Visualization for local flame quenching recovery mechanism by vortex interaction

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Abstract Local quenching phenomena occurs frequently in a turbulent combustion. In order to elucidate the local quenching phenomena by experimental approach, non-intrusive 3D optical diagnostics with time series data are powerful measurement technology. However, the 3D optical measurement costs too much and is not completely established. The important things to succeed the complicated combustion phenomena studies with limited funds are to use a simplified and a reproduced model flow deal with a 2D non-intrusive measuring method. Therefore, in this study, we proposed a wall impinging flat flame quenched with a periodical pulsating cold air jet to reproduce local quenching phenomena. A time series 2D laser tomographic flow visualization and a particle image velocimetry (PIV) are used as the flow visualization device. The flat flame is bent by the impacting air jet. Then the flame receives the bending strain and the flow divergence strain effects, simultaneously. The effective stain rate for the quenching trigger was defined as a sum of bending strain rate and flow divergence strain rate. The flame front locally quenches the effective strain rate exceeds than the laminar flat flame extinction strain rate. However, the local quenched flame is not necessarily developing to the whole flame extinction. The quenched flame can recover with the vortex induced local quenching recovery motion. The time series of the conditional sampling tomographic movies clearly visualized the decisive quenching recovering moment by the vortex motion. Then, the propagation speed of the quenching flame edge and the incoming speed of the unburnt combustible gas balance plays a key role for the quenching recovering mechanism.
Keywords: Combustion, Local quenching, Laser tomography

1 Introduction

Flame is a thin reacting zone of fuel and oxidizer. The reaction zone thickness is basically less than 100 micrometers for a premixed combustion. In a turbulent combustion, the reaction zone is bent by the turbulence. The part of flame front locally quenches due to strain induced by the turbulent motion, heat loss to the cold wall or gases and other external force. The local quenching phenomena will lead to combustion instabilities [1], [2]. In the worst case, the local quenching will be developed to whole flame extinction event. On the other hand, there is an advantage in the turbulent combustion. For example we reported that the whole flame extinction limits for turbulent premixed flames can be extend than laminar flame extinction limits [3], [4]. In the experiments, we tested four different turbulent conditions. The results were highest turbulent intensity and smallest scale of turbulence condition marked best results to extend the extinction limit better than laminar limits. Contrary in the weak and large scale of turbulence condition, the extinction limits marked lower than the laminar limits. Also some workers for the turbulent combustion including us recognized the local quenching phenomena especially in the wrinkled laminar flame regime. Up to now a lot of studies have been performed to elucidate the local quenching mechanisms. The methods are mostly a direct numerical simulation [5]~[7] or an optical laser diagnostics [8]~[13]. Actually if directly using a laser diagnostics to investigate a turbulent flame, three dimensional optics is the best method. However, three dimensional non-intrusive optical measurement system are extremely expensive devices and not perfect accuracy. Even if using a two dimensional optical measurement system, to use an appropriate flow model the mechanism of the local quenching and recovering phenomena can be possible to elucidate.

Therefore, in the present study, we propose a simplified flow model with a two dimensional laser optical diagnostics to elucidate the complicated local quenching phenomena in the turbulent combustion. The priority for the experimental burner system are a possibility to reproduce the local quenching and recovery periodically. The priority for the laser optical diagnostics are to identify when and where the local quenching start. Our proposed experimental model is a flat disk shaped premixed flame formed in an inverted stagnating flow with pulsating air jet. The flame is quenched by the pulsating jets driven by a loud speaker. The input signal to the speaker is a sine wave. The center of the flame is locally quenched due to the jet impacting. This experimental model can repeat the local quenching and recovering for the each cycle of the pulsating jets. The problem in this experiment is that we are using the Mie scattering visualization method. The Mie scattering method is difficult to precisely judge the quenching moment. Because Mie scatter tomography image can identify only hot and cold boundary. Even when the flame is quenched locally, the image still shows the hot and cold boundary. In order to overcome the disadvantage of the Mie scattering visualization method we use the conditional

