Local quenching phenomena of a lean premixed flat flame impinging with a pulsating air jet

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Abstract. Local quenching phenomena of a lean methane air premixed flat flame formed horizontally in a wall stagnating flow impinging with a pulsating air jet has been investigated experimentally. The burner system consists of 40mm inverted nozzle burner and a solid wall with 8mm diameter air jet placed in line vertically. The pulsating frequencies set up to 100Hz while the jet intensities generate up to 6 m/s by a loud speaker. Approximately 100mm disk shape flame front is curved by the pulsating air jet and the air jet impacting point is locally quenched. The fuel concentration of quenching start condition increases with increasing the intensity of air jet, because the increased jet intensity linked with the flame strain rate gain. For weak jet intensity range, the quenching hole becomes directly to develop the whole flame extinction. On the other hand, for moderate or strong jet condition, the flame can recover from the local quenching phenomena. In this condition, once the quenching hole creates, but the hole may close by the flame propagation or reigniting process. Then, the whole flame extinction limits are lower than no jet impacting condition depending on the circumstances.

1. Introduction
A part of flamelet locally quenching phenomena namely local quenching occurs in a turbulent combustion. Especially, in the lean combustion, the local quenching possibility increases with increasing lean burn rate. A flame strain due to flame front curvature or velocity gradient, and heat loss to the cold wall are major trigger for the quenching [1]. The local quenching induces unburnt gas emission and also causes for unstable combustion [2]. Those are typical negative factors for the lean combustion with the local quenching. Introducing the local quenching phenomena including that of recovering can be great interest for persons working in the turbulent combustion. However, quenching and recovering mechanisms are very complicated phenomena since those occur in the three-dimensional and are difficult to predict in time and space. Up to now, the local quenching possibility increases with approaching the whole flame extinction condition [3]. Local quenching may not directly trigger to the global extinction depending on the circumstance [1], [2], [4]. Most of case, the locally quenched flame can recover and the continuous flame front recreates. As our focusing points, first question is what the primary trigger for the local quenching is. Second question is how the flame can recover from the local quenching. In the previous study of the wall stagnating turbulent premixed flame, we used 4 stages of turbulence generator for different Lewis number premixed gases such as lean propane air and lean methane air. On one hand, in the weak turbulence condition the whole flame

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extinction equivalence ratios are higher than the laminar flame extinction, but on the other hand, in the
strong turbulence condition those are lower than the laminar [5], [6]. In addition, those phenomena are
clearly noticed for the lean methane air flames. The results show an interesting paradox, because the
turbulent flame receives additional flame strain effect by the flame having a curvature, so intuitively a
turbulent flame more extinguishable than a laminar flame. The question what the mechanism works to
extend the whole flame extinction for such kind of turbulent condition. However, in those studies, the
discussions have been concluded from averaged data.

In order to elucidate the local quenching phenomena changing in the position at every moment, a
time series analysis of detailed flame structures are important issues. As advanced recent studies, three
dimensional LES [7] and DNS [8], [9]or high speed laser diagnostics for example PLIF and three
dimensional PIV combined technique [10]–[13] adapt for the local structure of turbulent combustion.
However, it is quite hard to reproduce the same phenomena as before.

As one of the approach, we proposed a simplified experimental model for the local quenching and
recovering phenomena. The important priority matter for the model are to reproduce the...
local quenching position and time. Our proposed model is a lean premixed flat flame impinging with a pulsating air jet perpendicularly in order to re-create simplified quenching phenomena as an experimental model for turbulent combustion.

2. Experimental setup

Figure 1 shows the burner system. The burner system consists by the inverted nozzle burner module in the upper side and the pulsating air jet in the lower side. The lean methane air premixed gas from the inverted nozzle burner having 40mm exit diameter impinges to the 8mm steel flat wall and formed the flat flame in the stagnating flow field. This nozzle has dual nozzle structure which consists a main nozzle for combustible gas and a ring shape secondly air flowing nozzle having 5mm ring width to minimize turbulence due to shear stress. The flat velocity profile methane air lean premixed gas impinges to the flat plate. The mean velocity of the mixture sets 2.0m/s and equivalence ratio ($\phi$) range are from 0.72~0.85. At the lower part, the pulsating air jet sets on the center of solid plate. The pulse generates by the loud speaker set up 400mm downstream form the wall surface. Flow structures are obtained using a particle image velocimetry. Fig. 2 show the direct photograph with 1/40s shutter speed and the flows image respectively. In the no air jet condition, a typical stagnating flat shape flame formed parallel to the wall. With the pulsating air jet, the flame has a concave curvature to the unburnt gas due to the jet impinging as shown in Fig. 2 (a). Figure 2 (b) shows the local quenching flame photo and flow image. In this case, the concaved flame top locally quenches. From the quenching hole, the air jet probably impacts to the unburnt gas directly. The wall temperature is measured by K type thermocouple which installed in 3mm deep from the wall surface. The measured temperature is set at $300 \pm 50^\circ$C and the measuring point is $r=10$mm. The pulse intensity ($u'$) is defined as the difference from maximum to minimum velocity of the air jet measured at $y=2$mm and $r=0$mm by using a hot wire or PIV. The pulsating jet frequency set up to 100Hz. The local quenching phenomena (LQ) is visualized by laser tomography images. As tracer particles, 1 micro meter diameter of silicone oil droplets with vaporizing temperature 300°C is used for the premixed gas side, while same diameter of alumina particle for the pulsating air jet side. Then two boundaries such as the premixed flame front and the impinging surface can be identified. The judgment of the LQ is when the premixed side Mie scattering image touches with that of image by the pulsating air jet coming from the lower side. The two dimensional instantaneous velocity is measured by a cross-correlation particle image velocimetry having a 30mJ per pulse at 532nm emission energy Nd YAG laser.

