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MIXING CONDITIONS WITH SPRAY-JET INTERACTION FOR EFFECTIVE SOOT REDUCTION IN DIESEL COMBUSTION

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ABSTRACT−The authors have reported significant reductions in particulate emissions of diesel engines by generating strong turbulence during the combustion process. This study aims to identify optimum conditions of turbulent mixing for effective soot reduction during combustion. The experiments were conducted with a constant volume combustion vessel equipped with a jet-generating cell, in which a small amount of fuel is injected during the combustion of the main spray. The jet of burned gas from the cell impinges the main flame, causing changes in the mixing of fuel and air. Observation was made for a variety combinations of distances between spray nozzle and jet orifice at different directions of impingement. It is shown that compared with the case without jet flame soot decreases when the jet impinges. When the jet is very close to the flame, it penetrates the soot cloud and causes little mixing. There were no apparent differences in the combustion duration when the direction of impingement was varied, although the mechanisms of soot reduction seemed different. An analysis of local turbulent flows with PIV (Particle Image Velocimetry) showed the relationship between the scale of the turbulence and the size of the soot cloud.

KEY WORDS : Soot, Particulate, Spray, Combustion, Turbulence, Mixing, Jet impingement

1. INTRODUCTION

Reduction of soot and NO_x emitted from diesel engines are a major issue in engine research and there are many studies on emission control. Factors which can be controlled and which are important in emissions reduction are the distribution of the mixture concentration and the fuel/air mixing intensity.

There are previous reports of significant reductions in particulate emissions by generating strong turbulence during the combustion process (Murayama, 1988; Murayama, 1989; Konno, 1992). The strong turbulence was generated by injecting a small amount of fuel during the main combustion from an auxiliary chamber installed in the cylinder head. The combustion of the fuel in the cell creates jets aimed at the main flame and generates strong turbulence. The authors extended this system to a two-stage combustion concept, *i.e*. a primary stage with rich combustion to reduce NO_x and a secondary stage with strong turbulence to reduce particulate (Konno, 1993; Chikahisa, 1995).

The present research has analyzed the effect of the turbulent jet and identified the optimum condition of jet impingement for soot reduction. A constant volume combustion vessel was used in the observations of the combustion process with the turbulent jet. To analyze the relationship between turbulent eddy distribution and soot oxidation, PIV (Particle Image Velocimetry) analysis was applied with attention paid to the intensity and location of vortices.

Research related to combustion enhanced by turbulence is detailed in Ref. (Konno, 1992; Chikahisa, 1995).

2. EXPERIMENTAL APPARATUS AND PROCEDURES

A constant volume combustion vessel was made as outlined in Figure 1 for the observations of the combustion. This vessel has a 100 mm diameter and a 30 mm thickness as a test section. A small amount of fuel is injected in a turbulence-generating cell (volume 2.5 cc and path diameter 3.4 mm), named as the “Combustion Chamber for Disturbance” (abbreviated in the paper as CCD, and a CCD jet for the jet from the chamber). The combustion in the cell creates a jet aimed at the main flame and generates strong turbulence. Main spray nozzles are located on the cylinder wall and on the end plate, so that different settings of the main spray are possible.

Initially the chamber is filled with a pre-mixed charge

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of ethylene (5 vol %), nitrogen (60 vol %), and oxygen (35 vol %) at a pressure of 0.8 MPa. Then the charge is ignited by a spark, which creates a hot and high-pressure atmosphere for the following spray injection. At an appropriate condition, 900 K and 3.0 MPa in the present experiments, the main spray is injected into the chamber filled with combustion gas with sufficient oxygen, and this is followed by the secondary injection from the CCD.

Three different distances and four different directions of main fuel spray relative to the CCD jet were examined to investigate the effect on soot reduction. The distances between the nozzle and CCD orifice was 100, 75 and 50 mm for Cases 1, 2, and 3 in Figure 1, as listed in Table 1. The directions of the main spray relative to the CCD jet were varied in cases 4 to 7 as shown in Figure 2. The θ angles in Figure 2 are 180º, 135º, 90º, and 45º as also listed in Table 2, and the distance between the main spray and the center of the chamber was 32.5 mm.

The injection timing of the CCD jet was coordinated to collide when the main spray reached the same length in Cases 1 to 3. When the directions were varied, the timing was coordinated so that the CCD jet impinges on the main spray at the center of the chamber, Cases 4 to 7.

When the main nozzle is at the cylinder wall as shown in Figure 1 for Case 1, there are quartz glass windows at the both sides of the chamber for shadowgraph pictures. An Ar-ion laser was used for the shadowgraph, and to remove Schlieren effects in the surrounding air after the

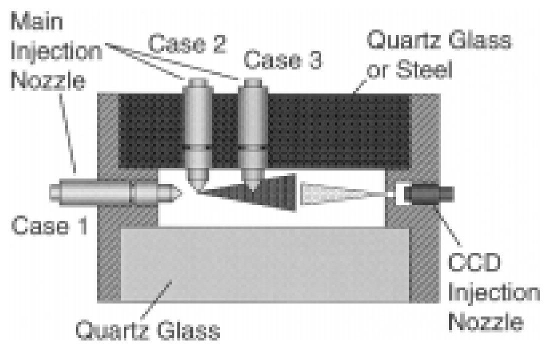

Figure 1. Location of main and CCD injection nozzles.

