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EFFECTS OF COMBUSTOR AERODYNAMICS ON THE IGNITION OF SOLID FUEL

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ABSTRACT

A traditional and a modified backward-facing steps were designed to investigate the effects of flow characteristics on the ignition of the solid fuel slab in a sudden expansion combustor. Experiments were conducted separately in the cold flow for the turbulent flow field and in a hot oxidizing flow stream for the ignition tests. The velocity flowfield was measured by a laser-Doppler anemometer (LDA) and the ignition process was observed by a high-speed video camera. The inlet flow velocity for the cold flowfield measurements was kept at 15 m/s, but was varied for the ignition tests, whereas the step height of the backstep was 29 mm. The results show that the higher turbulence intensity in the boundary layer near the separated point did not always cause a higher turbulence intensity in the recirculation zone. However, the combustor with a modified backstep generated greater reverse flow rate, turbulence intensity and Reynolds stress in the recirculation zone. As a result, the ignition delay of solid fuel in the modified combustor was significantly reduced as compared with the traditional combustor.

INTRODUCTION

The backward-facing step is a fundamental element of the inlet port of many sudden-expansion combustors. The air stream over a backward-facing step produces a separated-reattaching flow containing a recirculation zone and a shear layer. Such a flow pattern is intimately related to the performance of various devices such as diffusers, airfoils, and combustors. Extensive work on the flow field behind a backstep has been conducted; Eaton and Johnston (1981) summarized the factors influencing the reattachment length, Isomoto and Honami (1989) discovered that the turbulence intensity in the boundary layer at the separated point was a significant parameter governing the reattachment length and Etheridge and Kemp (1978) estimated that one sixth of the fluid present in the shear layer was rolled into the recirculation zone.

The flow field behind a backward-facing step affects the mass transfer, heat transfer and momentum transfer significiently. Lefebvre (1983) studied different shapes of flame holder and stated that the characteristic dimension of a bluff body should not be its geometric width, but rather the maximum width of the wake generated behind it. Sirka et al. (1989) reported that the mechanism of heat transfer in the wake flow was significantly affected by the flow pattern. Kundu et al. (1980) emphasized that the mass and heat transport between the main stream and the recirculation zone were proportional to the maximum reverse flow rate. Winterfeld (1965) measured the residence time of the gas within the recirculation zone and concluded that a close relation existed between flame stabilization and mass exchange. Yang et al. (1994) reported that good features of flame stabilization abbreviated the ignition delay.

Previous studies indicated that the aerodynamics of a backstep has a great influence on the flame stabilization and the combustion behavior of the condensed fuel. In addition, the combustor aerodynamics is very sensitive to the configuration of the backstep. It is thus worth finding a better configuration of backstep which has good characteristics of ignition and flame stabilization. Therefore, the objective of this work is to study the effects of combustor aerodynamics on the ignition of a solid fuel by varying the configuration of the backstep at the inlet of a combustor. The results would provide information for the interactions between aerodynamics and ignition behavior and also a beneficial idea of innovative design on the inlet part of sudden-expansion combustor.

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EXPERIMENTAL DESIGN

Test Rig

A schematic diagram of the wind tunnel and instrumentation appears in Fig. 1. Experiments were conducted in an open-circuit wind tunnel equipped with a 75 kW Roots blower with speed controlled by a frequency inverter. The blower provided a maximum flow rate of 50 m^3/min with a maximum static pressure of 70 kPa (gage pressure). The fluid in the test section was either a cold flow (for flowfield measurement) or a hot oxidizing gas stream (for ignition test). The hot flow stream was the combustion product of liquefied petroleum gas (LPG) and air in a vitiator before the settling chamber. The gas temperature was controlled by changing the flow rate of LPG and the oxygen concentration was varied by adding oxygen gas into the air.

The cross section of the combustor inlet was 50 mm high by 200 mm wide, and the step height of the sudden expansion was 29 mm. A quartz window was installed on one side wall of the combustor to measure the flowfield of cold flow and to visualize the ignition and flame developing processes. A polymethylmethacrylate (PMMA) slab of 10 mm thick, 400 mm long and 110 mm wide was used as the fuel.

The configurations of the traditional and the modified backstep are depicted in Fig. 2. The step heights in both cases were 29 mm. A small oblique surface was constructed on the modified step.

