Measurement of Detonation Front Structure in Methane-Oxygen Detonation by Multiple Ion-Probes

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1 Introduction

Multiple ion-probe method is the specialized method to capture the movement of propagating flame front along the wall surface of combustion vessel by using plural ion-probes[1-3]. This method is able to capture not only the propagation velocity along the wall surface, but also propagating direction and instantaneous shape of flame front. Ion-probe itself is physically and thermally strong. In addition, ion-probe allows fast data sampling rate. These features of ion-probe make this method possible to apply to the measurement on explosive combustion, such as detonation and engine knocking.

In this work, well developed detonation of stoichiometric methane-oxygen mixture was precisely measured by multiple ion-probe method. Convexo-concave of the flame front and fluctuation of local propagation velocity that may be caused by detonation cellular structure were found in captured data by this method.

2 Experimental apparatus

Figure1 shows the overview of measurement system for propagating flame by multiple ion-probe. Plural ion-probes are installed at the wall surface of combustion tube. Tip of the ion-probe were processed in the same plane as wall surface not to affect the combustion phenomenon. The positive voltage of 3V were added to the ion-probe from the combustion vessel as ground. Small electric current flows when flame front contacts with ion-probe, because flame contains the small number of ions and has small electric conductivity. From the above principle, timing of flame contact with each ion-probe is detected as ion current flow.

An operational amplifier with rapid response was used to amplify the ion-current flow, because ion-current is small and fluctuate rapidly. Additionally, amplification factor was made large enough to amplify ion-current signal saturated instantaneously when flame contacts with ion-probe. This eliminates the calibration of sensitivity among ion-probes. We have developed a 64 channel ion-signal acquisition system based on FPGA. In this concept of measurement, because the only thing that each ion-probe should detect is arrival time of propagating flame, that is, all of the information behind the flame front is not considered in this method, the requirement of recording data is merely detection or no-detection of flame arrival at individual

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ion-probe at a certain time. Therefore, data acquisition system only needs recording 1bit data from each ion-probe. The data acquisition system had 64 channels and recording data in each channel was 1bit and 65,000 words. Data sampling rate used in the experiments was 150MHz for each ion-probe. This system can record longer time duration because it was programed to eliminate duplicating data. Post processing of recorded data was performed for indirect visualization by using appropriate interpolation of spatially interspersed data.

Figure 2 shows the overview of the experimental apparatus. Combustion tube is a length of 1820 mm and an inner diameter of 58 mm. The disturbing section with 320 mm was installed at the ignition end of the combustion tube, which enhances the turbulence of the flame to shorten the distance to get developed state of the flame propagation. Detailed measurement section was located at another side from ignition end. Methane and oxygen were separately filled in the combustion tube by partial pressure method. Mixture filled in the tube was mechanically mixed by explosion proofed gas pump. Mixture conditions were CH_4: O_2 = 1: 2, initial pressure of 0.10 MPa, and initial temperature of room temperature. CJ detonation velocity of this mixture was 2394 m/s. Flame propagation velocity was measured by two ion-probes separately installed front and back from multiple ion-probes with their distance of 200 mm. In the series of experiments, the measured velocities by these ion-probes were in 0.5% from CJ detonation velocity. This indicates well developed detonation propagated the multiple ion-probe section.

Two types of multiple ion-probes were installed alternately. One of the multiple ion-probe was named 16x4 ion-probes. 16 ion-probes were installed on the same circumference with the separating angle of 22.5 degree (11.38 mm on inner tube wall surface). Four sets of 16 ion-probes were installed with the interval of 10 mm in tube axis direction. The other was named 8x8 ion-probes. This had 64 ion-probes installed as 8x8 of square matrix. Intervals of each ion-probe were 1.5 mm along the inner surface of the tube in tube axis direction and circumferential direction. Stainless wire with diameter of 0.5 mm was used for ion-probe. Electrical insulation was performed by ceramic tube with outer diameter of 1.0 mm.