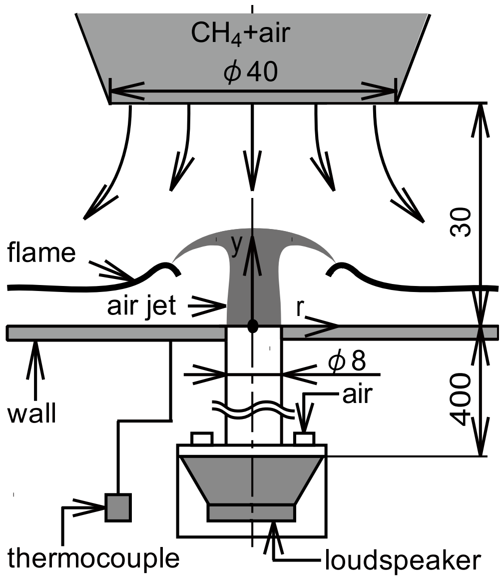
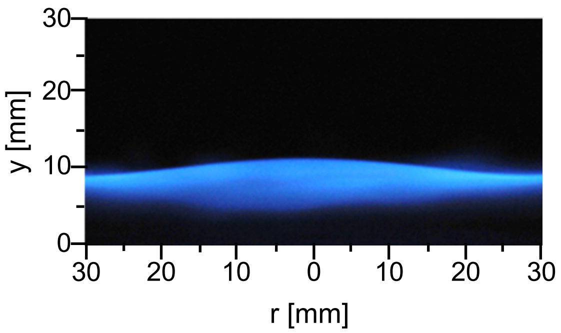
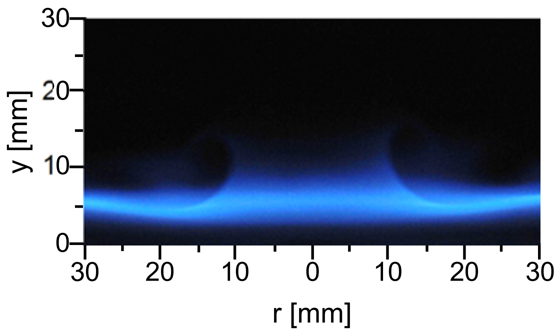


Fig. 1 Experimental setup.



(a) No local quenching.



(b) Local quenching.

Fig. 2 Direct photos.

sampling and image synthetic method will also adapt.

2. Experimental setup

Figure 1 shows the burner system. The burner system consists by two module. The upper side module is the inverted nozzle burner module having 40mm exit diameter. The lean methane air premixed gas issues this burner. In order to minimize the turbulence by shear stress between the gas flow and the surrounding, the secondly air flowing nozzle having 5mm over size ringed with the main nozzle. The uniform velocity profiled laminar gas flow impinges to the steel flat wall 8mm thick and a disk shape flat flame formed in this stagnating flow field. The mean velocity of the mixture sets 2.4m/s and equivalence ratio (φ) range are from 0.7 to 1.0. The wall and pulsating jet module sets in the lower side. The pulsating air jet located in the center of the wall is driven by the loud speaker. The speaker sets at 400mm downstream from the wall surface. The pulse frequency set at f=20Hz. The wall temperature is monitored by K type thermocouple which installed in 3mm deep from the wall surface and 10mm offset from the center. The set temperature is 300±50℃. The pulse intensity (u') is defend as the difference from maximum to minimum velocity of the air jet measured at y=2mm and r=0mm by a hot wire or a cross correlation particle image velocimetry (PIV). The used laser for the PIV is a 30mJ per pulse at 532nm emission energy Nd YAG laser. For the time series of visualization, a 4w Argon-Ion laser coherent inover-70 is used in the case of the time series of laser tomography. For tracer particles, 1 micro meter diameter of alumina particles or silicone oil droplets with vaporizing temperature 300℃ are used.
Figure 2 (a) and (b) show the direct photograph for the no local quenching flame and the flame with quenching hole by the pulsating jet respectively. The no quenched flame clearly identified the flame shape is almost similar with the flat disk shaped flame formed in the stagnating flow. On the other hand in the local quenching flame, the center of the disk shaped flame has a quenched hole which opens by the pulsating air jet penetration.

