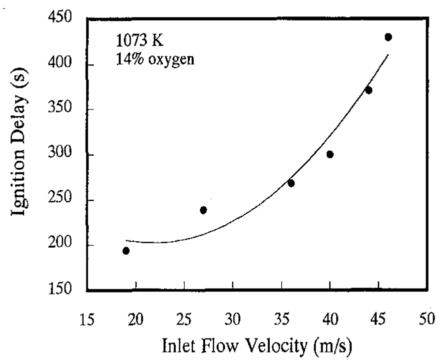

Fig. 10 Effect of flow velocity on ignition delay in the region of kinetic control.

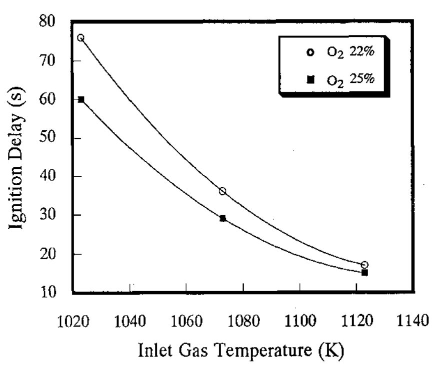

Fig. 11 Effect of inlet gas temperature on ignition delay at inlet flow velocity 27 m/s.

D. Period of Flame Spreading

After the first ignition the flame spread gradually, but discontinuously, over the surface of the solid fuel (Figs. 2 and 3), because of the great variation of the flowfield. The flame kernels were located randomly and occasionally extinguished; hence, it was difficult to define the rate of flame spreading. For that reason, we analyzed the duration of flame spreading, defined as the interval between the onset of ignition and the end of flame spreading over all the surface of the solid fuel, rather than its rate. The definition is similar to the second interval of the ignition transient defined by Kumar and Kuo.[3] Figure 12 shows that the period of flame spreading at 800 and 850°C decreased slightly with increasing oxygen concentration; it was about 0.15 s at 850°C, and 0.1 s at 800°C. In contrast to the features of the ignition delay, the duration of flame spreading at 850°C was greater than that at 800°C. That is because the period for exposure of the fuel slab to the hot flow was smaller at 850°C, and the temperature of the surface of the solid fuel was smaller at the beginning of ignition and during the period of flame development.

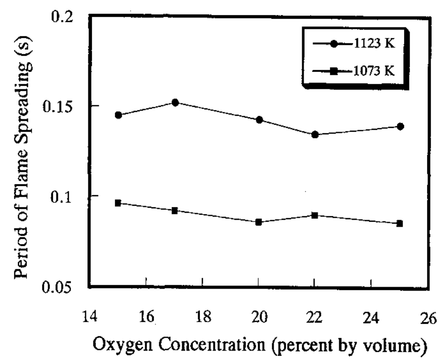

Fig. 12 Period of flame spreading with inlet flow velocity 27 m/s with various concentrations of oxygen at inlet temperatures 800 and 850°C.

IV. Concluding Remarks

The recirculation zone is favorable for ignition and flame stabilization of solid fuel in a sudden-expansion combustor. A large flame invariably developed in the recirculation zone before the flame became fully stabilized. Although the initial flame kernels were not always formed there due to the different controlling mechanisms of ignition.

Two mechanisms of ignition were observed in this work. One was controlled by diffusion and the other was controlled by chemical kinetics, depending on the concentration of oxygen. When the concentration of oxygen exceeded 20%, several initial flame kernels formed simultaneously near the reattachment point and adjacent to the surface of the solid fuel. The amount of pyrolyzed fuel vapor that diffused into the oxidizing flow controlled the ignition process. When the oxygen concentration was less than 15%, the flame kernels appeared in the recirculation zone and away from the solid fuel surface. Because ignition was controlled by chemical kinetics, this process is regarded as premixed combustion.

The ignition delay decreased with increasing concentration of oxygen in most cases of this experiment. In the region of diffusion control, the ignition delay depended upon the inverse square of the oxygen concentration. Decreasing the velocity of flow prolonged the ignition delay in the region of diffusion control, because it diminished the rate of convective heating and, thus, the rate of pyrolysis of fuel vapor. Decreased flow velocity abbreviated the ignition delay in the region controlled by chemical kinetics, because it increased the residence time of fuel vapor. The ignition delay decreased with increasing flow temperature, but its effect on the decreased ignition delay was limited for a much greater temperature of flow.

The period of flame spreading decreased slightly with the increasing concentration of oxygen at a constant temperature. The duration of flame spreading at 850°C exceeded that at 800°C, because the ignition delay at high temperature was so small that the surface of the solid fuel was not heated enough at the beginning of ignition.

Acknowledgments

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