

Effect of Strain Rate on NO_x Emission in Opposed Impinging Jet Flame Combustor

By

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ABSTRACT

The measurement of velocity and strain rate field has been performed to clarify the mechanism of NO_x reduction in an opposed impinging jet combustor using PIV technique. The highly strained velocity field was found in broad regions of the combustor when a smaller diameter orifice of the pre-chambers was used. Also, the ignition delay was observed in the combustor after the ejection of hot jet flames from the pre-chambers. During the ignition delay time, the flow in the combustor became highly turbulent flows. As a result, the intense combustion occurred within decreased combustion time of 10 msec using the smallest diameter orifice; the combustion time was reduced by more than 30% compared with the larger diameter case. Hence, the NO_x emission was substantially reduced by a factor of 1/2 while keeping combustion pressure as the same level as that in the conventional combustion devices. The reduction of NO_x emission can be attributed to the enhancement of the intermolecular mixing between cold and hot spots in fully turbulent flows. Also, it was found that an appropriate amount of offset in the pre-chamber orifice enhanced the additional reduction of NO_x emissions.

Keywords: opposed impinging jet combustion, NO_x emission, strain rate, distributed reaction, offset effect

1. INTRODUCTION

It has been known that the formation of NO_x is strongly influenced by the gas temperature so that many attempts to reduce the emission of NO_x have been closely related to the reduction of flame temperatures. However, the lower temperature may result in the reduction of combustion efficiency and consequent overall thermal efficiency. Fujimoto et al.(1984) proposed a pre-chamber combustor which utilized a pair of opposed impinging jet flame from pre-chambers (50 mm apart) immersed in flat cylindrical vessels as a low-NO_x device to satisfy the stringent NO_x emission regulations and to minimize the reduction of engine power. They found that the NO_x concentration was considerably reduced while keeping the maximum combustion pressure to the highest level by employing the impinging jet. They also reported that turbulence leads to the reduction of the combustion duration resulting in the reduction of NO_x. In general, NO_x emissions tend to increase as the maximum pressure increases. Figure 1 shows the previous experimental results by many researchers (Fujimoto et al., 1984; Jeong, 1988; Lee et al., 1997)

Fujimoto et al.(1984) and Lee et al.(1997) observed the high load and the low NO_x emissions (more than 50% reduction) were achieved by using the opposed impinging jet combustor with dual pre-chambers. Especially, Fujimoto et al.(1984) investigated the relationship of the NO_x emissions and turbulent intensity with various orifice diameters. And they found that the small scale and widely distributed turbulence in the combustor may reduce the NO_x emissions considerably. Lee et al.(1997) investigated the effects of impinging jet flame on ignition and combustion phase using LDV. And they analyzed the temperature distribution of the main chamber using CH radical images by an ICCD camera and found that the combustion phase could shift from the flamelet regime to the distributed reaction regime according to the turbulence intensity and length scale.

Xie et al.(1996) also found the effect of turbulence on the NO_x emissions in the opposed impinging jet reactor in which the mixture was supplied continuously. They found that a change in the level of turbulence intensity was not closely related to a change in the NO_x emissions. However, since they implemented low turbulence intensity in their experiment, they could not observe the effect of high turbulence intensity on the NO_x emissions. Hence, the sufficient explanation of turbulence effect in the opposed impinging jet combustor has not been reported.

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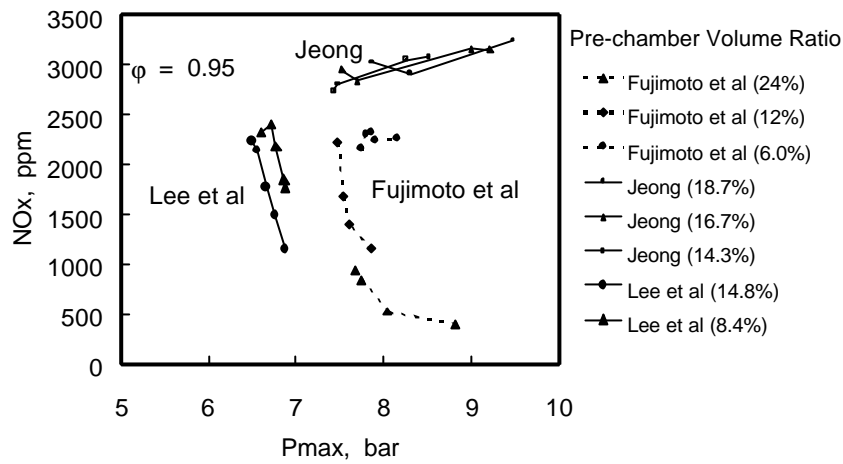