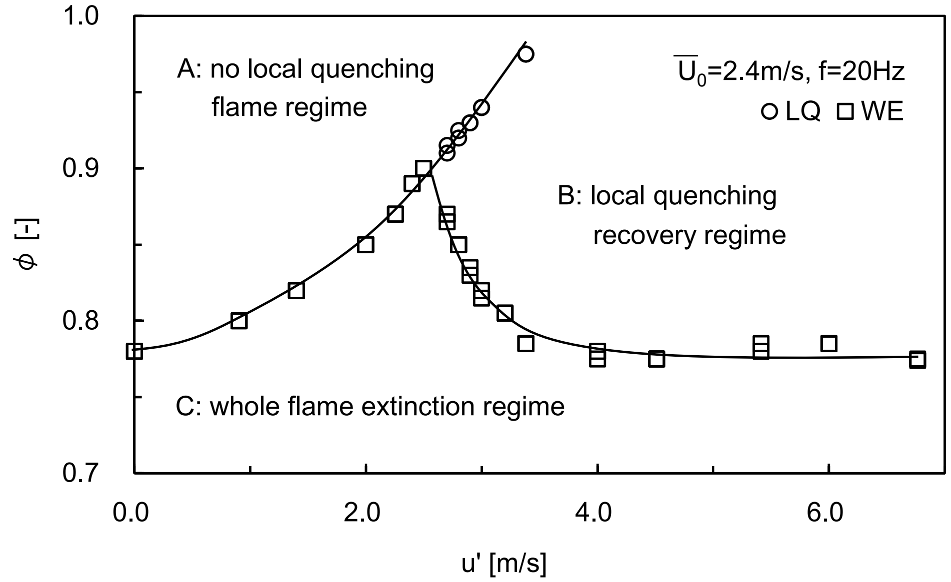


Fig. 3 Local quenching (LQ) and whole flame extinction (WE) boundaries for pulsating air jet intensities.

3. Results and Discussions

3.1 Local quenching and whole flame extinction regimes

Figure 3 shows the flame regimes of the no local quenching flame, local quenching and recovering flame and the global extinction. As shown in this figure, the regimes divide into three regions. In the A-C boundary that is the pulsating air jet intensity (u') up to about 2.6m/s, the whole flame is directly extinguished from the local quenching. On this boundary, the local quenching flame never recovers from the local quenching event. This means that once the local quenching occurs in the center of the flame. In the next moment the local quenching region develops to the end of the disk shaped flame. Then, the whole flame extinguishes. In the local quenching and recovering regime B, even though the flame is locally quenched by the air jet impacting, the quenched hole is possible to recover from the local quenching event. In the every pulsating cycle, quenching and recovering events may periodically repeated in this regime. Below the B-C boundary, the local quenching flame dose not recover from the event as same as the A-C boundary. The trigger of the local quenching mainly occurs by the flame strain due to flow divergent of premixed gas flow plus the flame strain due to the flame curvature [14].