Instrumentation

The velocities were measured with a three-beam, 2-component backward-scattering LDA, which was connected to a computer-controlled traversing system for two-dimensional movement. The resolution of the traverse system was 0.03 mm. The instruments were mounted on an optical bench that was placed on a traverse table for major movement.

The laser beam from an argon-ion laser (5 W), with radiation mainly at wavelengths of 514.5 nm and 488 nm, was split into two beams. One beam passed through a Bragg cell to produce a 40-MHz frequency shift and was then split again, through a color-selective beam splitter, into two beams, one of wavelength 514.5 nm and the other 488 nm. The resulting two beams and the original beam passed through a beam translator, a beam expander and a convergent lens of focal length 310 mm. The lengths of the two axes of the blue beam of the optical probe were 0.128 and 1.625 mm, whereas those of the green beam were 0.135 and 1.713 mm. A specific arrangement of the beams was proceeded in this experiment, thus the reliable measurement of the flow velocity at 2 mm above the wall was feasible. The backward-scattering Doppler signals were detected by two photomultipliers and processed by a coincidence filter and two counter processors. A beam-waist adjuster was used to improve signal strength. The seeding particles were generated by TSI 9306 jet atomizer and introduced into the air stream at the contraction section in the wind tunnel. The particles, with a diameter of the order of 1 μm, were made of 25% glycerin resolvent and a water solvent.

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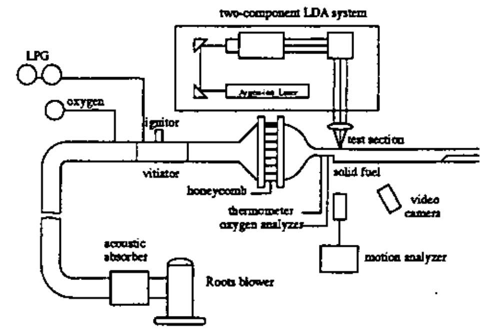

Fig. 1 A schematic diagram of the experimental apparatus.

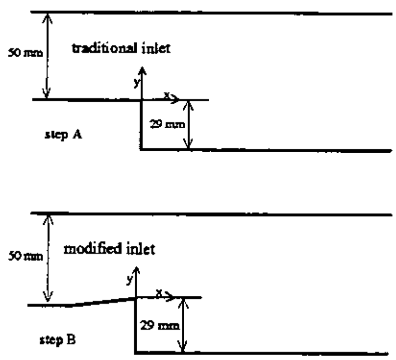

Fig. 2 Configurations of the traditional and the modified inlets of the sudden expansion combustor.

In the igoition experiments, the controlliog parameters were (1) oxygen conceotratinn (15~19%), (2) inlet gas velocity (15~27 m/s), aad (3) the shapes of the backstep (traditional and modified). The ignitian delay was measured with a C.C.D. camera (Sony) while the detailed ignitiaa process was recorded by a high speed video camera (Kodak) with the speed set at 2000 pictures per second.

Experimental Conditions and Data Accuracy

The flnw field was measured at atmospheric temperature and pressure with inlet flow velocity of 15 m/s. At each measuring point 2048 measurements were nnrmally made. The corresponding maximum uncertaiaties were 3.2 percent for meaa axial velocity, 4.9 percent fnr meao normal velocity and 4.9 percent for turbulence intensity at the 95 percent confidence level. The corresponding maximum uncertainty for Reynolds shear stress was 13 percent. The maxiosuos uncertainties nf the ignitinn delay determined hy five tests nf reproducibility were 7.3 percent.

RESULTS AND DISCUSSIONS

Inlet Conditions

The velocity distributions of the cold flowfield were determined by a laser-Doppler anemometer (LDA) with the inlet velocity (U_n) 15 m/s fnr both traditinnal aod modified combustnrs. The distributions nf the horizontal and the vertical velocity at the separated point of the two different backsteps are illustrated in Figs. 3 and 4, respectively. Those velocities were nnrmalized by the free stream velocity, U_n. The profiles nf the hnrizontal velocity nf the traditional and the mndified backsteps were nearly the same, except in the boundary layer. The horizontal velocity in the boundary layer of tbe modified backstep was slightly greater than that of the traditional (Fig. 3). The vertical velncity of the mndified backstep bowever, was much higher than that of the traditinnal one (Fig. 4). Botb tbe turbulence intensity and the Reyanlds shear stress (defined in section 3.3) at the inlet nf the modified combustor were smaller than thnse of the traditinnal as shnwn in Figs. 5 and 6. That might be caused by the contractinn effect nf the modified backstep.