Fig. 1 Previous results of the NO_x emissions of opposed impinging jet combustor at propane-air pre-mixture of $\Phi=0.95$

Abdel-Gayed and Bradley(1989) reported that the shear strain rates play an important role in changing the turbulent combustion phase; the distributed reaction zone flame can be observed in the conditions of strong shear strain rate fields and results in the NO_x reduction of the opposed impinging jet flame. Yoshida(1988) investigated the difference of flame structure of opposed jet flames between unburned and burned gas regions. In unburned regions, a thick wrinkled(not laminar) flame structure was found, whereas in burned regions the distributed reaction zone was achieved.

Gete and Evan(1993) studied the effect of the combustor configuration on the combustion characteristics by simply modifying the number of pre-chambers and the scale of offset in the orifice alignment. They reported that the offset could enhance the combustion efficiency by reducing the combustion duration considerably. However, they also found the excess of the radial flow in the combustor did not improve the combustion efficiency. From their results, it is expected that the offset in the orifice alignment could enhance the level of strain rates without inducing the complete flame extinction and reducing consequently the NO_x emissions.

In the present study, the constant volume combustor with an opposed dual pre-chamber, in which the propane-air mixture was ignited at both side of the chamber, was employed for clarifying the mechanism of the NO_x reduction in this combustor. Hence, the measurements of velocity and shear strain rate fields using PIV were performed for the characterization of turbulence induced by the high speed impinging jet flames in the middle of the combustor. And the effect of an offset in the opposing orifice on the NO_x emission was investigated as well.

2. EXPERIMENTAL APPARATUS

The schematic of constant volume chamber with the opposed dual pre-chambers is shown in Fig. 2. It is a cylindrical

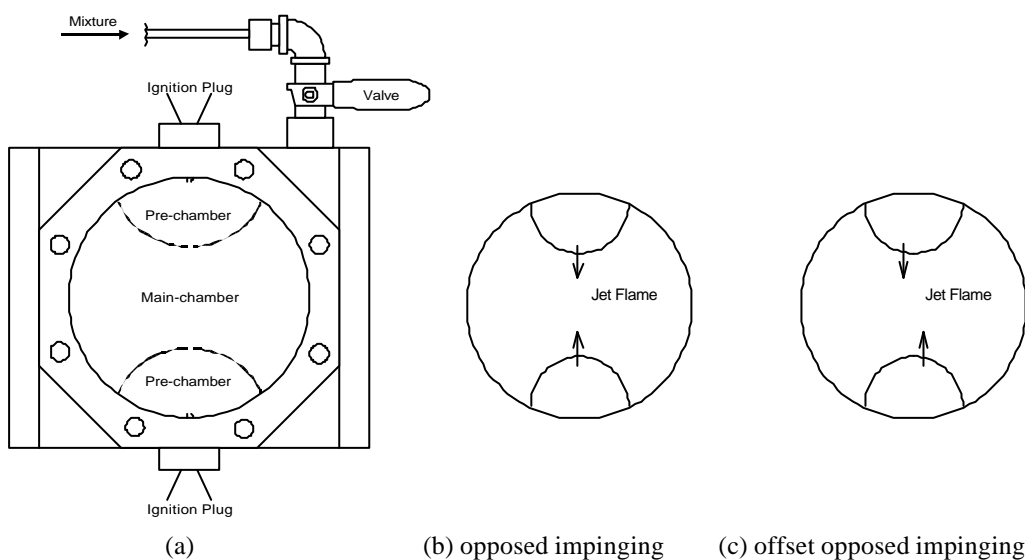


Fig. 2 Schematics of dual combustion chamber and offset opposed impinging

combustor of 120mm in diameter, 40mm in depth and consists of two pre-chambers of 67cc in volume. The volume of the pre-chambers occupies 14.8% of the total volume of the main chamber. All experiments were conducted with propane-air mixture of equivalence ratio $\Phi=0.95$ and the orifice diameters were varied from 5 to 13mm.