Table 1. Distance between main nozzle and CCD jet orifice, L_j, relative to the orifice diameter, d_j.

	Case 1	Case 2	Case 3
L_j (mm)	100	75	50
L_j/d_j	30	22.5	15

Table 2. Direction of main nozzle and CCD jet orifice relative to orifice.

	Case 4	Case 5	Case 6	Case 7
θ	180º	135º	90º	45º

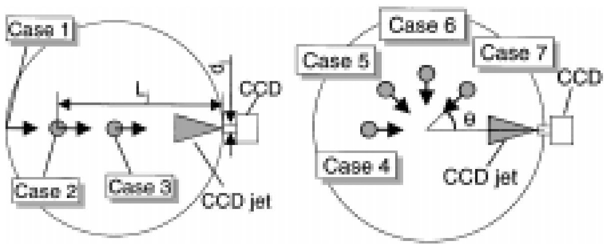

Figure 2. Location of main nozzles (shaded circles) and CCD jet orifice.

pre-mixed combustion, a scattering film was placed in a parallel beam set before an expanding lens. A band pass filter with center wavelength 488 nm was used to remove the luminous flame image. The combustion process was observed by a high-speed video camera at 13,500 frames per second.

In cases other than Case 1 only direct photographs were taken, because the nozzles were on a steel side plate as shown in Figure 1.

3. EXPERIMENTAL RESULTS AND DISCUSSION

Figures 3 and 4 show photographs of the direct flame

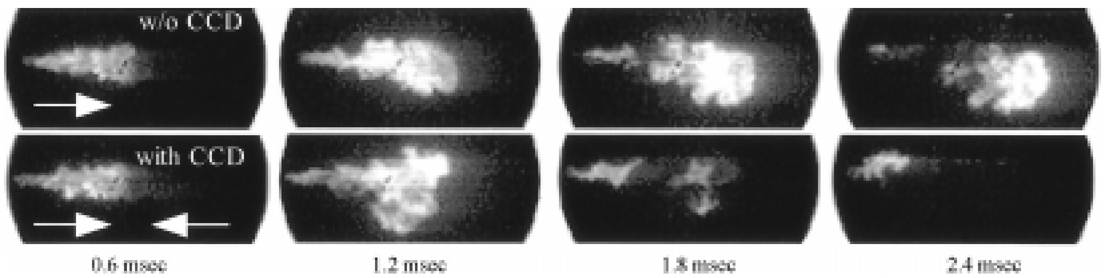

Figure 3. Photographs of combustion with and without CCD jets for the Case 1 nozzle location.

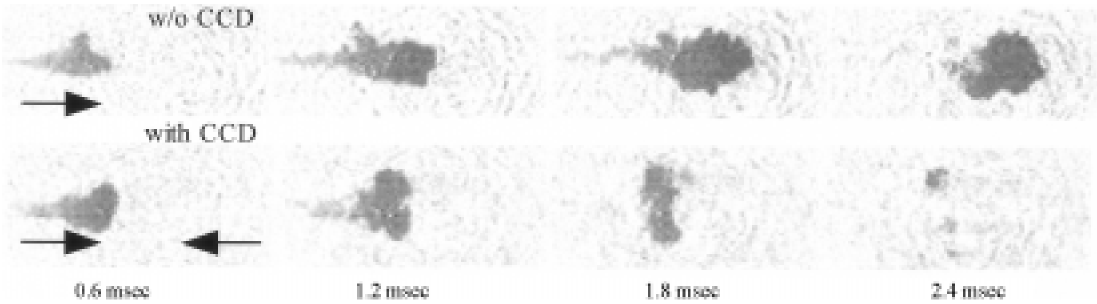

Figure 4. Soot images with and without CCD jets for the Case 1 nozzle location.

images and soot shadowgraphs with and without CCD jet at the Case 1 nozzle location. The time in figures is the period after the start of the main injection. The pictures in Figures 3 and 4 were photographed under very similar conditions with the main fuel injected horizontally from left to right, and the CCD jet from the right. Comparing Figures 3 and 4 shows that the soot distribution is similar to the flame, both with and without the CCD jet. Between the pictures of with and without the CCD jet, there are similar flame shapes and soot until 0.6 msec., when the CCD jet has not reached the flame. After the CCD jet reaches the injected fuel, the flame and soot disappear rapidly. This indicates that the CCD jet causes a rapid mixture of soot and surrounding air resulting in quick oxidation of the soot.

Figure 5 shows the averaged areas of luminous flames and soot with and without the CCD jet for the conditions in Figures 3 and 4. With the CCD jet both luminous flame and soot areas diminish earlier than without the CCD jet. The areas change similarly, and the soot behavior may be estimated from the flame pictures, as mentioned above.

