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A visual study on turnabout phenomenon of vortex roll-up in forced jet diffusion flames

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Abstract

An experimental study on the effect of forcing amplitude in forced jet diffusion flames has been conducted. Various flow visualization techniques are employed using optical schemes, including light scattering photography, high speed imaging by motion analysis, and determination of velocity vector and vorticity fields from PIV data. Particular attention is focused on the turnabout mechanism around the elongated flame, which has not been reported previously, and on the inner coherent structure of the forced jet in the attached flame regime. In particular, we present a schematic diagram that aids in the understanding of the turnabout mechanism of vortex roll-up. This diagram explains why the forced flame is elongated under moderate forcing amplitudes but shortens again when the forcing amplitude is further increased.

Keywords: Coherent structure behavior; Elongated flame; Fluctuating velocity; Forced jet flame; Forcing amplitude; In-burning flame; Phase synchronization; Turnout of vortex roll-up

1. Introduction

In jet flows, the coherent structures of naturally formed large eddies exhibit strong periodic organization, but achieving a detailed understanding of such structures is hindered by their spatially irregular jittering as they move downstream. Therefore, numerous studies [1-3] have introduced forced excitation techniques related to the preferred mode of coherent structures in order to reduce the irregular jittering. However, the imposition of even a small-amplitude forced excitation into a jet flow modifies the development process such that it is quite different from that in the absence of the forcing. In jet diffusion flames, the main issues associated with forced excitation are firstly to clarify the interaction between the flame and the vortex motion, and secondly to suggest a viable method for mixing control through the introduction of forced excitation.

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Anthony and Braid [4] showed that, in jet flames excited at the flame flickering frequency, the inner and outer structures had the same period and length scale. Pearson et al. [5] reported that the preferred mode was a function of the acoustic characteristics of the apparatus, irrespective of the Reynolds number, and that increasing the excitation amplitude caused the position of vortex formation to move upstream.

Gutmark et al. [6] using the PLIF technique, showed that acoustic excitation induced a dramatic change in the jet spreading rate, but that the flame near the braid region of the vortex was extinguished due to the increase in the local strain rate. The findings of the above studies indicate that, in general, the most effective approach is to use the preferred mode of a jet flow as the forced excitation frequency.

However, a study of tone-excited laminar jet flames [7] showed that excitation at the resonant frequency of the fuel tube caused the laminar flame to shorten dramatically and the flow near the nozzle exit to become turbulent. These phenomena were attributed to flow separation just inside the fuel tube exit.

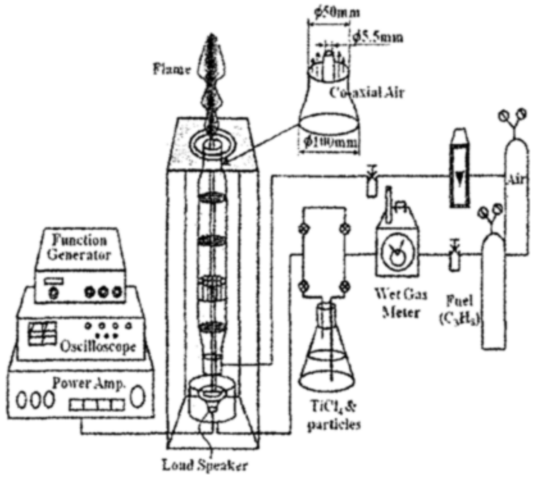
In the present study, we sought to systematically extend the experimental findings of Lee et al. [8], with particular focus on understanding the turnabout phenomenon of vortex roll-up in forced jet diffusion flames. For this purpose, we varied the forcing amplitude while holding the forcing frequency fixed at the resonant frequency of the fuel tube. Several flame modes appearing in different forcing amplitude ranges are identified and discussed in detail. We show that the experimental findings of Lee et al. [8] can be well defined in terms of the flame stability curve generated in the present work.