3.2 Local quenching process

Figure 4 shows the local quenching process. The local quenching process is discussed by four type of time series images for the first half of one cycle flame motions with the pulsating jet. The flow conditions for the main premixed gas are φ=0.95 and U_0=2.4m/s. The maximum pulsating jet intensity are u'=3.38m/s and the frequency of the jet is f=20Hz. The series (a) in left side of figure 4 are direct photos using a digital steal camera (Nikon D4). The angle of the camera has at 10 degree to the horizontal plane. The series (b) in mid-left images show two dimensional laser tomography images. In this case, the fine alumina particles about 1 micrometer are used as the seeder. The seeding particles are added only in the premixed gas side. No particles are added in the pulsating gas side. The series (c) in mid-right images show the conditional sampling tomography images. In order to visualize only the cold air jet formed by the pulsating jet nozzle, silicone oil droplets are used as the seeding particles. And those are added only in the pulsating jet flow. The boiling point of the silicone oil is 300 degree Celsius. Therefore the silicone oil droplets is evaporated by impacting the high temperature burnt gas. And it can visualize the isothermal boundary between the burnt gas and cold air. If the part of the visualized cold air heated by the high temperature gas, the droplets in heated air must disappear in there.

In the Fig. 4 (a) t=0ms, the flame location (y_f) becomes minimum point in the cycle and the jet velocity is also minimum. Even if in the minimum condition, the flame has slightly convex curvature to the unburnt gas. Since the jets has 0.3m/s of average velocity in order to maintain the fresh air in the jet generating chamber. At (b) t=3ms, the center of the flame r=0mm is swollen because of the jet Impact. Images of (b-2) and (b-3) show right after the jet injection. Images of (c) at