The parameters nf the boundary-layers corresponding to the two different comhustnrs are summarized in Tahle 1. The boundary-layer thicknesses of the two cases were almnst the same, whereas the mnmentum thickness of tbe modified backstep was greater than the traditinnal. The Reynnlds numbers, which were based on the mnmentum thickness, was about 890 for the modified backstep, but was only 756 fnr the traditinnal. According to the report of Pitz and Daily (1983) the transitinnal value between laminar and turhulent regimes was 390, both boundary layers were thus fully turbulent.

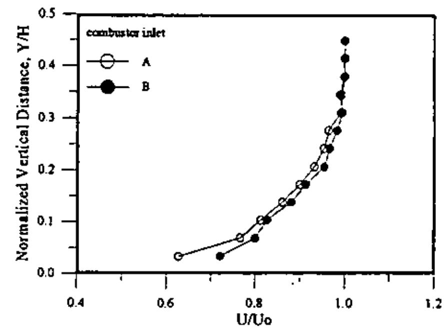

Fig. 3 Distributions of the horizontal velocity at the inlets (A) traditional, (B) modified.
(uncertainty in mean horizontal velocity is less than ±3.2%)

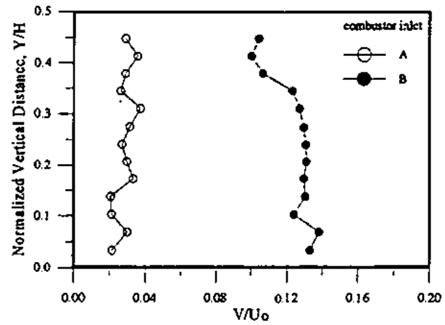

Fig. 4 Distributions of the vertical velocity at the inlets (A) traditional, (B) modified.
(uncertainty in dimensionless reverse flow rate is less than ±3.2%)

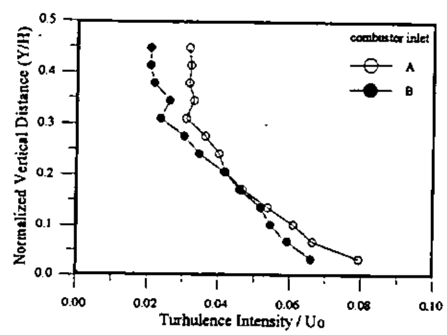

Fig. 5 Distributions of the turbulence intensity at the inlets (A) traditional, (B) modified.
(uncertainty in turbulence intensity is less than ±4.9 %)

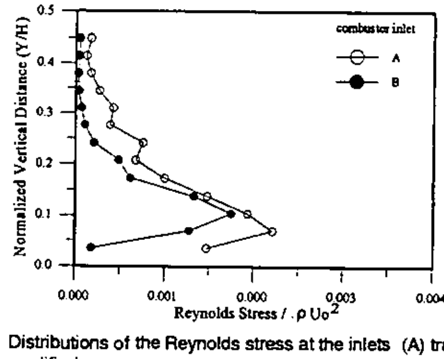

Fig. 6 Distributions of the Reynolds stress at the inlets (A) traditional, (B) modified.
(uncertainty in Reynolds stress is less than ±13 %)

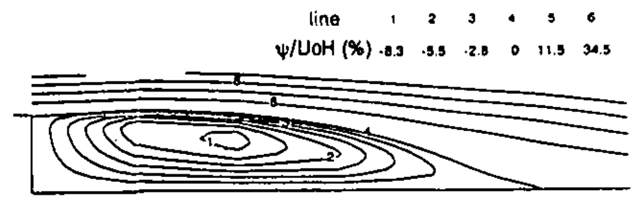

Fig. 7 Streamlines of the flow field in the traditional combustor. (uncertainty in mean horizontal velocity is less than ±3.2%)