From preliminary experiments for some ion-probes, the rise time of the amplified flame signal from 0 V to 1.6 V that was the threshold of FPGA was 9.0-9.5 $\times 10^{-8}$ seconds, their standard deviation of each ion probe was 2.7-3.4 $\times 10^{-8}$ seconds. Deviation of signal rise delay would cause the measurement error. The above standard deviations correspond to 6.5-8.1 $\times 10^{-2}$ mm at CJ detonation velocity of 2394 m/s. These are 4.3-5.4 % with respect to the propagation period of the CJ detonation in the interval of 1.5 mm with 8x8 ion-probes.

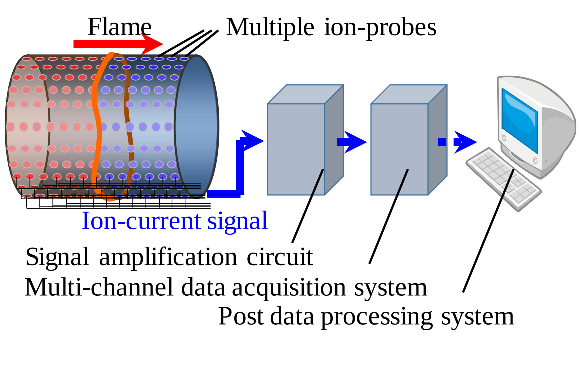

Figure 1. Concept of flame measurement by multiple ion-probe method

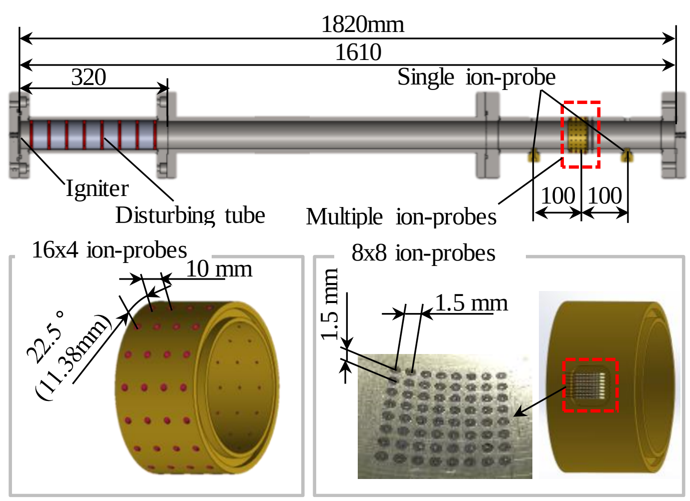

Figure 2. Details of combustion tube and multiple ion-probes

3 Experimental results and discussion

Experimental result measured by 16x4 ion-probes are shown in fig.3, fig.4 and fig.5. Fig.3 shows the contour map of flame detection time. Each contour line represents the shape of flame front at each moment. This contour map was drawn by using interpolated data made by cubic spline. The distance to the next contour line is proportional to the flame propagation velocity. In the figure, flame propagates from upper side to bottom side as a red arrow denotes. The contour lines mostly straight and perpendicular to the tube axis. However, the lines are not perfectly straight. The precise investigations were performed in fig.4 and fig.5. Fig.4 shows the propagation velocities calculated by adjacent ion-probes in tube axis direction. Although the detonation propagating at multiple ion-probe section is well developed, flame velocities measured by multiple ion-probes are fluctuated. The range of velocity fluctuation is from –100 m/s to +100 m/s against CJ detonation velocity of 2394 m/s. Fig.5 shows the positions of relative flame front. The position of relative flame front was calculated by multiplying CJ detonation velocity and the time difference between flame detection time and averaged detection time among 16 ion-probe in the same circumference position in tube axis direction. The position of relative flame front varies in ±0.4 mm. This is obviously larger than measurement error of 6.5-8.1 $\times 10^{-2}$ mm above mentioned. This deviation is 0.7% against the tube diameter of 58 mm. Detonation surface is quite planer and perpendicular to the tube axis.