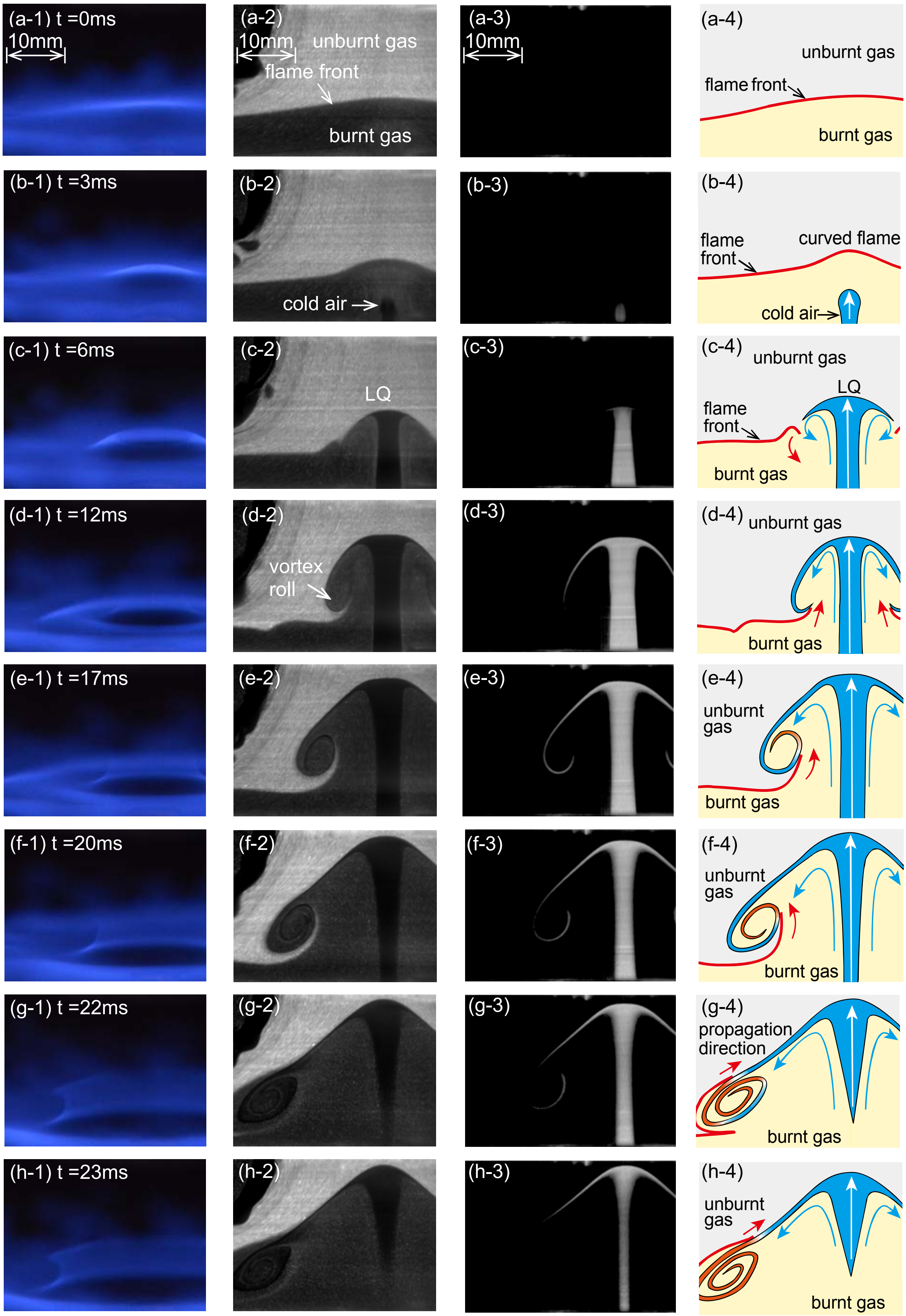
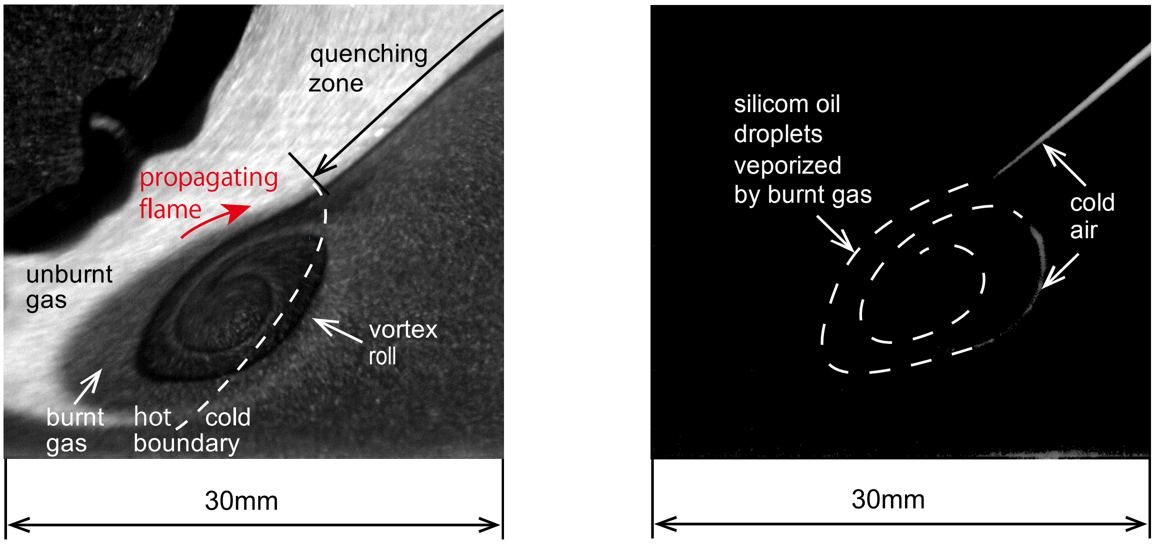


Fig.4 Time series images of the process to local quenching. (U_0=2.4m/s, ϕ =0.95, u'=3.38m/s)



(a) Alumina tracer suspend in the premixed gas side

(b) Silicone oil droplets suspend in the air side.