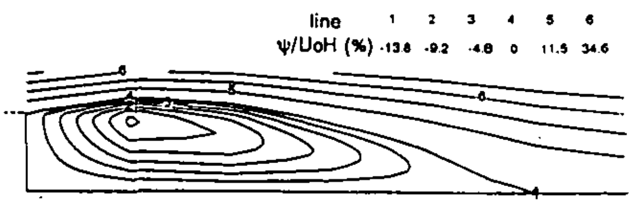

Fig. 8 streamlines of the flow field in the modified combustor. (uncertainty in mean horizontal velocity is less than ±3.2%)

Table 1. Inlet flow conditions and reattachment length at U_0=15 m/s and 298K (uncertainty in reattachment length is less than ±1.4%)

Inlet Configuration	Reynolds Number (Re_H)	Boundary Layer Thickness (mm)	Momentum Thickness (mm)	Momentum Reynolds Number (Re_θ)	Reattachment Length (X_r)
traditional	27700	9	0.93	890	7.7 step height
modified	27700	9	0.79	756	7.7 step height

Aerodynamics

The reattachment length was defined as the point where the average reverse flow velocity very close to the wall was zero. It was measured by the LDA at 2 mm above the wall along the centerline of the combustor. Both the reattachment lengths of the traditional and the modified backsteps were 7.7 times the step height.

The streamlines in the combustors with the traditional inlet and the modified inlet are depicted in Figs. 7 and 8, respectively. Although the lengths of the recirculation zone for both cases were the same, the thickness of the recirculation zone of the modified combustor was larger than that of the traditional. In addition, the minimum value of the normalized stream function of the modified combustor was -13.8%, which was 66% greater than that of the traditional.

To further investigate the flow features, a dimensionless local reverse flow rate is defined as

$$Q_r / U_o H = -\int_{-H}^{y^*} U_r dy / U_o H \qquad (1)$$

where, Q_r is the reverse flow rate, U_r is the reverse flow velocity, U_o is the free stream velocity at the inlet, H is the step height, and y^* corresponds to the point of zero horizontal velocity with negative horizontal velocity between $y = -H$ and y^*. A comparison of the local reverse flow rate at various cross sections between the two combustors is depicted in Fig. 9, in which X_r is the reattachment length. The reverse flow rate on each cross section of the modified combustor, especially those through the front region of the recirculation zone, was much greater than the corresponding sections of the traditional.

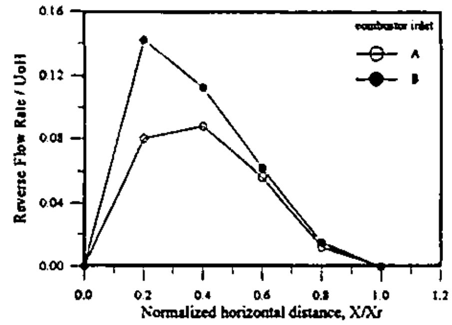

Fig. 9 Dimensionless reverse flow rates at various cross sections of the two different combustors. (uncertainty in dimensionless reverse flow rate is less than ±3.2%)

Turbulent Features

The two-dimensional turbulence intensity, which denotes the mean kinetic energy of the turbulence per unit mass, is defined as follows.

$$\text{Turbulence intensity} = \left(\frac{\overline{u^2} + \overline{v^2}}{2}\right)^{1/2} \qquad (2)$$

where u and v are the fluctuations of the horizontal and the vertical velocity, respectively, U_0 is the free stream velocity at the inlet. The Reynolds shear stress, defined as $-\rho\overline{uv}$, was obtained from the velocity data which were measured with the two-component LDA system, where ρ is the density. The conventional gradient-diffusion turbulence modeling employed by Pan et al. (1992) showed that the Reynolds shear stress was proportional to the rate of turbulent momentum transfer. The turbulence intensity and the Reynolds stress in Figs. 12 and 13 were normalized by U_o and ρU_o^2, respectively. Both the profiles of turbulence intensity and Reynolds stress at various cross sections behind the backstep were similar to the previous work of Yang et al. (1993) and Driver and Seegmiller (1985). The maximum values of turbulence intensity and Reynolds stress on each cross section are shown in Figs. 10 and 11, and those values along the dividing streamline of the recirculation zone are depicted in Figs. 12 and 13. Those values increased monotonically from the separated point to a maximum at 0.6~0.8 reattachment length downstream the step. Thereafter, the turbulence intensity and the Reynolds stress decayed gradually. The peak of those curves was located at further downstream in the traditional combustor than in the modified. The curves of the turbulence intensity and the Reynolds stress along the dividing streamline in Figs. 12 and 13 deviated only slightly from those of the maximum turbulence intensity and Reynolds stress on each cross section. It denotes that the maximum turbulence intensity and the Reynolds stress were located near the dividing streamline of the recirculation zone. Both the turbulence intensity and the Reynolds shear stress of the flow were larger in the modified combustor than in the traditional. Therefore, the turbulent diffusion was enhanced in the modified combustor.