3. Results and discussions

3.1. Flame front movements

Figures 3 (a) and (b) show the high speed tomographic movies for one cycle of the flame motions. The conditions are $\phi=0.8$ and $f=20$Hz, where first image, $t=0$ms corresponds with the flame front position ($y_f$) come to minimum in the cycle. The difference between (a) and (b) are the intensity of pulsating air jet ($u'$). In the no LQ condition shown in Fig. 3 (a), the flame front synchronies with the jet. The air jet forms a mushroom shape flow pattern to impact the flame. The flame front bends and moves as an up and down motion. On the other hand, in the $u'=4.6$m/s shown in Fig. 3 (b), the air jet inertia force is stronger than $u'=1.6$m/s shown in Fig. 3 (a). Therefore the flame front bending motion and its amplitude are strong. At $t=12$ms, the air jet penetrates the flame front. In a moment, the air jet attached with the unburnt combustible mixture. The local quenching zone shown as a dotted line spread widely into the flame front. Then, the end of the mushroom shaped impacting jet formed axisymmetric vortex roll (see $t=24$ms). In the next, at $t=36$ms, the vortex roll disappeared. The flame seems to be recovering from the local quenching phenomena. In the images from $t=36$ms to $t=0$ms, the remaining air from the jet are still attaching with the unburnt mixture. It is hard to judge the flame completely recovers from the local quenching phenomena in this case. However, it is certain that the local quenching never develops to the global extinction. Those kinds of the local quenching and the
recovery phenomena are repeating on every cycle. The quenching area increases with decreasing the equivalence ratio. Finally the flame cannot recover from the local quenching event.

Figure 3. High speed tomographic movies for one cycle of the regular flame motion and the flame with local quenching and recovering motion (f=20Hz, \( \phi = 0.8 \)).
3.2 Global extinction and local quenching

Figure 4 shows the flame regimes of the stable flame, the local quenching and the global extinction. Basically, the local quenching starting equivalence ratio almost lineally increases with increasing the pulsating air jet intensity \( u' \). For the weak \( u' \) condition, the local quenching line and the global extinction line overlap in the range of \( u' \) up to about 1.5 m/s. This indicates that the local quenching becomes directly to develop the global extinction. The flame has no chance to recover from the local quenching in this regime, namely direct global extinction mode. On the other hand, for \( u' \leq 1.5 \) m/s, the overlapped global extinction line branch off from the local quenching line. From this branch condition, the local quenching flame dose not directly become the global extinction. The flame can recover from the local quenching as described in Fig. 3 (a). The branched global extinction line shows getting low with increasing the \( u' \). And finally the equivalence ratio of global extinction line pass the laminar flame extinction equivalence ratio shown as the dotted line. This means that the disturbance flame has a potential to improve than the laminar flame in some cases.

Figure 4. Flames map for stable flame regime, local quenching regime and global extinction regime for \( f=20\text{Hz} \). The dotted line indicate the laminar flame extinction limit for this burner.

Figure 5. Flame front responsibility for pulsating jet intensity \( u'=1.6 \) m/s. \( V_i(t) \) indicates input voltage of the loud speaker and the flame location \( (y_f) \) corresponds as the distance from the exit of air jet to the center of the flame front.

(a) \( f=20\text{Hz} \).

(b) \( f=60\text{Hz} \).