Fig.5 Close up images of the structure at the local quenching process switching to the recovering process.

t=6ms shows just after the jet penetrates the center of the flame. Images (c-2) and (c-3) clearly indicate the edge of the air attached to the unburnt gas. Those images become evidence that the cold air jet impacting is a trigger for the local quenching. The impacted cold air jet forms a mushroom shape and the mushroom is developing as shown in images from (d) to (f). The direct photo (d-1) shows the blue flame disappears in the center. The quenching hole is also identified by this image. To see images (d-2) and (d-3), it is confirmed that the cold air cut into the flesh mixture and the squashed air is forming a thin sheet and spreading to the outer side. In the end of the quenching hole corresponding with the edge of the spreading air sheet, the vortex roll is forming. In the next images (e) t=17ms, the quenching hole is further developing. The cold air edge leads into the burnt gas with rolled motion as shown in the image (e-2). The image (e-3) shows that the edge temperature is still keeping below the silicone oil droplet vaporization point. In images (f) the vortex roll keeps developing and the vortex structure becomes a Swiss-roll. The double vortex roll can be observed in the image (f-2). However in the image (f-3), the inner part of the double rolled air vortex cannot be identified. This means that the cold air is probably heated by the high temperature burnt gas. The residence time was probably sufficient to preheating the cold air. This is the evidence that the temperature of the inner roll should became higher than the silicone oil droplet vaporization point. Those tendency become clear in images (g). As shown in image (g-2) the vortex roll is transported to outer side by the spreading flow. In the part of the outer vortex roll and the inner, the silicone oil droplet are disappeared. This points the turning point for the flame recovering from the local quenching.

3.3 Detail structure at the turning point

Figure 5 (a) and (b) show close up images from Fig. 4 (g-2) and (g-3). As discussed in the end of the previous section, those images show the turning point the local quenching process is switching to the recovering process. In Fig. 5 (a), it is clear that the quenched edge is the end of the quenching zone. After the edge the unburnt zone and burnt gas zone is clearly visualized as the reduced number density due to the thermal expansion. Figure 5 (b) shows silicone oil droplets in the half of the vortex roll are disappeared by the burnt gas. The vortex rotating direction is counter clockwise in this figure. Therefore, the high temperature burnt gas is supplied by the vortex. The motion supports the flame propagation. In other words, the vortex roll plays a key role for the local quenching mechanism.

3.4 Quenching recovering process

Figure 6 shows quenching recovering process for the latter half of the one cycle of the pulsating jets. Images (h) are same as discussed in previous section. As shown in images (h), the vortex roll drifts to the main flow divergence. The edge flame is propagated into the quenched hole and the quenched hole is shrinking as shown in (h) to (l). As shown in the time series images of the silicone oil droplets from (g-3) to (k-3), Mie scattering image disappeared at the t=40ms (k-3).