Ignition Phenomena

Although the turbulent features of the hot flow for the ignition test might deviate slightly from those of cold flow, the trends of turbulent diffusion and the characteristics of the flame stabilization are expected to be similar. Therefore the ignition phenomena were interpreted from the aerodynamics data obtained from the cold flow.

After the fuel slab was put into the test section containing a hot oxidizing gas stream, the surface of the solid fuel was first elevated to the pyrolysis temperature. Then the pyrolyzed fuel vapor was heated continuously and mixed with the oxygen. Ignition occurred at the time and location that the rate of reaction reached a suitable runaway condition and the whole process was monitored by high-speed photography. At the beginning of ignition, one or several flame kernels initiated in the recirculation zone and then other individual kernels developed and kept spreading. Finally, all flame kernels joined to form a continuous flame zone. The details of the ignition transion was described by Wu and Yang (1993). The photographs of ignition process indicated that the ignition mechanisms of the solid fuel of the two combustors were similar.

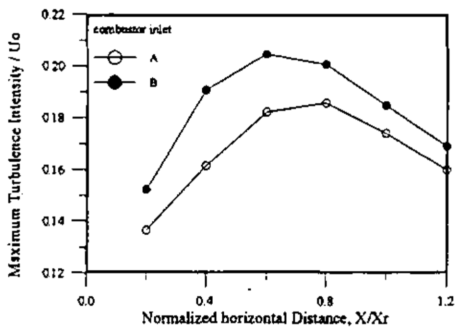

Fig. 10 Maximum turbulence intensities at various cross sections of the two different combustors. (uncertainty in turbulence intensity is less than ±4.9 %)

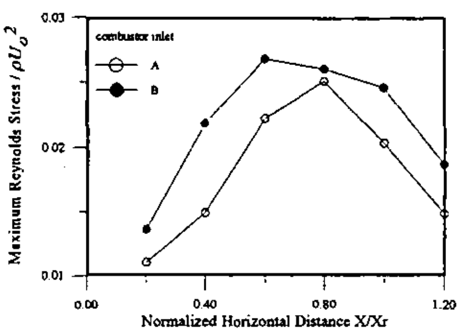

Fig. 11 Maximum Reynolds stresses at various cross sections of the two different combustors. (uncertainty in Reynolds stress is less than ±13 %)

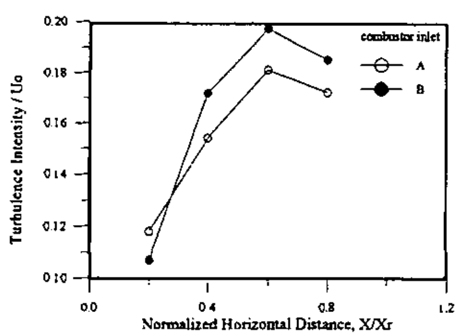

Fig. 12 Comparisons of the turbulence intensities along the dividing streamlines of the recirculation zone of the two different combustors. (A) traditional, (B) modified.
(uncertainty in turbulence intensity is less than ±4.9 %)

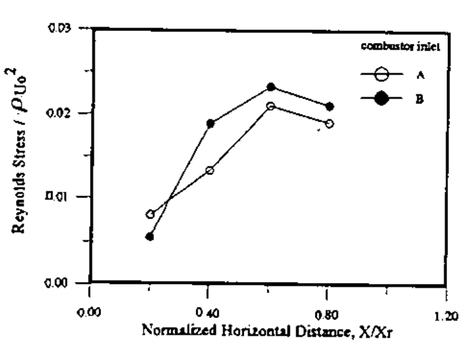

Fig. 13 Comparisons of the Reynolds stress along the dividing streamlines of the recirculation zone of the two different combustors. (A) traditional, (B) modified.
(uncertainty in Reynolds stress is less than ±13 %)