The measurements of velocity and shear strain rate using PIV have been performed in the middle of combustion chamber. A dual pulse ruby laser (JK-2000) with $8\mu\text{s}$ pulse separation time was used. Each of pulse energy was 20mJ/pulse with 30ns pulse duration. The high resolution KODAK DCS460 camera (3060 x 2036 pixels) was used for image acquisition. Image shifting technique was adopted for solving the directional ambiguity and implementing the cross-correlation images using a scanning mirror. The image magnification ratio was 27.6 pixel/mm. The interrogation areas of 64×64 pixels overlapped 75% to maximize the spatial resolution and to resolve the smaller turbulent structure. Thus, each vector was obtained at the area of $0.580 \times 0.580 \text{ mm}^2$. Figure 3 shows a schematic of PIV system used in the experiments.

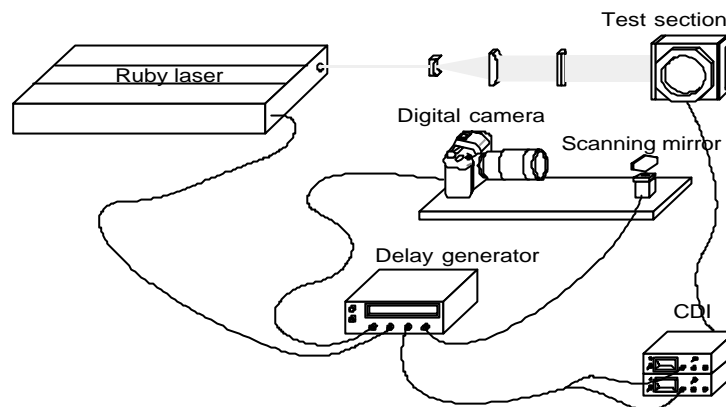


Fig. 3. Schematics of PIV setup

3. RESULTS AND DISCUSSION

Effect of Strain Rates

It is known that the structure of turbulent premixed flame is classified by turbulent Reynolds number, Re , Damkohler number, Da , and Karlovitz number, Ka ; the important quantities are turbulent intensity and turbulent length scales as shown in Fig. 4, which is known as Borghi(1984) diagram. The $Ka=1$ boundary, generally known as the Klimov-Williams criterion, separates the regimes of wrinkled laminar flames that have thin reaction zones from flames with thicker distributed reaction zones.

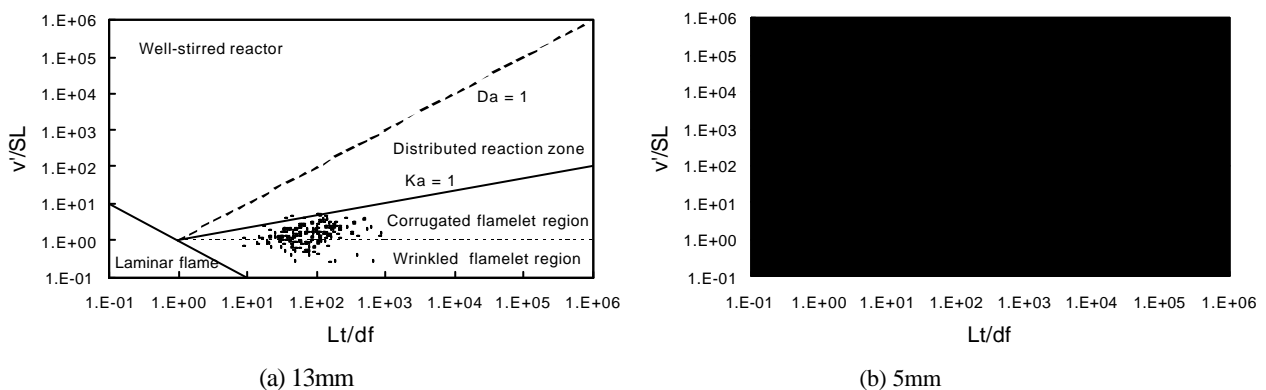


Fig. 4. Effect of strain rate on combustion phase using Borghi diagram.

