Flame Behavior in Expanding Flow

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1 Introduction

A flame ejects through the opening of an enclosure when a fire source ignites combustible mixture in the enclosure [1]. The front of the ejected flame propagates in a combustible mixture of expanding flow. On the stretched flame front, the chemical reaction rate reduces. As the expanding flow develops, the circulation of ring vortex increases. These effects of flow field on flame propagation [2] were investigated using a model enclosure. Employing simultaneous two-point ignition, we studied a formed flame kernel ejected into an expanding flow. An optical system of schlieren with high-speed camera was used to record the expanding flow and flame front.

2 Experimental Apparatus

The open enclosure used in this study was fabricated using a 3D printer to form the flame kernel ejected into an expanding flow. Several models were used for the experiment. The models suffered structural damages during test runs owing to pressure and heat stresses. Figure 1 shows the model enclosure created from acrylonitrile butadien styrene(ABS). The thickness of wall was 10 mm. An opening was placed at the top of the model enclosure. The diameter of the opening was 40 mm. The separation between the upper and lower gaps was 177 mm. As the upper gap separated from the opening, the probability of ignition and the traveling time for the formed flame kernel increased. The upper gap was located 13 mm below the opening to fabricate observation of the early behavior of the flame. Steel wires of 0.5 mm diameter were used as the ignition electrodes to reduce flow field and flame shape deformations. An optical system of two 200 mm concave mirrors, an LED lamp, a knife edge, and a high-speed camera with a f1.2 58 mm lens was used to record the flame and flow behaviors at 100,000 frames/s and 236,000 1/s exposure. The size of recorded image was 320 pixel x 192 pixel. The knife edge was set horizontal to visualize the vertical density gradient.

3 Experimental Procedure

The internal volume of the model was 1.2 l. Ethanol(1 ml) was injected in the enclosure and a seal covered the opening for 10 min at 24 degree Celsius [3]. After the seal cover was removed, a piezoelectric device ignited the formed mixture at the upper and lower gaps simultaneously. The electromagnetic

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noise of electric spark triggered an LED lamp connected to a coherer [4]. The LED lamp was turned on by the spark and remained on until a mechanical shock turned off the coherer. The LED lamp connected to the coherer is shown in Fig. 2 as a spark indicator. The formed flame kernel developed with time and an optical system recorded the induced mixture flow and flame front. The high-speed camera started recording before ignition. After flame propagation, the high-speed camera was triggered to terminate the recordings.

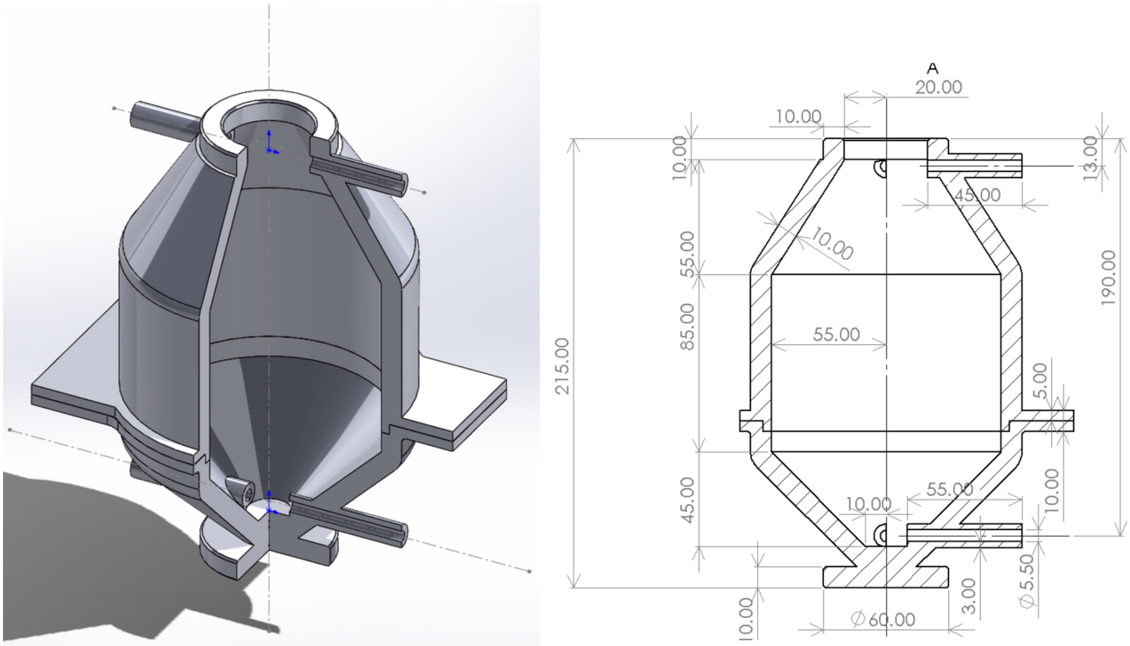

Figure 1: Model enclosure.