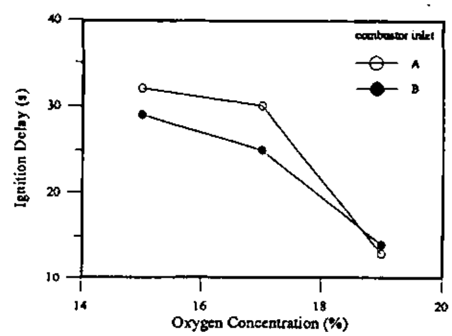

Fig. 14 Effects of oxygen content of the flow on the ignition delay at U_0 = 15 m/s. (uncertainty in ignition delay is less than ±7.3%)

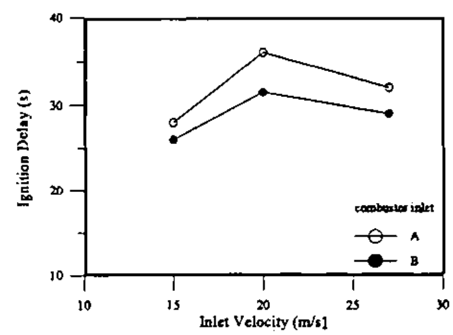

Fig. 15 Effects of inlet velocity of the flow on the ignition delay at oxygen concentration of 15%. (uncertainty in ignition delay is less than ±7.3%)

The ignition delay is defined as the period between the time the fuel plate was put into the test section and the first apperance of the flame. The ignition delay in the modified combustor was shorter than that of traditional combustor in most of the experimental conditions. Figure 14 shows that the ignition delay of the modified combustor was shorter when the oxygen concentration was smaller than 18%. At oxygen concentration of 19%, the initiated flame kernel of ignition was observed located near the reattachment point, where the features of flame holding was not important. Besides, the turbulence intensity and Reynolds stress near the reattachment point were so large that they did not cause notable difference between the ignition delays of two combustors. Since the ignition process is usually controlled by the flow pattern when the oxygen content of the flow is small, the ignition delay is significantly affected by the variation of the inlet geometry of the combustor, and the modified combustor should possesses better aerodynamic features for ignition and flame stabilization. The effects of inlet velocity on the ignition delay at oxygen concentration of 15% for the two combustors are alike, as shown in Fig. 15. The ignition delays of the modified combustor at all three velocities were shorter than those of the traditional, which further contrast the superiority of the modified configuration of the inlet geometry.

The relationship between the velocity and the ignition delay was not clear in Fig. 15, because the ignition mode at oxygen concentration 15% was in the transition regime between chemical kinetics control and diffusion control. Wu and Yang (1993) observed those two ignition mechanisms and reported that the effects of flow velocity on the ignition delay in these two mechanisms were opposite. The effect of oxygen concentration on the ignition delay was also investigated in-depth by Wu and Yang (1993). Under a dilute oxygen concentration of gas stream the combustor aerodynamics is a good factor to improve the ignition characteristics, although the influence of the oxygen concentration is more important for other situations.

CONCLUSIONS

This work analyzed features of both aerodynamics of the separated-reattaching flow and ignition of the solid fuel behind a traditional and a modified backsteps in a combustor. The modified configuration of the backward-facing step with an oblique surface did not generate much difference of the inlet flow characteristics from the traditional one, except the vertical velocity of the flow. The modified combustor has a thicker recirculation zone, greater reverse flow rate, higher turbulence intensity and Reynolds stress within the whole recirculation zone might caused by the higher vertical velocity at the inlet. Those variations might enhance the mixing between the hot oxidizing gas and the vaporized fuel and thus provide a good features for flame holding in a sudden expansion combustor. The ignition mechanism and the phenomena of flame spreading were nearly the same for both of the two configurations, but the ignition delay was shortened due to the geometric modification. As the oxygen concentration was raised to 19 percent, the effect of aerodynamics on ignition diminished and the ignition delays in the two configurations of combustors were nearly the same. However, the modified combustor is a good approach to abbreviate the ignition delay at the inlet gas stream with low oxygen concentration. This work showed a favorable design of the inlet port of a sudden-expansion combustor and further work needs to be done to confirm if the greater reverse flow rate, the higher turbulence intensity and Reynolds stress are the sufficient conditions to improve the ignition process.

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