Experimental result obtained by using 8x8 ion-probes are shown in fig.6 and later. Fig.6 shows the calculated velocities by flame detection time obtained by neighbor ion-probes in tube axis direction. Comparing with the velocity fluctuation measured by 16x4 ion-probes shown in fig.4, the range of fluctuation is larger, and its range is from -500 m/s to +1500 m/s against CJ detonation velocity. Because the installation interval of

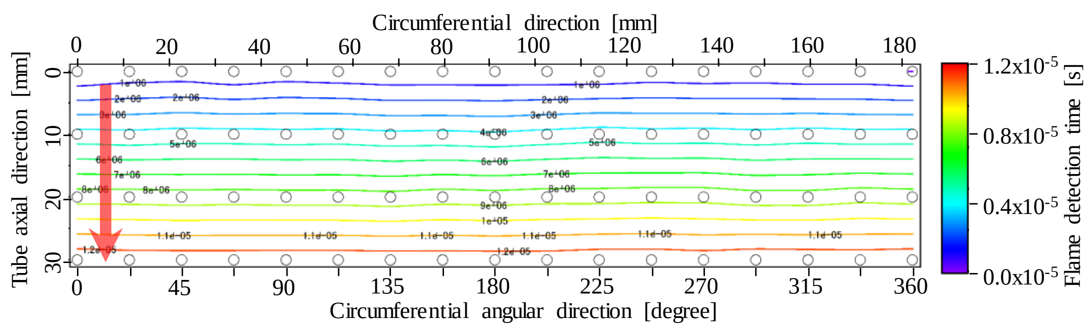

Figure 3. Contour map of flame detection time captured by 16x4 ion-probes

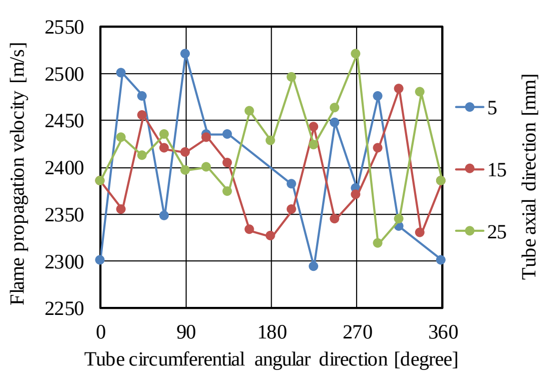

Figure 4. Local flame propagation velocity captured by 16x4 ion-probes

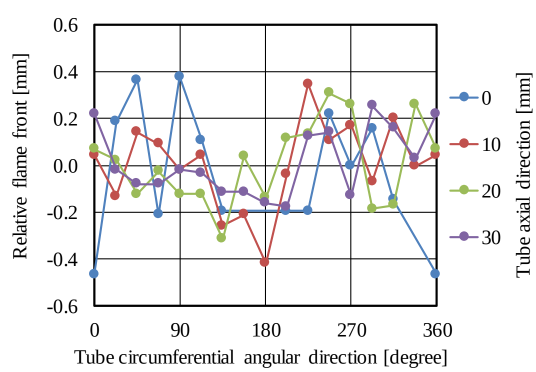

Figure 5. Position of relative flame front captured by 16x4 ion-probes

ion-probe in 8x8 ion-probes is smaller than that of 16x4 ion-probes, 8x8 ion-probes is more sensitive to spatially smaller scale of flame velocity fluctuation and results measured fluctuation large. Fig.7 shows the position of relative flame front calculated by same manner as fig.5. The position of relative flame front varies between ±0.4 mm and this is the same level as measured result by 16x4 ion-probe shown in fig.5.