In this work, several visualization techniques are employed using optical schemes, including light scattering photography, high speed imaging by motion analysis, and determination of velocity vector and vorticity fields by using PIV. Particular attention is given to the turnabout mechanism around the elongated flame, which has not been previously reported, and on the reversal of the direction of vortex roll-up in the attached flame regime.

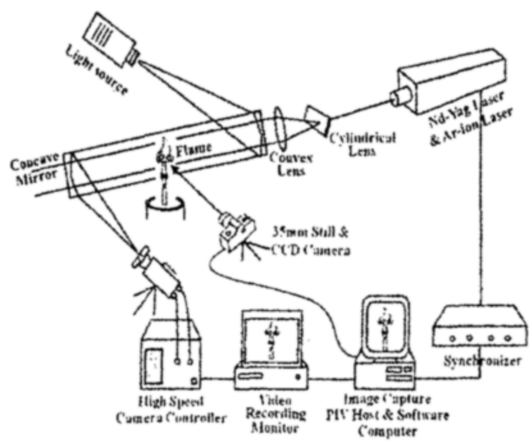
2. Experiments

2.1 Experimental apparatus

Fig. 1 shows a schematic of the flow system and experimental apparatus used in this study. Air flows through a regulator and an orifice prior to entering a wind tunnel, and is then injected into ambient air. The burner system consists of a sharp-edged inner tube (5.5 mm inner diameter) and a concentric outer nozzle with a contraction ratio of 4.0 and an exit diameter of 50 mm. The coflowing air velocity was set to be very low so as not to disturb the flame characteristics by inherent fuel flow. A transparent Pyrex tube (length 715 mm, inner diameter 5.5 mm) was used as the fuel tube to allow observation of the flame behavior inside the tube. The nozzle exit tip was sharply polished to remove the effect of flame holding. The fuel used was commercial grade propane (purity 99.5%). To minimize room drafts, the jet was enclosed in a 1.2 m × 1.2 m × 2.5 m high double-screened curtain, open on the upper side and made of a 0.5 mm mesh screen. To control the jet flow acoustically, a 100 W, 6 inch diameter loudspeaker driven by a function generator and a power amplifier was mounted coaxially beneath the fuel tube.



(a) Schematic of burner and flow system



(b) Optic and visualization system

Fig. 1. Schematic diagram of the experimental setup and visualization system.

2.2 Experimental method

To observe the flame behavior and the flow pattern near the nozzle exit, we used RMS(Reactive Mie-Scattering) with TiO_2 particles, formed by reactions with $TiCl_4$ vapor and kerosene vapor, as a scattering source. A 50-mJ Nd-Yag pulse laser, which was adopted in the PIV system, and a 4-Watt Argon-ion laser beam, which was adopted in a sectional visualization, were converted by a cylindrical lens into a vertical sheet of thickness 0.4 mm that passed through the flow near the nozzle exit. The images were recorded at a 90° angle to the direction of light propagation with a 35 mm camera and digital CCD camera equipped with a micro-lens.

3. Results and discussions

3.1 General features

3.1.1 Characteristics of flame length and shape

In general, previous studies have found that the flame length is reduced when a forcing is applied to a jet diffusion flame due to mixing enhancement. Fig. 2 shows the variation of the flame length (normalized by the unforced flame length, L_O) as a function of the forcing amplitude; the various flame modes are marked on the curve. As the forcing amplitude is increased in the attached flame region, the flame length increases initially, then decreases to a minimum at a fat flame mode, then increases to a maximum at the elongated flame mode, and then decreases again, passing through the in-burning flame mode. On further increase of the forcing amplitude, the systems moves into the lift-off flame regime, where the flame length decreases monotonically. Thus, the present results disclose the very interesting result that application of a moderate forcing causes the jet flame to become longer in spite of being forced. Such a lengthening of a jet flame under moderate forcing has not been observed in previous studies. Moreover, the turnabout phenomenon of vortex roll-up (described in detail in the next section) always occurred with this elongated flame mode. Although previous studies have depicted the suck-back phenomenon of the flame and the entrained air, they give little insight into why flame elongation would occur at the same condition as the vortex turnabout.