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Figure 4 shows the flame regimes of the stable flame, the local quenching and the global extinction. Basically, the local quenching starting equivalence ratio almost lineally increases with increasing the pulsating air jet intensity \( u' \). For the weak \( u' \) condition, the local quenching starting line and the global extinction line overlap in the range of \( u' \) up to about 1.5 m/s. This indicates that the local quenching becomes directly to develop the global extinction. The flame has no chance to recover from the local quenching in this regime, namely direct global extinction mode. On the other hand, for \( u' \leq 1.5 \) m/s, the overlapped global extinction line branch off from the local quenching line. From this branch condition, the local quenching flame dose not directly become the global extinction. The flame can recover from the local quenching as described in Fig. 3 (a). The branched global extinction line shows getting low with increasing the \( u' \). And finally the equivalence ratio of global extinction line pass the laminar flame extinction equivalence ratio shown as the dotted line. This means that the disturbance flame has a potential to improve than the laminar flame in some cases.
3.3. Flame front response characteristic for pulsating jet

In this section, we discussed about the flame front response against the pulsating jet. The temperature in the flame zone steeply increases more than 4 times of room temperature. For example, when the burnt gas temperature is 2000K, then the dynamic viscosity just behind the flame is 6 times higher than that of the unburnt gas. It means Reynolds number also steeply decreases in the reaction zone. Our question is how transfer and follow the pulsating jet energy to the flame. Figure 5 shows the flame front movement for input pulse in the no LQ condition. As shown in Fig. 5 (a), for \( f = 20 \text{Hz} \), the flame position at the flow center (\( y_f \)) is synchronized with the pulsating jet frequency. In this case, the cross-correlation function for the flame position and input pulse (\( C_{yf} \)) marks 0.98. For \( f = 60 \text{Hz} \) shown in Fig. 5 (b), \( C_{yf} \) is 0.77 and the amplitude of \( y_f \) decreases approximately 20% of \( f = 20 \text{Hz} \). In the case of \( f = 60 \text{Hz} \), in order to generate \( u' = 1.6 \text{m/s} \), the input voltage \( V_i(t) \) needs more than triple of \( f = 20 \text{Hz} \). This is the cause for the viscous dissipation in the tube.

Figure 6 shows the cross-correlation functions for the flame position (\( C_{yf} \)) and impinging surface (\( C_{yIS} \)) versus pulsating air jet frequency (\( f \)) at \( \phi = 0.8 \) and \( u' = 1.6 \text{m/s} \), where the impinging surface (IS) is defined as the upper side flow and the lower flow impacting surface. In other words, IS corresponds with the boundary of the hot gas and the cold gas. \( C_{yf} \) and \( C_{yIS} \) drops with increasing \( f \). Both drop rates steeply increase from about 40Hz. This means that the flame cannot perfectly follow the air jet motion.
3.4. Total strain rate

Important flame strain effects for turbulent flames are a main flow velocity gradient and a flamelet curvature due to the turbulence. In this study, we proposed total strain rate consisting from the sum of strain rate by main premixed gas divergence and flame front curvature by pulsating jet flow as described in Fig. 7. Then, the total strain rate defined as

$$K_T = \frac{du}{dy} + \frac{2S_{L0}}{R_f}$$

where $du/dy$ is the strain rate due to main flow divergence and $2S_{L0}/R_f$ is that due to flame curvature. Figure 8 shows the LQ quenching starting equivalence ratio for different pulsating jet frequencies. The $f=0\text{Hz}$ means no pulsating jet condition which corresponds with laminar stagnating flame global extinction limits. All of data can be plotted on the straight line. This means the LQ is triggered by total strain.

3.5. Possible local quenching and recovering mode

As discussed in previous section, the LQ trigger is mainly a flame strain. However, it is difficult to elucidate the recovering mechanisms from the present our having data. Figure 9 shows two possible recovering mechanisms in present stage. One is an edge flame propagation recovering mode as shown in Fig. 9 (a). The edge flame exists on the boundary between the quenching hole and reacting area. The edge flame has a propagation property to the unburnt gas region. The balance of the edge flame propagation speed and unburnt gas expanding speed determines the LQ hole size. Other mode is a new flame front recreating mode as shown in Fig. 9 (b). In this mode, the hot product is transported by the rolled vortex to the unburnt gas zone. The unburnt gas reignites by the heat transfer or transportation of hot product. The new flame front recreate in the hole and propagate to whole area of the LQ hole.

4. Concluding remarks

There are two distinct local quenching phenomena observed depending on the jet intensity. When the jet intensity is weak, the local quenching becomes directly trigger to the whole flame extinction, namely direct extinction mode. When the jet intensity is moderate or strong, the flame can recover from the local quenching phenomena, namely quenching recovery mode. In the quenching recovery
mode, while the quenching start condition increases with increasing the jet intensity almost lineally, the whole extinction fuel concentration decreases with increasing the jet intensity. In the end, the whole extinction fuel concentration for the high jet intensity has lowered than that of flat flame without the pulsating jet. That is the pulsating jet has a potential to prolong the whole flame extinction and to extend lean burn limits. The pulsating jet plays two important work as a negative and a positive. The negative work is a trigger for the local quenching. The positive work is a recovering from the local quenching. We proposed the following possible positive works; to reduce the effect of main strain in here stretch due to flow divergence, to assist the quenched flame edge propagation and to transport high temperature burnt gas to the local quenching part. Those local quenching recovering mechanism may be possible to adapt for a turbulent premixed combustion. The whole flame extinction limits can extend more than that of a laminar flame if the recovering mechanism works well.

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