Figure 6 shows pictures of spray flames with and without the CCD jet for Case 2, where the distance between main nozzle and CCD orifice is shorter than in

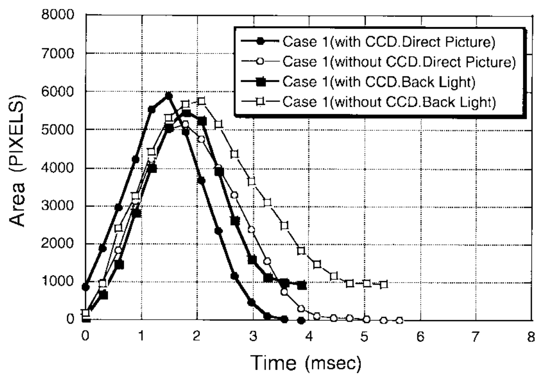

Figure 5. Flame and soot areas for Case 1.

Case 1. Without the CCD jet, the luminous flame remains around the right wall of the combustion chamber until about 6.5 msec., with the CCD jet the combustion terminates earlier than without the CCD jet as also seen in Figure 7. The changes are similar to Case 1.

Figure 8 shows pictures for Case 3 where the distance between the main nozzle and CCD orifice is the shortest. Figure 9 shows the changes in luminous flame area. Without the CCD jet, the spray flame injected from the

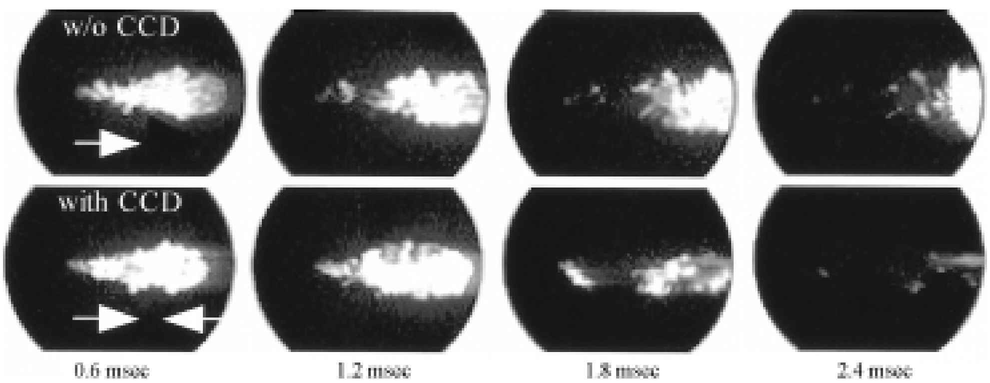

Figure 6. Photographs of combustion with and w/o CCD jets for Case 2.

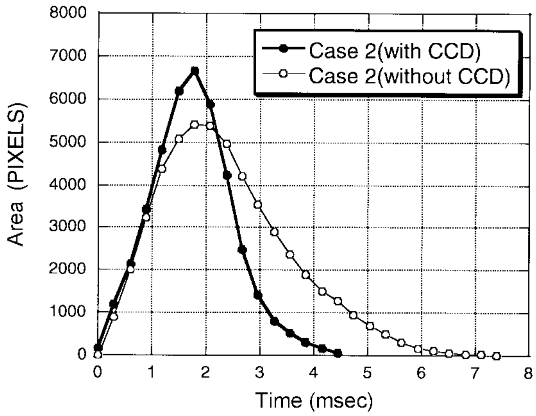

Figure 7. Flame areas for Case 2.

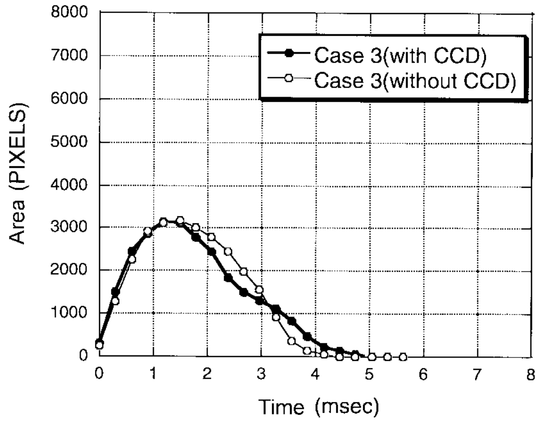

Figure 9. Flame areas for Case 3.

center of the combustion chamber remains for a long time, spreading along the wall. With the CCD jet, the jet penetrates the flame, and there are no apparent differences with and without the CCD jet, different from Cases 1 and 2.

These results indicate that impingement of the jet promotes oxidation of soot, but that when the jet is close to the spray flame it only penetrates the flame with no combustion enhancement.

Next, experiments changing the direction of impingement were performed. Figures 10 to 13 show photos of the flame development for different impinging directions left and also the changes of luminous flame areas right.