To check the systematic error of the measurement, independent three experimental results of same experimental conditions were compared in fig.8 and fig.9. Fig.8 shows the comparison of measured velocity among three independent experiment. In this figure, two experimental results are able to be compared by putting velocity data of one experiment in horizontal axis and another in vertical axis. If velocity fluctuation is mainly caused by the characteristics of the measurement system, data points displayed in fig.8 locate beside the broken line. However, actual data points do not gather vicinity of broken line but locate randomly. This indicates that this velocity fluctuation is caused not by the characteristics of the measurement system, but by actual phenomena occurred at the measurement area by 8x8 ion-probes. Range of fluctuation is mostly from -500 m/s to +1500 m/s against CJ detonation velocity in all experimental results. Velocity deviation from CJ detonation velocity is large in positive side and vice versa. This may indicate that 8x8 multiple ion-probes capture the micro-explosion in detonation front[4]. Fig.9 shows the position of relative flame front among three independent experiment. The position of relative flame front varies between ±0.4

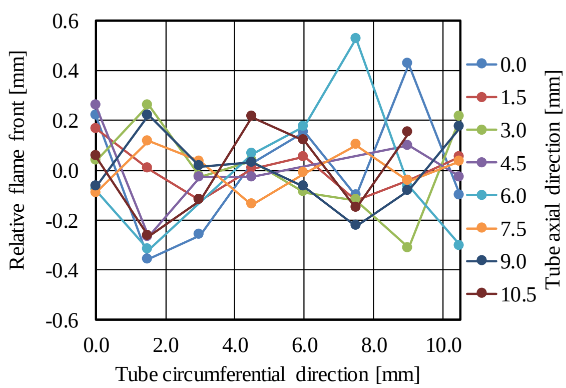

Figure 6. Local flame propagation velocity captured by 8x8 ion-probes

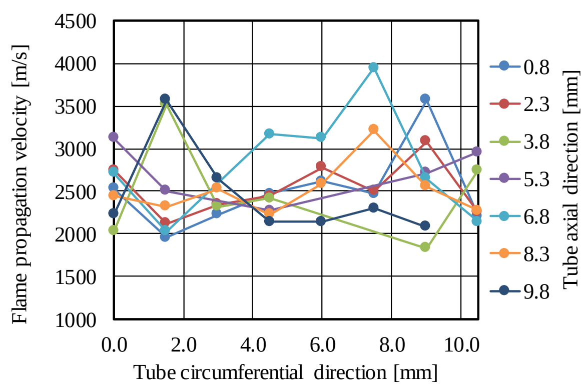

Figure 7. Position of relative flame front captured by 8x8 ion-probes

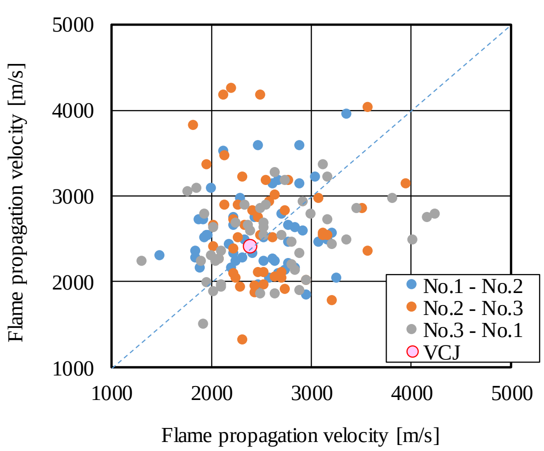

Figure 8. Comparison of local flame propagation velocity between independent experiments captured by 8x8 ion-probes

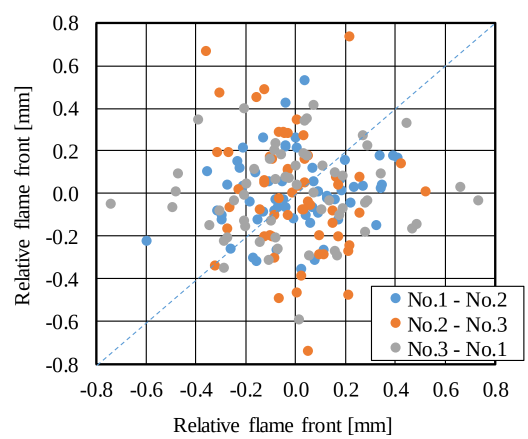

Figure 9. Comparison of relative flame front between independent experiments captured by 8x8 ion-probes

mm and the degree of deviation is almost the same in positive and negative side. In addition, the degree of deviation is the same level in all experimental results.