Strain rates, which are represented by velocity gradient along x and y axes, indicate a degree of flow distortion defined as follows.

$$\mathbf{a} = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \quad (1)$$

Strain rates indicate a degree of flow distortion and are intimately related with Karlovitz number which is a measure of flame stretch in the flow fields. Thus, the strain rate is one of the important parameters that represent the flame structure characteristics. Strain rates can be measured from the raw velocity measurements by PIV and calculated by the formula as follows.

$$\mathbf{e}_{i,j} = \frac{(v_{i+1,j-1} + 2 \times v_{i+1,j} + v_{i+1,j+1})}{8h} - \frac{(v_{i-1,j-1} + 2 \times v_{i-1,j} + v_{i-1,j+1})}{8h} + \frac{(u_{i-1,j+1} + 2 \times u_{i,j+1} + u_{i+1,j+1})}{8h} - \frac{(u_{i-1,j-1} + 2 \times u_{i,j-1} + u_{i+1,j-1})}{8h} \quad (2)$$

Here, u and v are the velocity components in x, y directions and h denotes a cell size. PIV measurements were made for the single pre-chamber to find the how the strain rates behave near the flame. Figure 5(a) shows the raw PIV image and Fig. 5(b) represents the strain rate distribution of the same flow field. It is noted that the lower part of the frame (a), containing a lot of particles, is the unburned mixture and the upper part is the burned region. Hence, the boundary manifested by the density difference of the particles, is considered to be the flame front. It is also noted that the highly negative values of intense strain rates are observed at the flame front; the negative intense strain rate which indicates the local expansion of flows, is believed to be caused by high temperature gradient due to the flame propagating downward. Therefore, it is expected that the high stained trajectory near the flame would be a good indicator of the flame front.

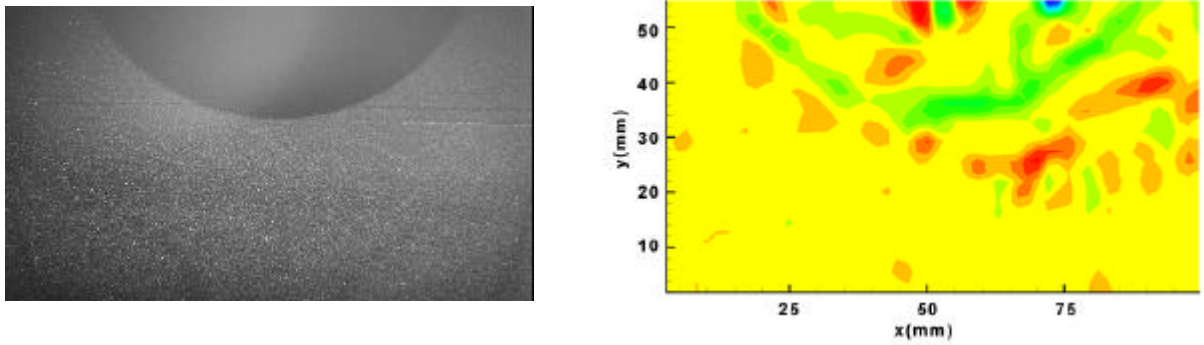
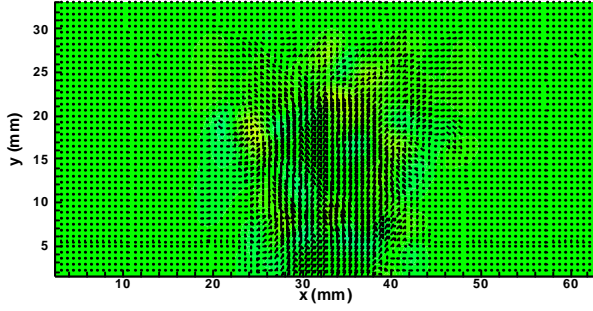


Fig. 5. (a) PIV raw image using single pre-chamber

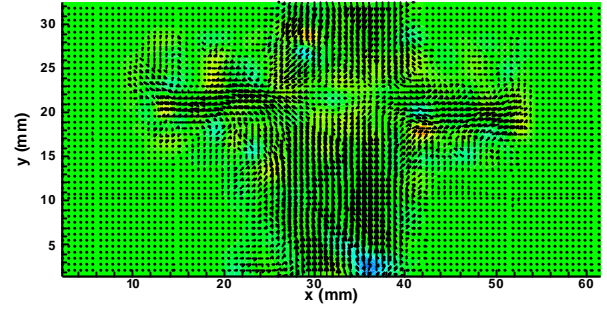
(b) Strain rate contour indicating the frame front

PIV measurements have been conducted for both single and the dual pre-chamber configurations. Figure 6 represents the variation of velocities and shear strain rates in the case of single pre-chamber when varying the orifice diameter from 5 to 13mm. Figure 7 shows the same measurements of dual pre-chambers in conditions as the single pre-chamber. All images were captured at 12ms after ignition. The arrows represent local velocity vectors and the background contours indicate the strain rates. It is found that the background contours were highly fluctuated using a smaller orifice diameter of 5mm than a larger orifice diameter. This indicates that a large amount of highly strained area was produced as the orifice diameter decreased, which is expected to be due to the high ejection velocity from small orifices and thus these high injection jets changed the flow characteristics generating high strain rates.