Figure 10 is the pictures for Case 4, with the same nozzle arrangement as Case 2 in Figure 6, except for the differences in the timing of the CCD jet as mentioned

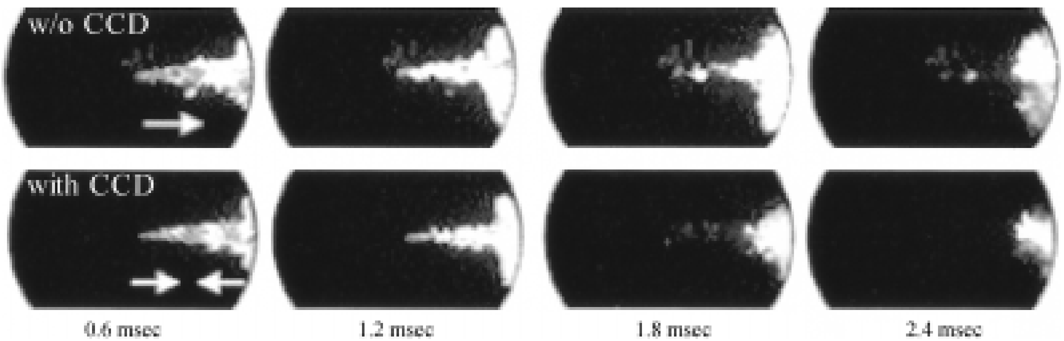

Figure 8. Photographs of combustion with and w/o CCD jets for the Case 3.

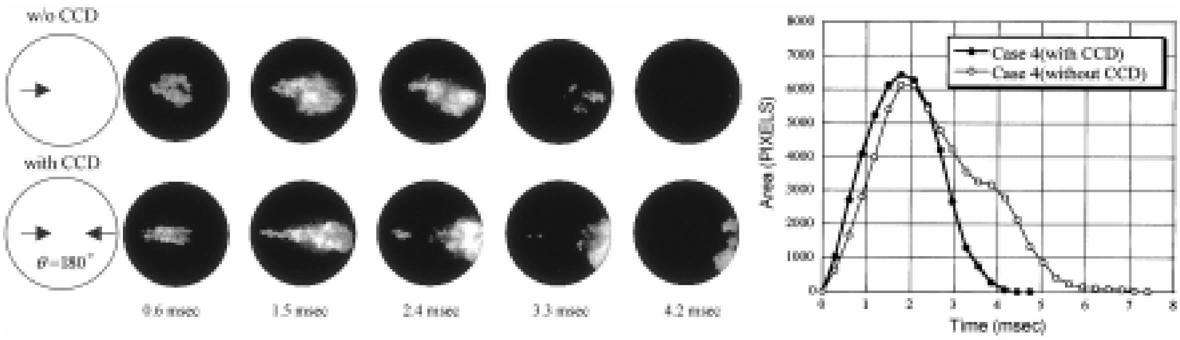

Figure 10. Photographs of combustion with and w/o CCD jets for Case 4.

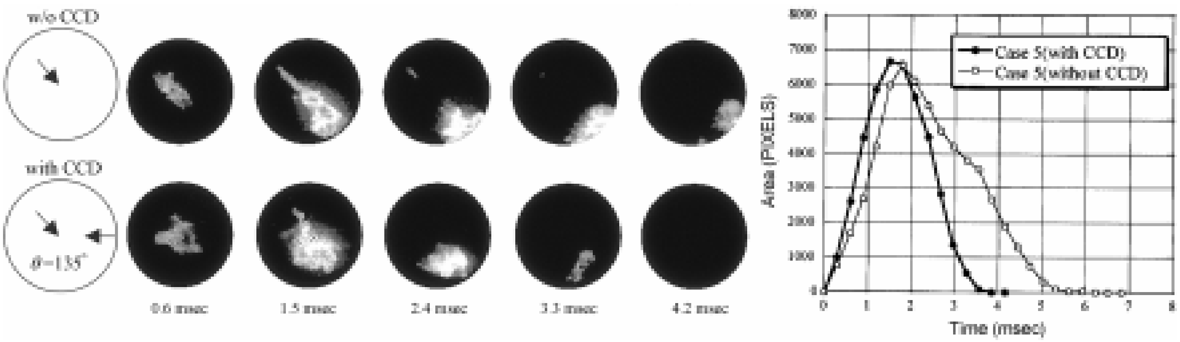

Figure 11. Photographs of combustion with and w/o CCD jets for Case 5.

above. The CCD jet impinges on the spray flame before 0.6 msec., and the luminous flame rapidly disappears after the impingement similar to Case 2.

Figure 11 shows pictures for Case 5 with and without CCD, when the angle between the main spray injection and the CCD jet is 135°. The CCD jet impinges on the spray flame at about 0.6 msec., and the combustion terminates earlier with the CCD jet than without. The decreased combustion duration is almost the same as in Case 4, although the shape of the flame is different in the two cases. The flame contact to the wall is limited by the jet, and preventing the slowing down of soot oxidation with cooling by the wall. The CCD jet penetrates the spray flame at about 1.5 msec. at this angle.

In Case 6 in Figure 12 and Case 7 in Figure 13, with impinging angles of 90 and 45 degrees, the flame is carried by the CCD jet and reaches the wall at high velocity. Even when the temperature in the vicinity of the wall is lower than the other parts of the combustion chamber, the flame disappears as early as in Cases 4 and