Figure 10 shows the combination of contour map of flame detection time, vector of flame propagation direction and absolute flame propagation velocity. These are drawn with calculation by interpolated data from cubic spline. Flame propagates from left hand side to right hand side in the figures. Contour lines shown in fig.10(a) have concavo-convex. Vectors of flame propagation in fig.10(b) shows that converging of the vector is more notable than diverging. This means that concavo of contour line is more notable than convex. The fig.10(c) of combination of absolute velocity and contour line shows that large absolute velocity occurs just ahead of contour line's concavo. This is also shown in fig.10(d) that large absolute velocity regions are located at converging region of vectors. These facts represent that some part of flame front decelerates firstly, and subsequently this part re-accelerates and catches up. The contrary is not obvious. This must be the traces of detonation cell structures caused by deceleration of shock flame decoupling and subsequent re-acceleration by micro-explosion.

Figure 11 shows soot-foil record obtained by the independent experiment with same experimental conditions. The scale of 10.5 mm shown beside the record is same length as one side of 8x8 multiple ion-probe. Fig.12

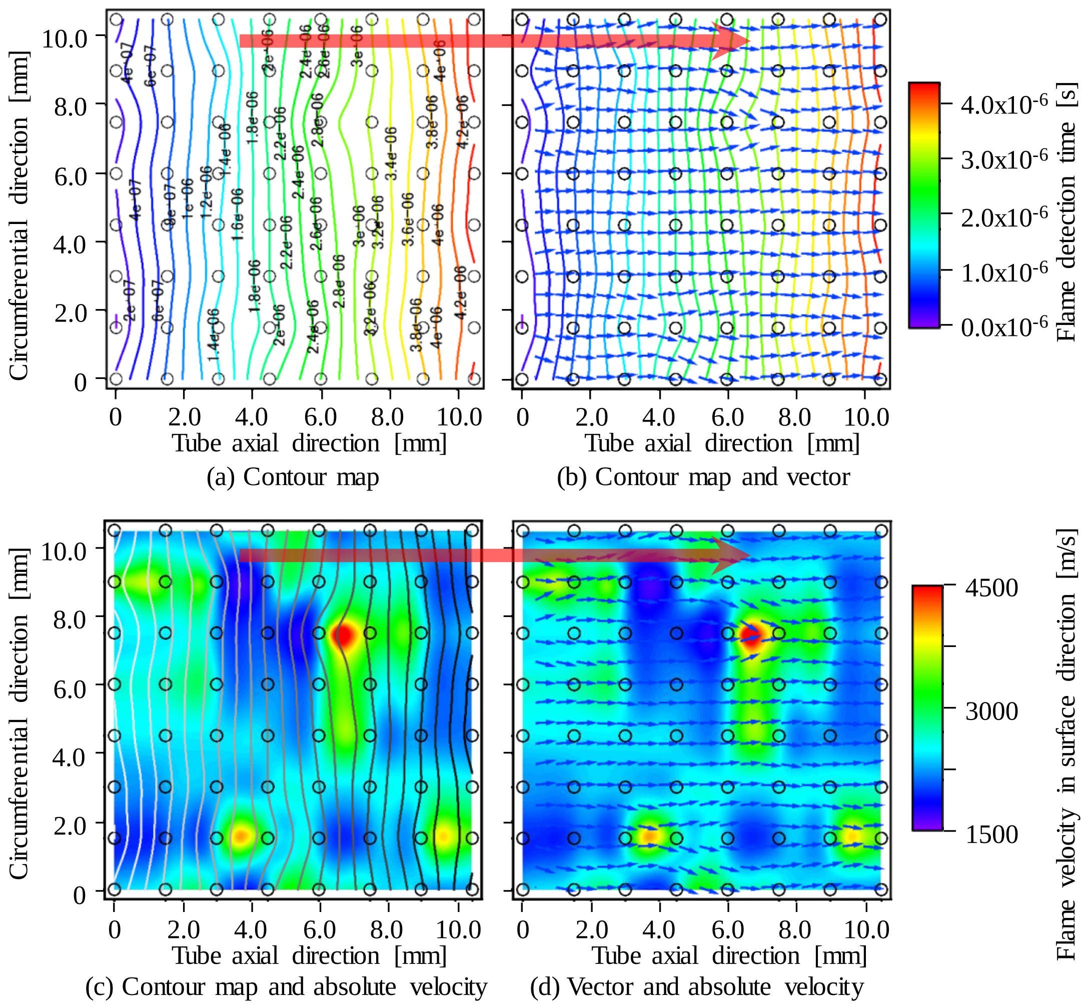

Figure 10. Regenerated local flame propagation behavior based on data captured by 8x8 ion-probes