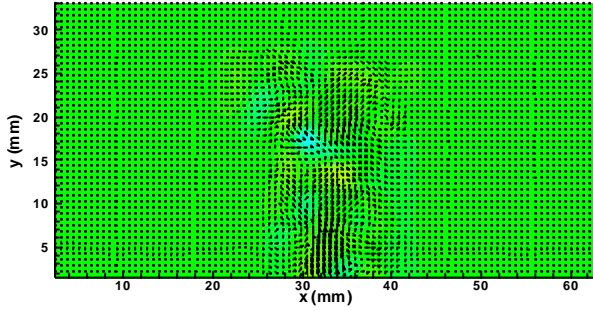
When the dual pre-chambers were used, the high velocity ejection jets were colliding at the center of the combustor and then the stagnation plane was formed as shown in Fig. 7. After the delay period (10-20ms), the re-ignition started to occur around the stagnation plane. It should be noted that the small structures of highly strained pockets was observed in the dual pre-chambers. However, too much strained pockets from the orifice diameter less than 4mm could lead to the complete flame extinction (Lee et al., 1997). Hence, an appropriate degree of highly strained region should be important to maximize the effect of the impinging jet in the main combustor resulting in the decrease of the NO_x emission.



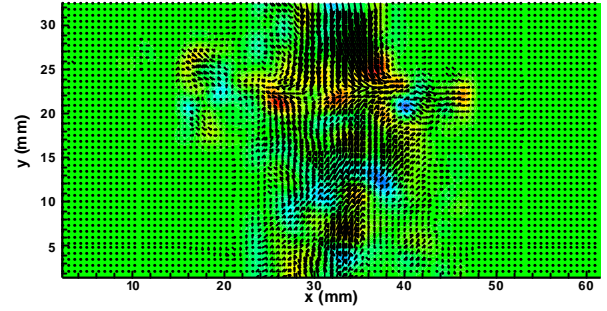
(a) 13mm



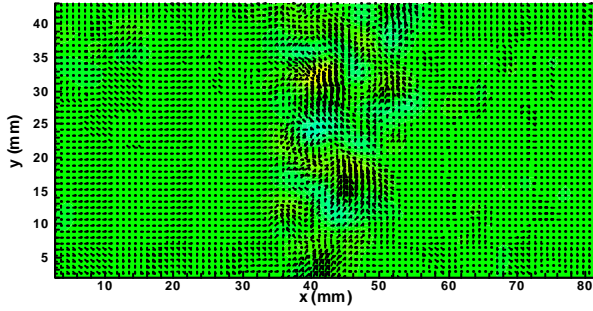
(a) 13mm



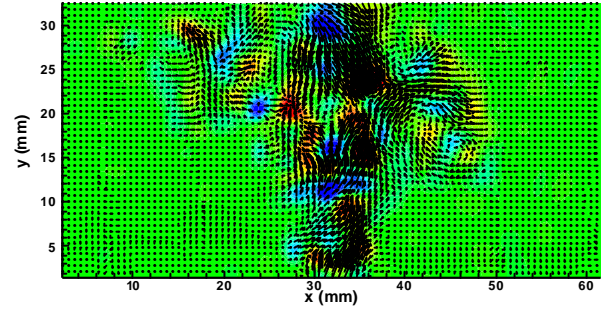
(b) 9mm



(b) 9mm



(c) 5mm



(c) 5mm

Fig. 6. Velocity measurement and strain rate fields in case of single pre-chamber

Fig. 7. Velocity measurement and strain rate fields in case of dual pre-chambers

Figure 8 shows the corresponding PDF distribution of strain rates in the single pre-chamber and dual pre-chambers. By comparing two cases, it was found the highly strained regions are widely distributed in the middle of the chamber in case of dual pre-chambers. The strain rates of less than $|\pm 10|$ (1/sec) are dominantly observed in case of single pre-chamber (Fig. 8(b)), whereas the higher values of strain rates are found for dual pre-chambers, which is larger than $|\pm 10|$ (1/sec) as shown in Fig. 8(b). Thus, the highly turbulent eddies in the main chamber is believed to delay the ignition and to reduce the combustion period in the main combustor. Consequently, the flow characteristics of the unburned mixture are substantially changed to the highly stretched flame structures due to high shear forces exerted by jet flames as observed by Yoshida et al.(1996) and Bedat and Cheng(1995).