4 Results and Discussion

Figure 2 shows a series of schlieren pictures of the flame ignited at the upper and lower gaps. $t$is the time after the spark indicator was turned on. At t = 0, no mixture flow appears on the image. A shadow image of the model enclosure is depicted at the lower part of frame. The outer diameter of the opening area of model enclosure was 60 mm. At t = 5.39 ms, the ejected mixture and flame front appeared. The velocity of the leading edge of the flame was 2.4 m/s. At t = 8.75 ms, the ejected flame kernel had a mushroom shape owing to the strong ring vortex around the ejecting mixture. At t = 9.22 ms, the bottom of the flame kernel was nearly flat. At t = 9.92 ms, the rim of flame kernel spread to the center of the ring vortex. At t = 14.32 ms, the rim of flame kernel rolled around the vortex. A fine flame turbulence appeared on the inner surface of deformed flame kernel. The center of the leading and bottom flame front shifted upward. The flow direction at the center of ring vortex was upward and appeared to deform the flame shape. At t = 21.03 ms, a narrow mixture layer was observed near the leading flame front. The fine flame turbulence was stretched on the inner surface of flame. At t = 24.05 ms, most parts of ejected mixture was filled with combustion products. At t = 31.80 ms, the flame from the lower gap appeared with a smooth surface. The combustible mixture between the flame from lower gap and fine turbulent flame was heated from two sides.

Figure 3 shows the x-t diagram along the center of the opening. This figure shows 24 ms from the ignition. The height of this diagram is 115 mm. The leading edge of flame front appears as a line. The leading edge traveled at a constant velocity, and the deceleration in expanding flow was compensated

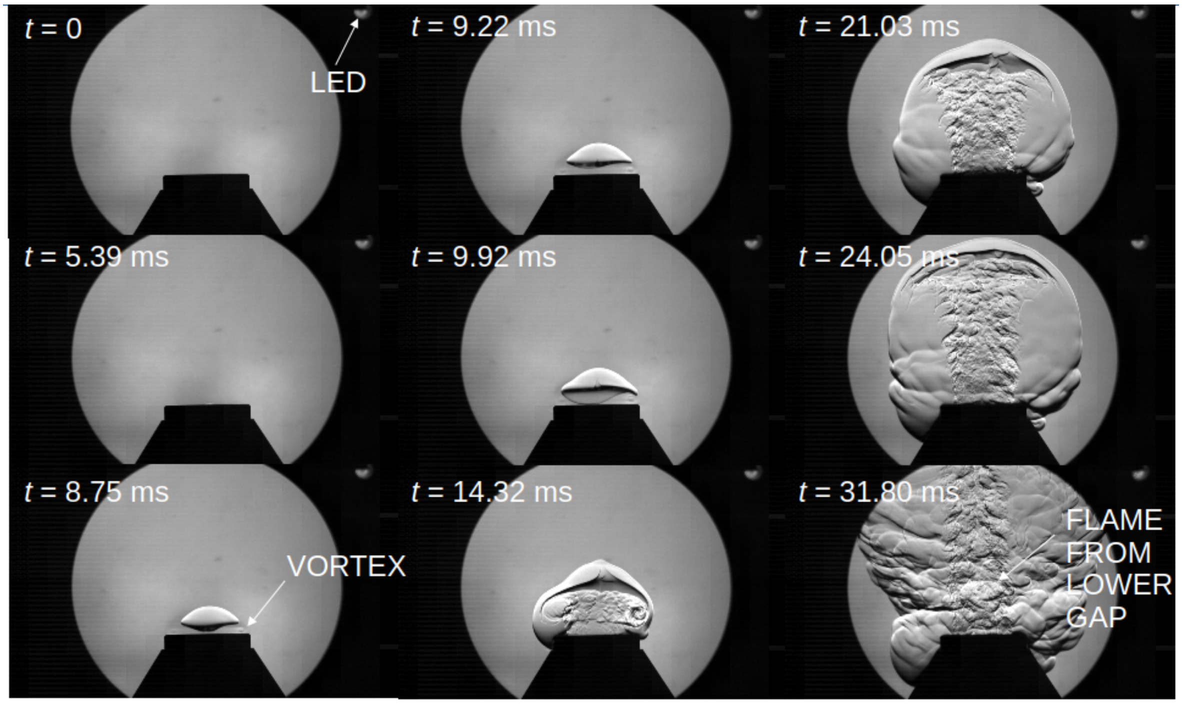

Figure 2: Flame shape change.

for the gas expansion of the combustion product. The trace of bottom of flame kernel was accelerating at about t = 20 ms. Based on the traveling distance from the upper gap to the upper boundary of frame, the leading flame front propagated at 4 m/s. Curved lines of a downward moving flame also appear in this figure. These downward lines were the lower edge of the mushroom-shaped flame. The fine upward curved lines indicate the fine flame turbulence. The flame front turbulence appeared from the opening and disappeared as the combustible mixture burned at the flame front.