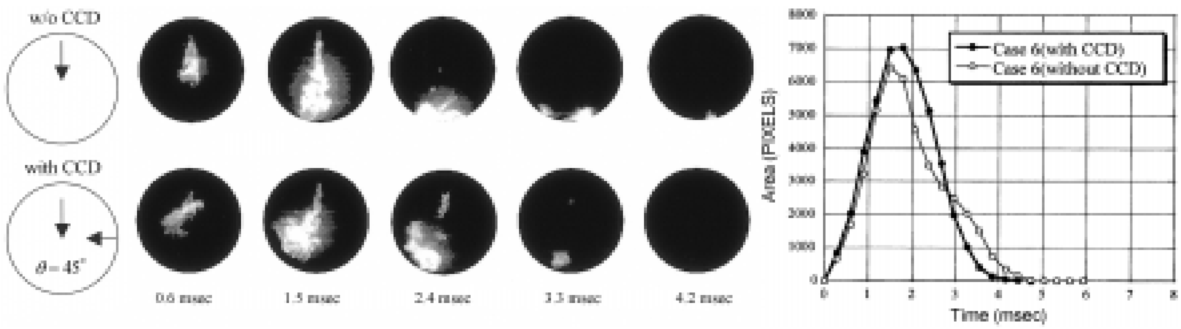

Figure 12. Photographs of combustion with and w/o CCD jets for Case 6.

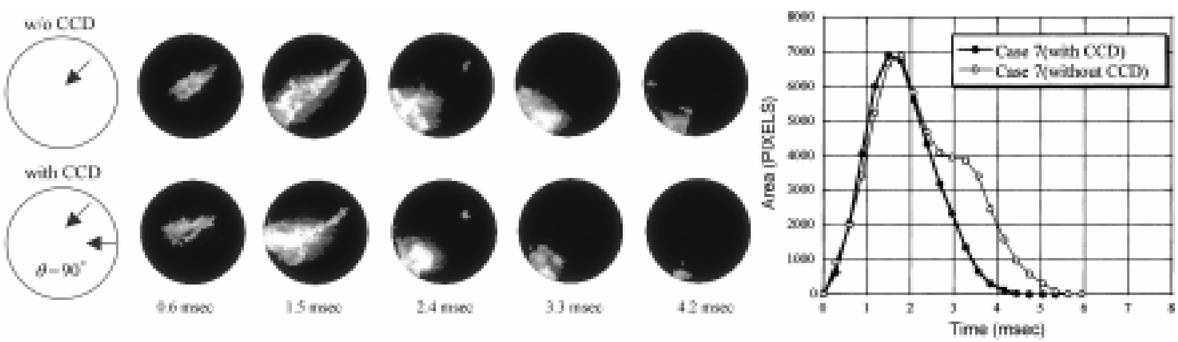

Figure 13. Photographs of combustion with and w/o CCD jets for Case 7.

5 with the CCD jet, and there are no apparent differences in the combustion duration in these conditions.

At all the directions of impingement here the spray flame diminishes at almost same time with the CCD jet and earlier than without the CCD jet. However, the mechanism of flame extinction appears to be different at different directions. In Cases 4 and 5 the opposing CCD jet limits the flame reaching the wall, and oxidation of soot is achieved at the high temperature zone with strong turbulence by the jet. In Cases 6 and 7, the luminous flame reaches the wall at high velocity due to the CCD jet, and turbulence is generated by the impingement of flame to wall. This secondary turbulence at the wall together with the direct turbulence by the jet collision enhances the oxidation of soot even in the low temperature region in the vicinity of the wall.

4. LOCAL STRUCTURE OF FLAME AND TURBULENT FLOW

As mentioned above the CCD jet enhances mixing of fuel and air where the jet impinges directly and also at the wall where the spray impinges. To confirm the effect and to identify the relationship between the scale of the turbulence and the scale of the soot cloud in the disappearance of the soot, the turbulence structure was analyzed by PIV (Particle Image Velocimetry). The PIV analysis was made with spatial correlation of the flame movement.

Figures 14 and 15 are images in 1.8 msec. from the beginning of the main spray injection in Case 2 with (Figure 14) and without (Figure 15) the CCD jet, together with the PIV analysis for windows 1 and 2. It confirms that with the CCD there is a strong vortex at the tip of the main spray, while there is no intensive vortex without the CCD jet.

The strong vortices exist mostly behind the tip of the spray flame as shown in Figures 16 and 17 for the Case 3 at 2.4 msec. Comparing the situation at the tip of the spray for Cases 2 and 3 with the CCD jet, the jet penetrates the flame in both cases, but the vorticity is much stronger in Case 2 than in Case 3. This difference