shows the distribution of width and length of cells in the soot-foil record of identical experiment shown in fig.11. The cell size was measured with one person's eyes and the total number of measured cell was 406. Although previous study[5] says that the cell width at this condition is 2.4-3.0mm, measured cell width and length vary widely as shown in fig.12 and unclear boundary of cells are often observed in the soot-foil record. This indicates that position and strength of local deceleration and re-acceleration of detonation front are relatively irregular. The tendency of the irregularly corresponds to the result shown in fig.10.

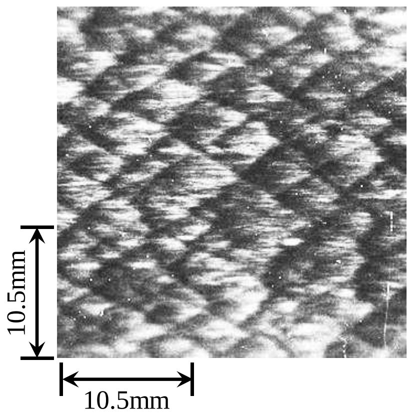

Figure 11. Soot-foil record of stoichiometric methane-oxygen detonation

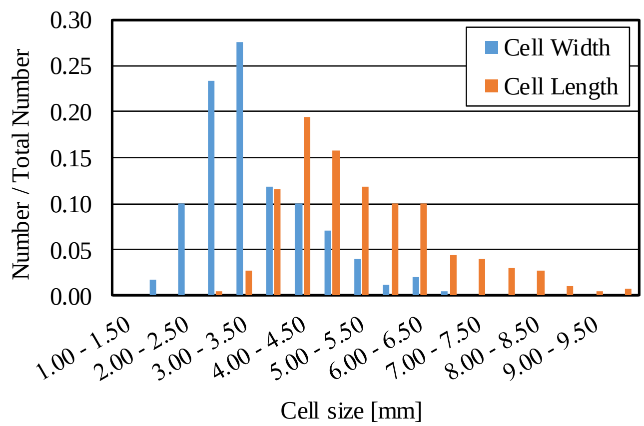

Figure 12. Distribution of cell width and cell length measured in soot-foil record

4 Conclusion

Well developed stoichiometric methane-oxygen detonation was measured by multiple ion-probes method. Convexo-concave of about ±0.4 mm was found in detonation front. The fluctuation of local flame propagation velocity measured by ion-probes with installation interval of 1.5 mm was from -500 m/s to +1500 m/s comparing with CJ detonation velocity. These convexo-concave of detonation front and the fluctuation of the velocity is considered to originate from detonation cellular structure. Trend of irregularity in the captured results by multiple ion-probes and soot-foil record were consistent.

References

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