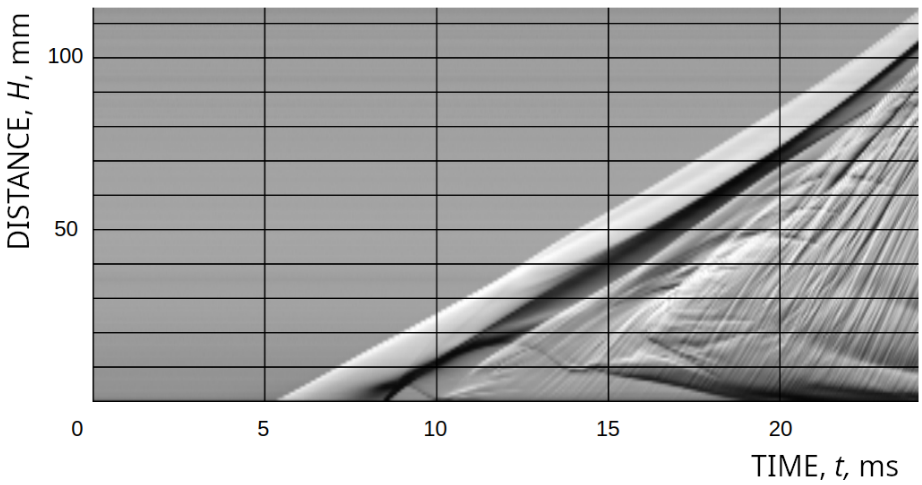

Figure 3: x-t diagram.

Figure 4 shows an enhanced image of ring vortex in the combustible mixture. This ring vortex was recorded for an ignition failure at the upper gap. The combustion product of the flame ignited at the lower gap expanded and ejected the combustible mixture. The upper part of the ring vortex was uniform, whereas the lower part was turbulent. Compearing with Figure 5, the deformed flame kernel propagated through the uniform upper part, whereas a fine turbulent flame appeared in the lower turbulent part. A line appeared along the center of ring vortex where the flame deformation was large. The voyancy effect of the low-density combution product accelerated the upward movement. This movement resulted in the additional flame stretch that lowered the chemical reaction rate. A fine turbulence of the combustible mixture flow appeared around the opening.

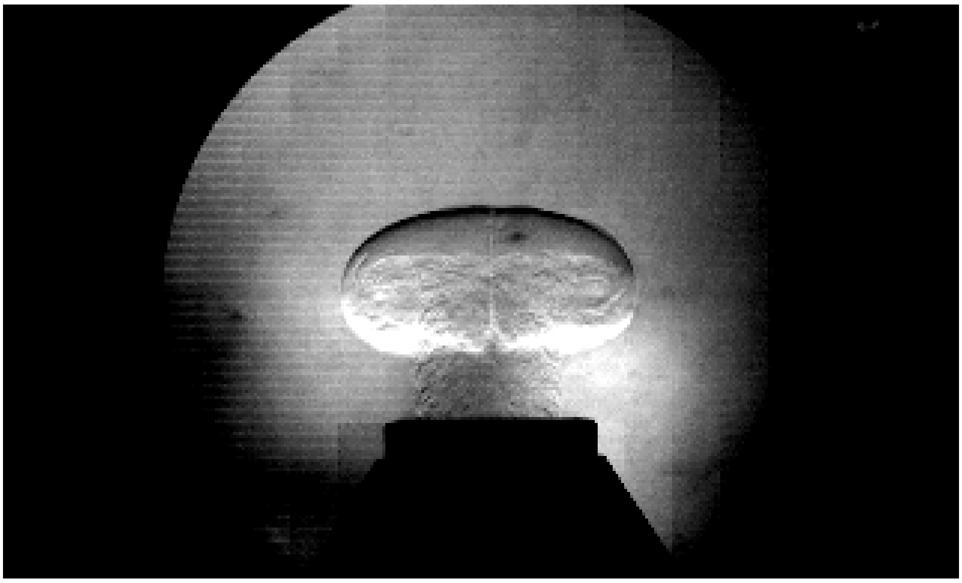

Figure 4: Ring vortex in the combustible mixture.