Fig. 3 shows images obtained by using the RMS method of the inner flow structure of flames under different forcing amplitudes. Application of even a feeble forcing on flame causes an inner vortex structure which is prevailing irrespective if the outer and the flame length with forcing amplitude is changed. This indicates that the flame length is closely related to the vortex evolution of the inner structure. When forcing amplitudes of 1.5 and 2.0 V are applied, rolled-up vortices at both the lower and upper parts along the fuel branch are formed near the nozzle exit. Increasing the forcing amplitude to 2.4 V gives rise to a turnabout phenomenon of the direction of vortex roll-up. Further increase of the forcing induces a re-turnabout phenomenon of the roll-up vortices.

It should be noted, however, that at forcing amplitudes in the range 1.5–2.4 V, the fuel stem and the fuel branch have a form resembling a cross, whereas at the higher forcing amplitude of 4.0 V they show a parallel form. These dramatic changes of the direction of vortex roll-up and the shape of the fuel stem and radial fuel branch must be associated with variations in the dominant flow directions as a function of forcing amplitude.

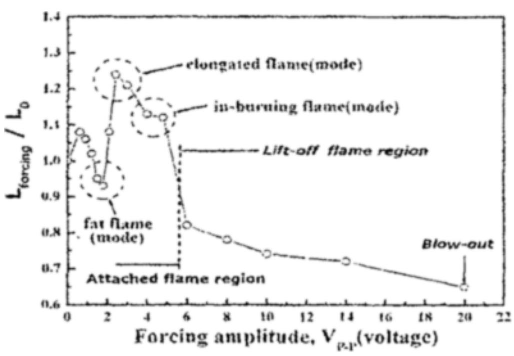
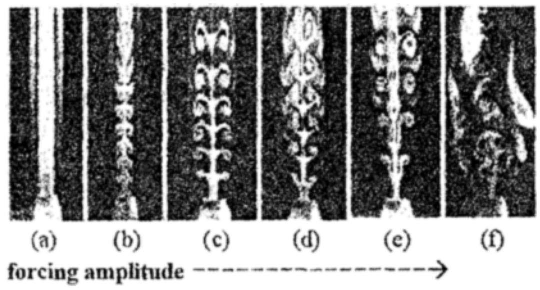


Fig. 2. Normalized flame length as a function of forcing amplitude.

3.1.2 The turnabout phenomenon of vortex roll-up

Fig. 4 provides a detailed depiction of a typical case of the turnabout phenomenon of vortex roll-up prior to flame lift-off, which occurs due to the collapsible



(a) unforced flame (b) feeble flame(0.6Volts) (c) fat flame(1.5Volts) (d) elongated flame(2.4Volts) (e) in-burning flame(4.0Volts) (f) lift-off flame(6.0Volts)

Fig. 3. Flame mode according to the forcing amplitude (vertical cross-cut images by the RMS method).

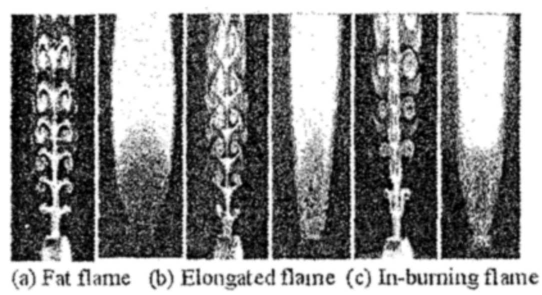


Fig. 4. Visual images of the turnabout phenomenon of vortex roll-up around an elongated flame.

mixing [7]. The left side of each photo shows a cross-cut image obtained by using the titanium tetrachloride technique of RMS, and the right side shows an integral image of direct photos. These images were obtained with a still camera; the cross-cut images were recorded using an aperture of f1.4 and an exposure time of 4000^{-1} sec, and the integral images were recorded using an exposure time of 125^{-1} sec and f1.4 and were shown a double flame by eye measurement.