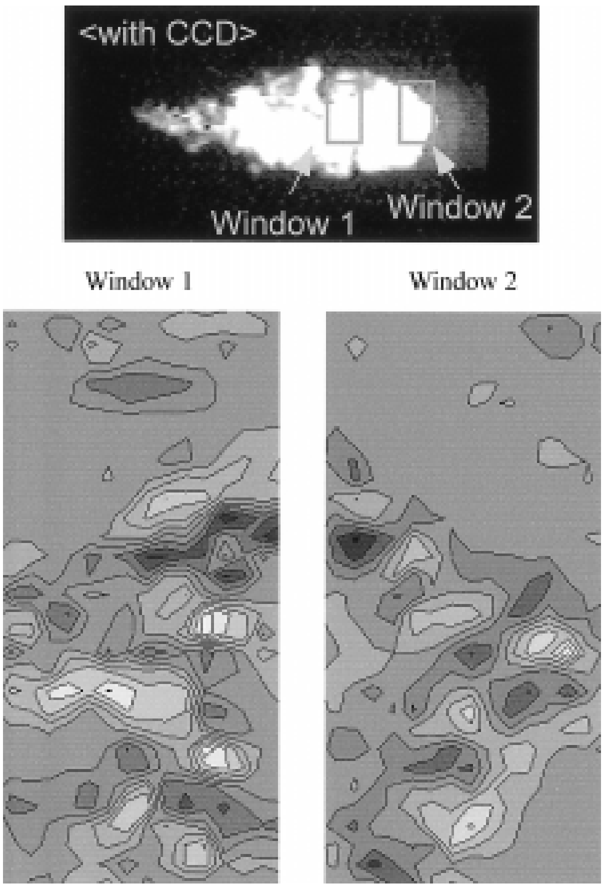

Figure 14. Vorticity distribution with CCD at 1.8 msec. for Case 2.

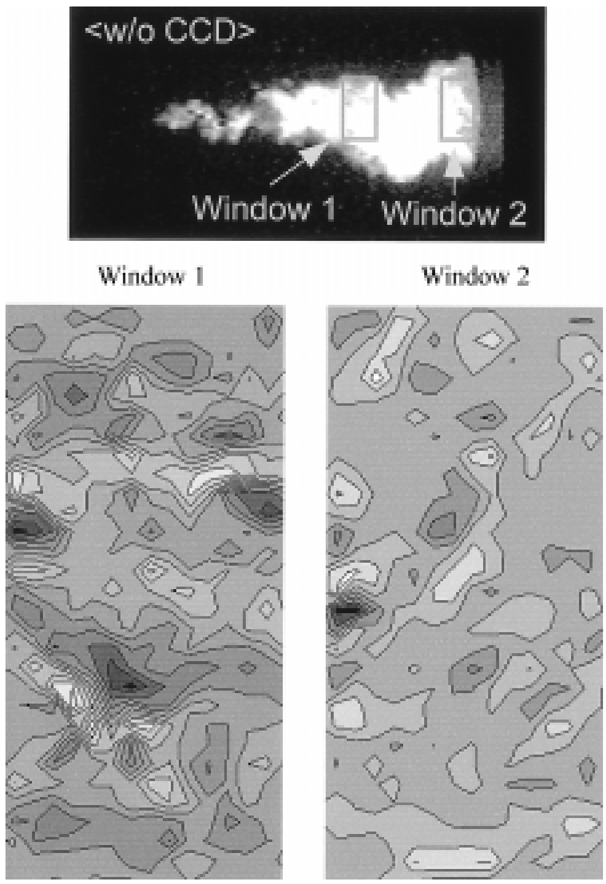

Figure 15. Vorticity distribution without CCD at 1.8 msec. for Case 2.

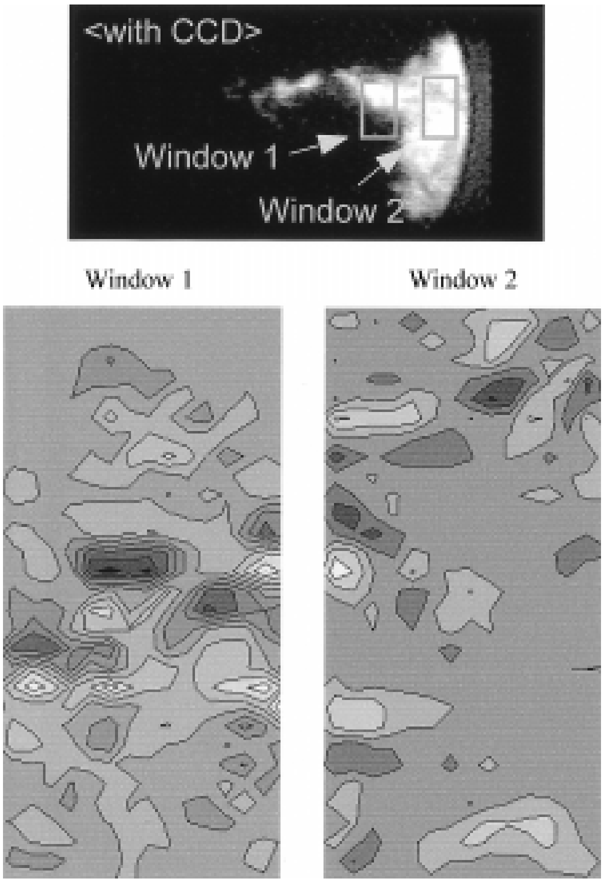

Figure 16. Vorticity distribution with CCD at 2.4 msec. for Case 3.