Yoshida(1988) reported that the bundle of small-scale turbulences were dominantly distributed in the burned region. And this bundle was presumably responsible for a certain period of ignition delay as shown in the PDF distribution of Fig. 9. Also, he observed distributed reaction zone consists of vortex tubes of preheated unburned mixture or partially reacted gas with an intermediated temperature resulting in the small-scale mixing enhancement.

In order to clarify the relation between the strain rate and ignition delay, the area mean strain rate is adopted as follow in Eqn. 3.

$$\bar{\epsilon}(x, y) = \sqrt{\frac{\int_A \epsilon^2(x, y) dA}{A}} \quad (3)$$

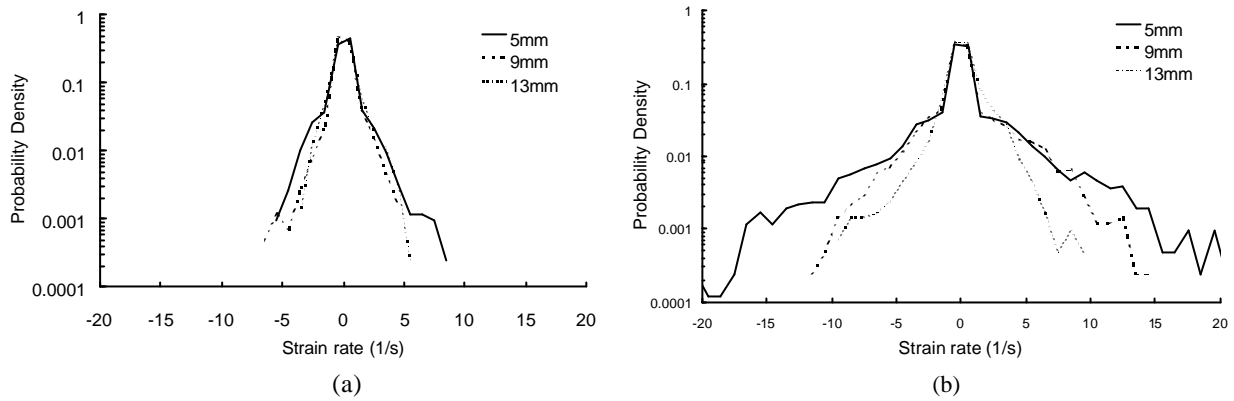


Fig. 8. Probability distribution of strain rates calculated from PIV measurements for (a) single prechamber, and (b) dual pre-chamber.

The ignition delay is defined the time period from the ignition of pre-chamber to the re-ignition of main chamber by the flame kernel ejected from the pre-chambers. The combustion period is defined as the time lapse from the instant of 10% burning to the 90% burning of the mixture. Figure 9 shows the effect of mean strain rate on the ignition delay and combustion period. The ignition delay and the combustion period are calculated from the pressure measurement with piezo-electric sensors. From the analysis of the relation between the ignition delay, the main combustion period and the NO_x emissions, the strain rates are shown to be a key parameter to increase the ignition delay and decrease the main combustion period resulting in the reduction of the NO_x emissions. During the ignition delay, the flow field is expected to have a chance to be changed from laminar to turbulent flows before the main chamber combustion occurs; if the ignition delay is getting longer, the unburned mixture in the main chamber and the ejected hot gas are mixed almost homogeneously during the ignition delay time leading to intense combustion in the main chamber. Hence, the longer the ignition delay is, the shorter the main combustion period as shown in Fig.9.