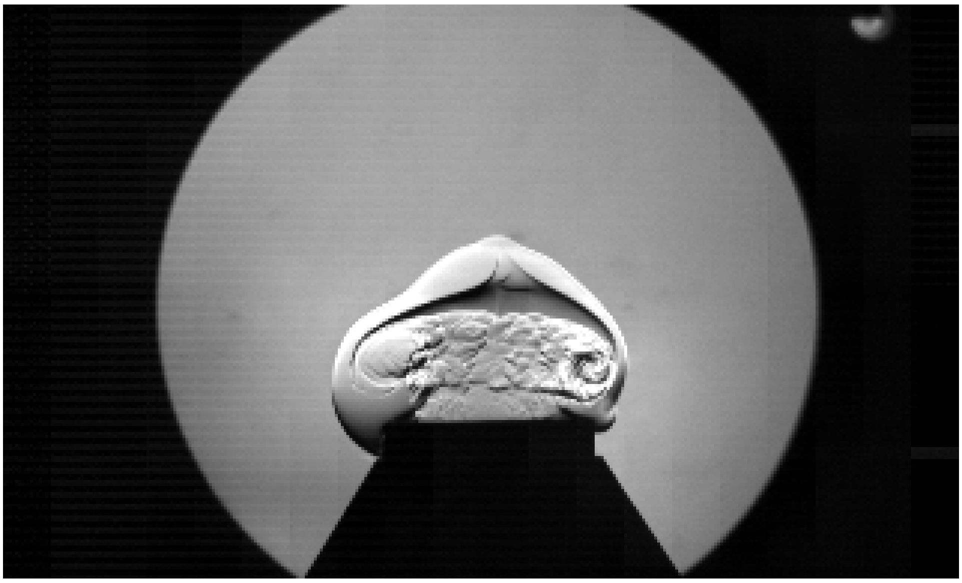

Figure 5: Flame shape at t = 14.32 ms.

Figure 6 shows flame shapes at t = 33 and 51.5 ms. The combustible mixture between the flame from the lower gap and fine turbulent flame was heated from two sides. The fine structure in the flame disappeared at t = 51.5 ms at the upper part of the frame indicated with a dotted circle. The fine structure in the flame was observed at the lower part of the frame.

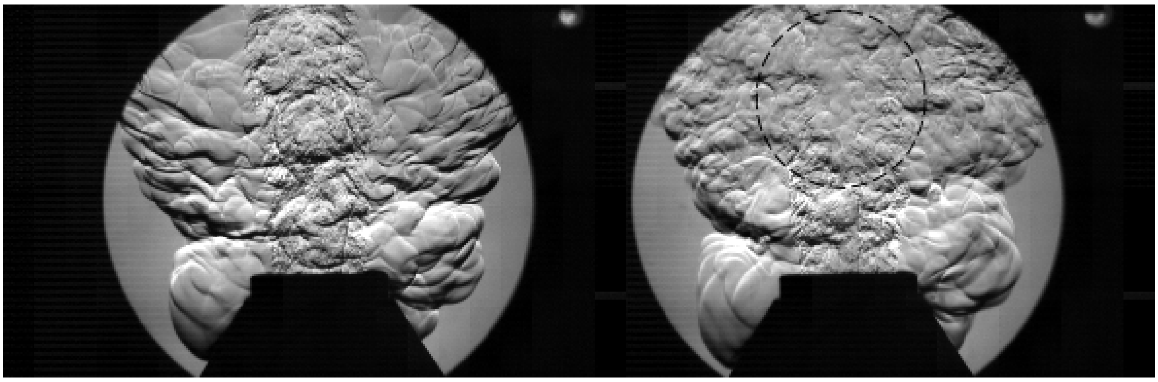

Figure 6: Flame shapes at t = 33 and 51.5 ms.

5 Conclusions

Employing simultaneous two-point ignition, we studied a formed flame kernel ejected into an expanding flow. The ejected flame kernel has a mushroom shape owing to the strong ring vortex in the ejecting mixture. The upper part of ring vortex was uniform, whereas the lower part was turbulent. The deformed flame kernel propagated through the uniform upper part, whereas the fine turbulent flame appeared in the lower turbulent part. A line appears along the center of the ring vortex in which the flame deformation is large. The voyancy effect of the low-density combustion product accelerated the upward movement. This movement resulted in the additional flame stretch that lowers the chemical reaction rate. A fine turbulence of the combustible mixture flow appears around the opening. The combustible mixture between flame from lower gap and fine turbulent flame is heated from two sides.

References

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