As in Fig. 3, we can compare the vortical motions of forcing flames in Fig. 4 that have shown a turnabout and re-turnabout around the elongated flame. While the direction of vortex roll-up follows the traditional rule near the nozzle exit even under small and moderate forcing amplitudes, as shown in Fig. 3(b) to 3(c) and the fat flame in Fig. 4, the direction in the elongated flame is reversed despite the increase in forcing amplitude. That is, vortex roll-up is directed upward in the elongated flame mode, but is directed downward in the fat flame and in-burning flame modes.

As described briefly above, it is very interesting that the vortex turnabout phenomenon always occurs whenever a forced flame elongates in the attached flame regime. Two theories could be put forward to account for the observed turnabout of vortex roll-up. One is the buoyancy effect, which makes a flame subjected to a zero or small forcing flicker with a low frequency due to the buoyancy force. The other is the negative part of acoustic excitation, which makes a forcing jet suck-back into the nozzle and induces upward vortex roll-up. Since increasing the forcing amplitude means increasing the flow velocity at particular phases in the acoustic cycle, the observed behavior cannot be attributed simply to the buoyancy effect. Hence, we attribute the turnabout phenomenon of vortex roll-up to the negative part of the acoustic cycle under the influence of a sufficiently strong positive pressure gradient. This strongly indicates that the direction of vortex roll-up is determined by the strong degree of the individual positive and negative parts of the acoustic cycle.

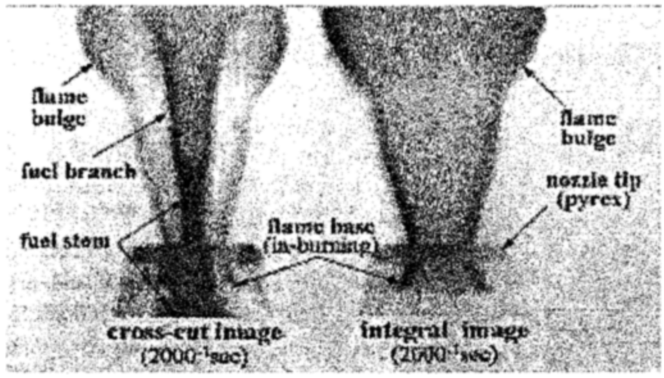
In Fig. 4, the shape and direction of the fuel branch part can help one imagine the velocity field. For small forcing amplitudes such as 1.5 V, the mean velocity seems to be larger than the periodically fluctuating velocity and hence the flow characteristics resemble those in general jet flows. Therefore, the direction of the fuel branch part was naturally directed downward and the vortex roll-up was positioned at the lower part of the radial fuel branch. However, the width of the fuel step is shown to be less than the nozzle diameter, indicating that a negative part of the acoustic excitation is causing the surrounding air to be sucked back into the fuel tube. Moreover, it is seen that, in comparison with the system with a forcing amplitude of 0.6 V in Fig. 3, the number of shedding vortices is decreased and the distance between those vortices becomes larger at the higher forcing amplitude of 1.5 V. This implies that increasing the forcing amplitude increases the global flow velocity. On further increase of the forcing amplitude to 2.4 V, the direction of the fuel branch part is inclined upward and the fuel stem becomes much narrower. Even if the convective flow goes downstream, the motion becomes very weak and the sucked-back flow dominates. As a result, the turnabout phenomenon occurs.

In this situation, where the surrounding air is entrained between shedding vortices, the entrained air should be directed downward, and thus the motion induced by the entrainment should be highly hindered.

This is the direct reason why there exists an elongated flame region on a normalized flame length curve as in Fig. 2. For a forcing amplitude of 4.0 V, a re-turnabout phenomenon of vortex motion occurs. To investigate the turnabout of vortex roll-up, we examined the flame in greater detail using a PIV and a high motion analysis system with a time interval of 2000^{-1} sec between consecutive images.