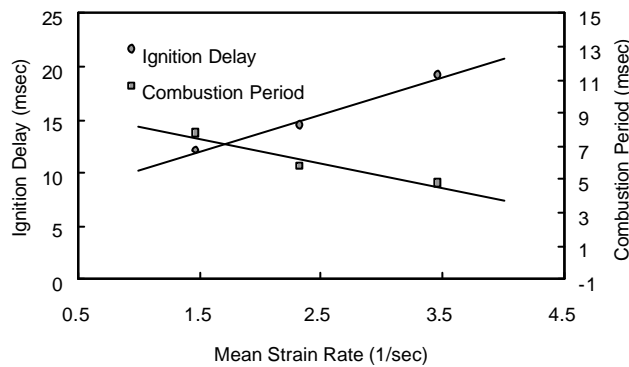


Fig. 9. Effect of strain rates on ignition delay and combustion period in the main combustor

Consequently, the decrease of the orifice diameter could lead to the combustion phase changes from the flamelet regime to the distributed reaction regime in the dual pre-chambers as shown in Fig. 4 (Lee et al., 1997). This indicates that the turbulent flow from a smaller diameter of 5mm tends to enhance the intermixing process between a hot burned gas and a cold unburned gas due to intense strain rates. Hence, it is expected that the hot spots of temperature over 1800K, where NO_x is mainly produced, decreased substantially. In addition, the high strain rates reduce the combustion period resulting in the decrease of residence time of mixture exposed to high temperature in the main combustor.

Effect of Offset

The increase of the strain rate in the main combustor is known to be the crucial factor for reducing the NO_x emissions when dual impinging jets were used. However, it is very difficult to further increase the strain rate around the stagnation plane by simply increasing the ejection speed through a smaller orifice diameter. The excess of ejection speed using a too small orifice diameter can lead to the complete flame extinction. This was observed when the orifice diameter of 3mm was used (Lee et al., 1997). Thus, the offset effect in the orifice configuration is shown to be an alternative way to increase the

effective strain rate distribution. Gete and Evans(1993) studied the effect of various pre-chamber configurations on the combustion characteristics. They reported that the turbulence ejected from the offset-orifice could last longer than the case without offset by the results of LDV measurements and schlieren photography. Although no further studies have been reported, it is considered that the swirl flow induced by the offset effect in the combustor could provide the continuous turbulent kinetic energy through the cascade of turbulence dissipation, which results in the longer duration of strong shear turbulence.

Thus, experiments were conducted with a set of combustor configurations; pre-chamber volumes of 13 and 19% with orifice diameters of 4, 5, 6mm and the scales of offset of 0, 5, 10mm. Figure 10 shows the NOx emissions against the combustion period and ignition delay for various combustor configurations. Results show that the case of dual pre-chambers with an offset indicates the best configuration for the efficient way of NOx reduction. And the normal dual pre-chamber configuration shows reasonably good results. It is noted that the NOx emission in the single pre-chamber was about 1600ppm, whereas offset dual pre-chamber could produce only 1000ppm; more than 30% extra NOx reduction was obtained from the offset dual pre-chamber configuration. This indicates that an appropriate amount of offset in the orifice alignment allows us to reduce NOx emission effectively compared with the pre-chamber configuration with no offset.