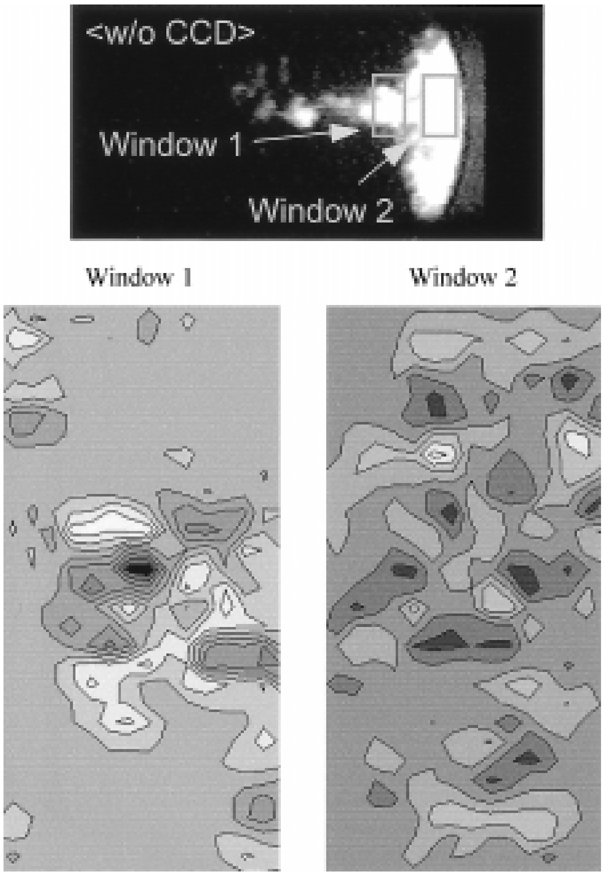

Figure 17. Vorticity distribution without CCD at 2.4 msec. for Case 3.

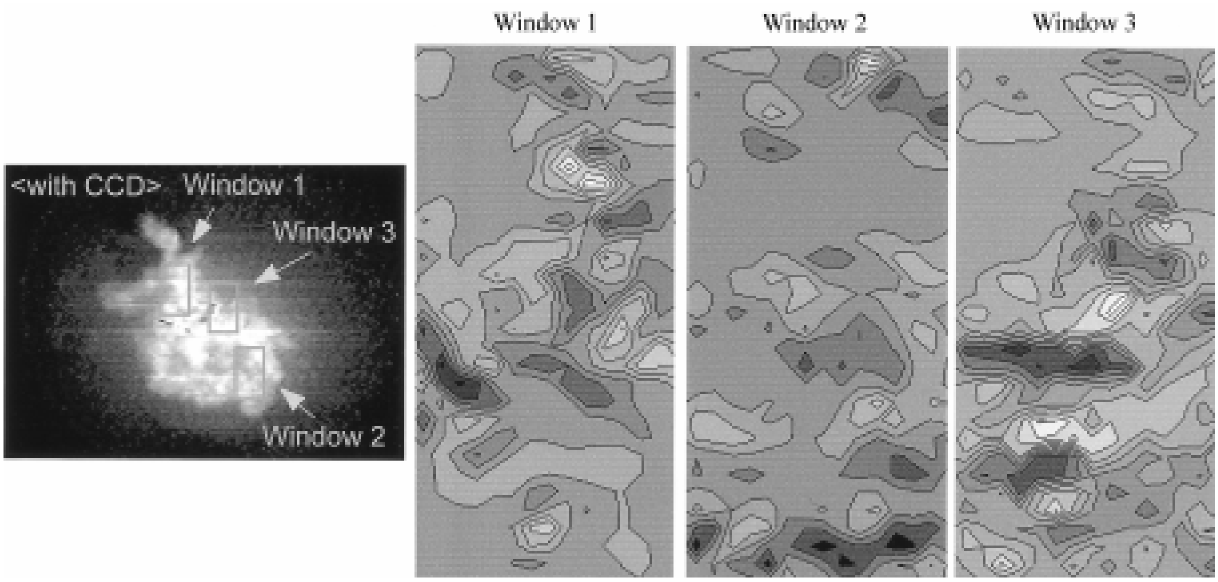

Figure 18. Vorticity distribution with CCD at 1.5 msec. for Case 5.

in the vorticity appears to be a cause of the differences in the soot reduction effects of the CCD jets as described above.

The image of Case 5 at 1.5 msec. with the CCD jet is shown in Figure 18 together with the PIV analysis at windows 1 to 3. There are strong, large-scale vortices in windows 1 and 3. Differently directed vortices distribute equally throughout the region. Ambient air is enveloped into this flame region by the vortices and the flame disappeared shortly after this. There are also strong vortices in window 2, but the spray just rotates without enhancing air mixing. This suggests that the large vortices distort and stretch the flame when the boundary locates across the flame, but when it overlaps the flame cloud it only rotates the flame with little mixing. Small-scale vortices appear to increase diffusion, but deformation and stretch of the flame shape by the vortices is not as significant as with large-scale vortices.

Figure 19 shows the image of Case 6 at 2.4 msec. with the CCD jet and the PIV results at windows 1 and 2. There are comparatively strong vortices at windows 1 and 2, but the air entrainment into the flame is stronger at window 2. In window 1 the flame only rotates in the large vortex in the spray.