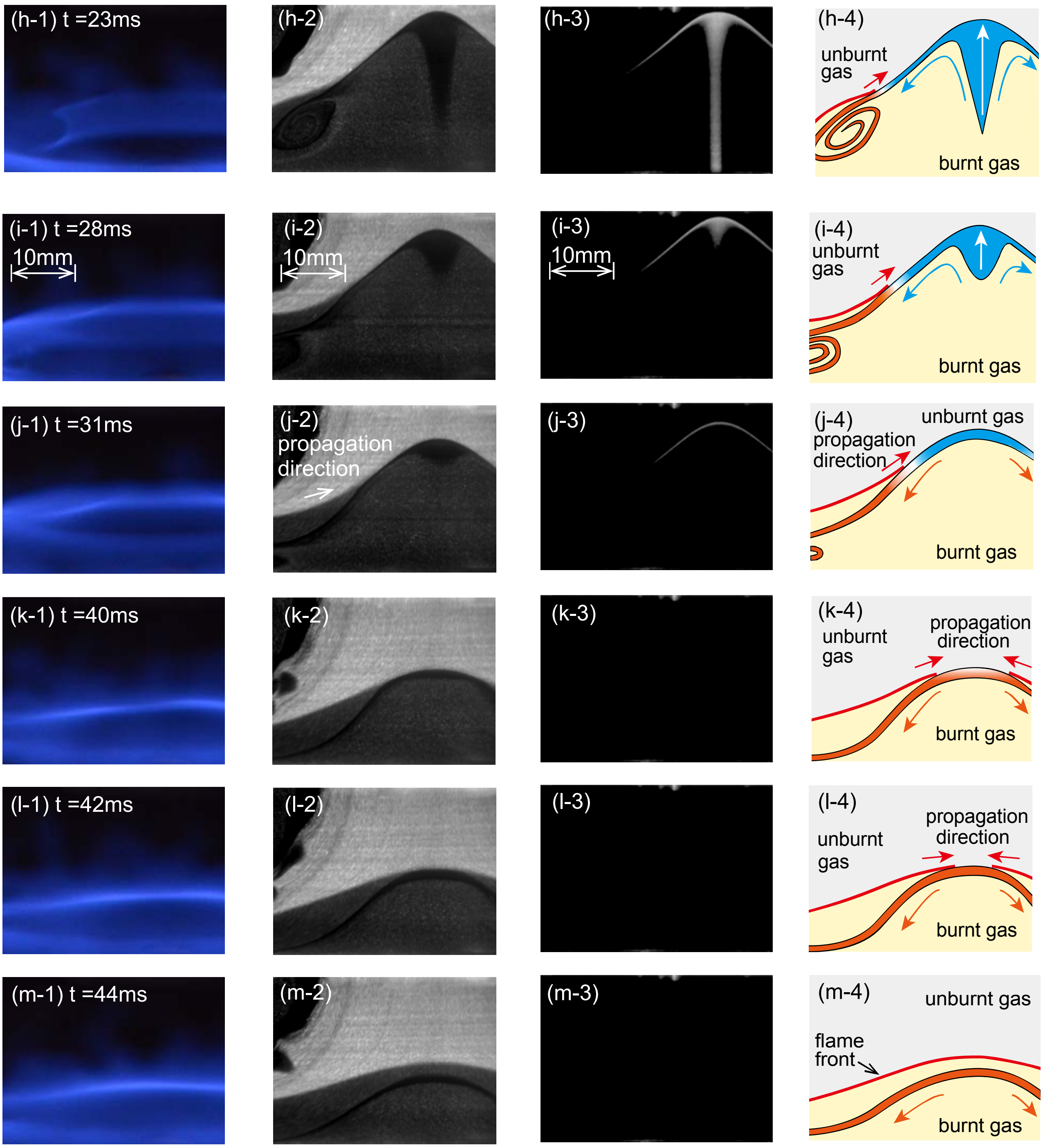


Fig.6 Time series images of the process of recovering from local quenching. (U_0=2.4m/s, ϕ=0.95, u'=3.38m/s)

However, as shown in (k-2), the cold air is touching with the unburnt gas in the flow center. This shows that the attaching region corresponds with the quenched hole. The end of the local quenching event can be judged by comparing two different tracer laser tomography images. The propagating edge seems to be a cutter or a peeler for the joint surface of the unburnt gas and the cold air. Finally, the propagating flame edge fills up the hole as shown in images (m).

4 Concluding remarks

The local quenching and recovering process for the lean premixed flat flame formed in the wall stagnating flow. The quenching is triggered by the pulsating cold air jet impact and the processes are discussed using the time series of tomographic images.

The center of the flat flame local quenches by the pulsating air jet. The quenched hole develops until approximately the main flow nozzle size. In the quenched flame edge, Swiss roll type vortex is formed and this vortex roll plays a key role to turning the quenching development. The vortex roll transports the high temperature burnt gas to the cold gas and it helps to reform the new flame zone. The edge of the new flame propagate into the quenched zone. The edge flame propagating works as a peeler to remove the cold gas enveloping the unburnt gas. Finally the flame recover from the local quenching.

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