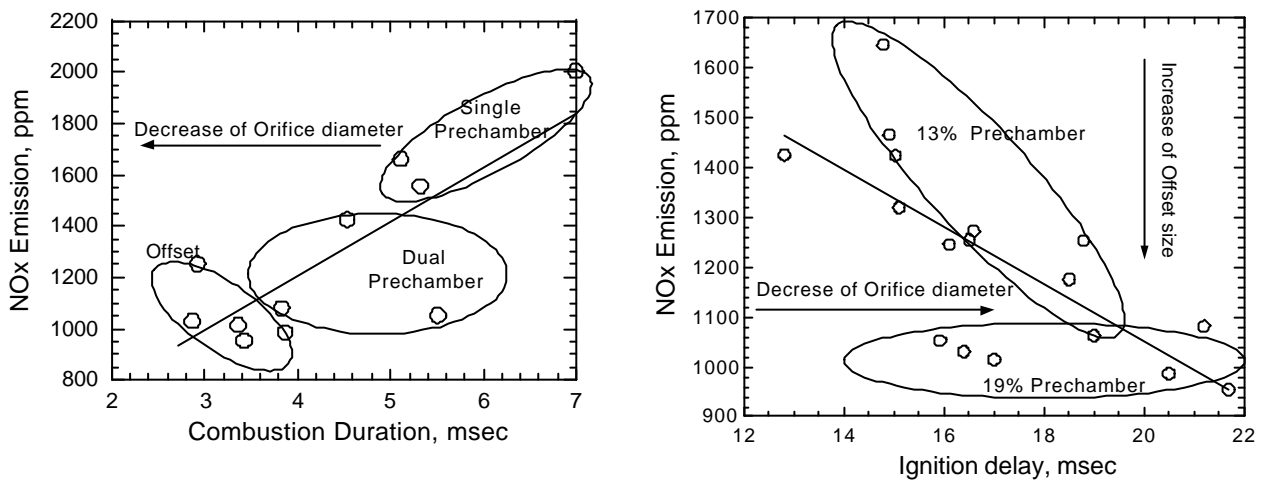
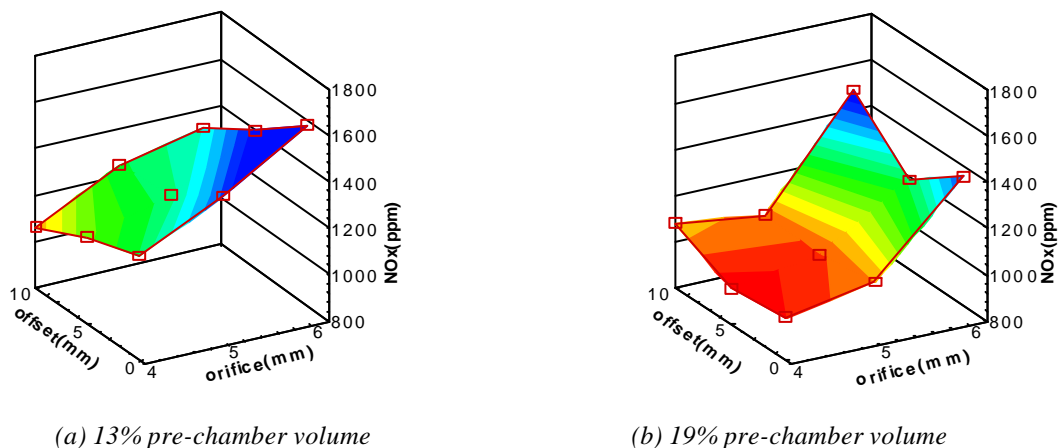


Fig. 10 (a) NOx emissions vs. combustion durations
(b) NOx emissions vs. ignition delay when varying the combustor configurations

Figure 11 shows 3-D plots of the NOx emissions against the various orifice diameters and offset scales when the pre-chamber volumes are 13% and 19% of total volume, respectively. As mentioned previously, for case of 13% pre-chamber volume, NOx emissions showed the tendency of linear reduction as the decrease in the orifice diameter for the fixed amount of offset scales of 0, 5 and 10mm, respectively. However, for case of 19% pre-chamber volume, it is noted that the minimum the NOx emission(954ppm) was found in case of 5mm offset scale configuration; 987ppm in case of 0mm offset scale and 1082ppm in case 10mm offset scale. This implies that the excess amount of offset scale may not be effective for the NOx



(a) 13% pre-chamber volume
(b) 19% pre-chamber volume
Fig. 11 Three-dimensional plot of NOx emissions vs. the variation of orifice diameter and offset scale.

reduction. Also, it is known that the initial swirling flow formed in the combustor due to the offset effect should be an important parameter as well as the strain rate induced by the high shear forces due to the impinging jet.

4. CONCLUSION

The results obtained from the opposed impinging jet flame combustor using PIV can be summarized as follows.

1. As the orifice diameter decreases, the main combustor mixtures are highly strained due to impinging jets injected from the pre-chambers and the small structures of high strain rate pockets are broadly spread throughout the main combustor. Also, it is found that the ignition is delayed in the main chamber due to the highly strain rated mixtures. Meantime, the flow is completely changed to the highly turbulent flow.

2. Main combustion time is decreased significantly as the orifice diameter decreases. Hence, the emission of NO_x can be reduced more than 50% compared with those in conventional combustors. This is believed to be the fact that the hot spots where the temperature is over 1800K are reduced substantially due to the enhanced intermolecular mixing between hot and cold spots generated by turbulent eddies.

3. Accordingly, the combustion phase moves from the wrinkled laminar flamelet regime in case of orifice diameter of 13mm to the distributed reaction regime in case of 5mm. However, the further decrease of orifice diameter may cause the flame extinction due to excessively high strain rates.

4. The slight modification of dual pre-chamber combustors using the offset configuration was found to be another way of further decrease of the NO_x emissions by increasing swirling motions as well as turbulence. As a result, the offset could enhance the reduction of the combustion period and the increase of the ignition delay. However, too much offset may lead to the increase in NO_x emissions. Thus, an optimal amount of offset should be determined to produce the lowest NO_x emissions for a given combustor geometry.

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