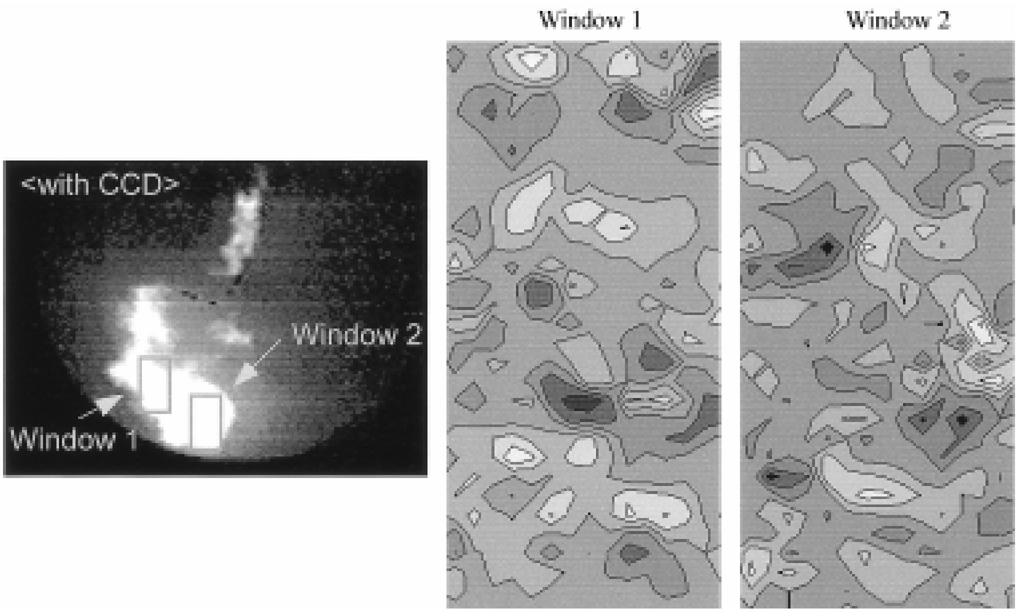

Figure 19. Vorticity distribution with CCD at 2.4 msec. for Case 6.

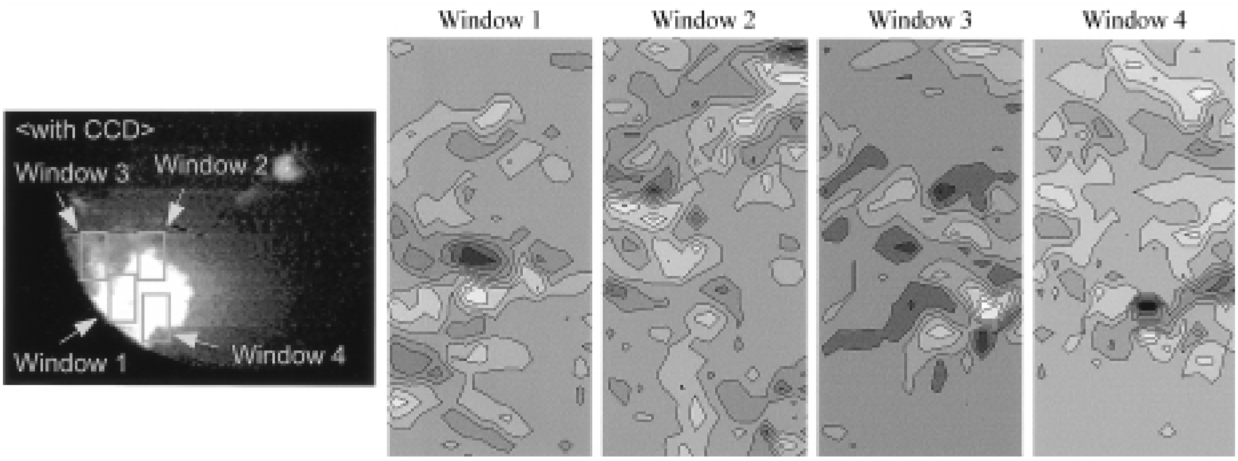

Figure 20. Vorticity distribution with CCD at 2.4 msec. for Case 7.

Figure 20 is the image of Case 7 at 2.4 msec. with the CCD jet and the PIV results at windows 1-4. In window 3 there are small scale vortices formed by strong impingement of the spray to the wall surface, and this makes mixing with air significant. There are large vortices at the right corner of window 4 and air entrainment was also intensive here. In windows 1 and 2, the vortices are equivalent to the flame cloud size, and only rotate the flame similar to the situation above.

The PIV analysis showed that the vorticity increased by the CCD jet at the region of spray impingement and at the wall after the spray impinges on the wall, and that the result is an increase in air mixing. When the vortex sizes are equivalent to the flame cloud and when they overlapped the flame, the flame only rotates without enhancing mixing with air. At this scale the relative locations of vortices and flame are important for the distortion of the flame.

5. CONCLUSIONS

(1) It was observed that the soot cloud in a spray flame oxidized and disappeared quickly by the impingement of a turbulent jet. When the distance between the main spray and the turbulent jet was too short, the turbulent jet penetrated the soot cloud without causing effective mixing.
(2) The decrease of combustion duration by the CCD jet was similar regardless of the direction of the impinging jet. However, different directions appear to result in different mechanisms of soot reduction: enhanced mixing at the impinging region (available in all directions), preventing the flame from reaching the cool wall surface (at angles θ larger than 90^o in Figure 2), or enhanced vorticity at the wall after the flame hits the wall (at angles θ less than 90^o).
(3) Analysis of local turbulent flows with PIV showed that when the vortex size is equivalent to the flame cloud and overlaps the flame, the flame only rotates without enhancing mixing with air. At this size scale the relative locations of vortices and flame are important in the distortion of the flame.

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