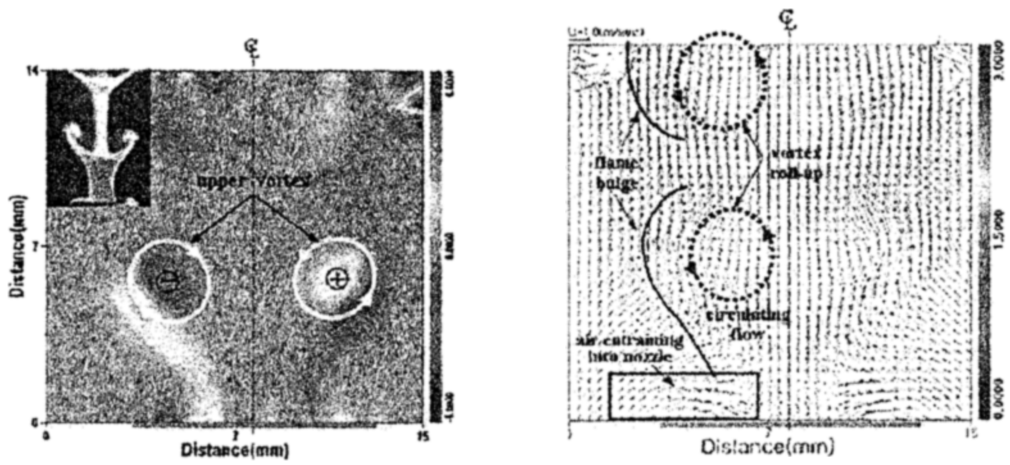
Fig. 5 shows representative instantaneous images captured by the high motion analyzer of the flame under a forcing of 2.4 and 4.0 V. These images depict the turnabout of vortex roll-up with phase synchronization between an elongated flame and an in-burning flame. The left side of each image shows a cross-cut image with kerosene particles as tracer particles and the right side shows a direct integral image. Each image was taken by an image processor with a PC controller.

From the images in Fig. 5, we can also ascertain the direction of vortex roll-up: the elongated flame shows upward motion, whereas apparently the in-burning flame exhibits motion downward. While the flame base of the in-burning flame was positioned in the nozzle due to the strong negative part of the periodic forcing cycle, the base of the elongated flame did not exhibit suck-back into the nozzle. These characteristics indicate that the negative part of the fluctuating velocity of the in-burning flame is stronger than that of the elongated flame, and that the air surrounding



(a) Elongated flame (2.4 Volts) (b) In-burning flame (4.0 Volts)

Fig. 5. Phase synchronized images of the forcing flame; time interval between images is 2000^{-1} sec.



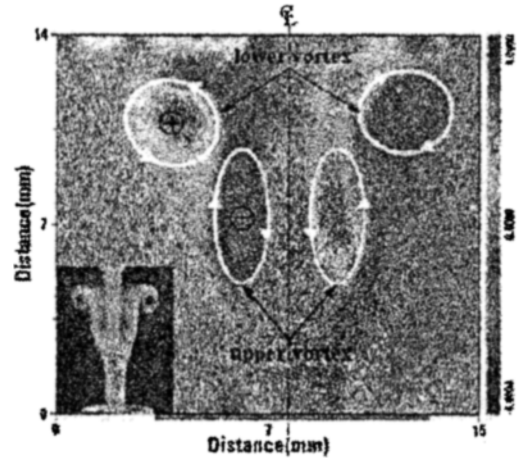
(a) Vorticity field (vorticity contour) (b) Velocity field (unit scale is 1 m/s)

Fig. 6. Vorticity and velocity fields of the elongated flame measured with PIV (270° phase). Small image in the left-upper corner shows an instantaneous direct photo image of the flame from which the vorticity and velocity fields were measured.

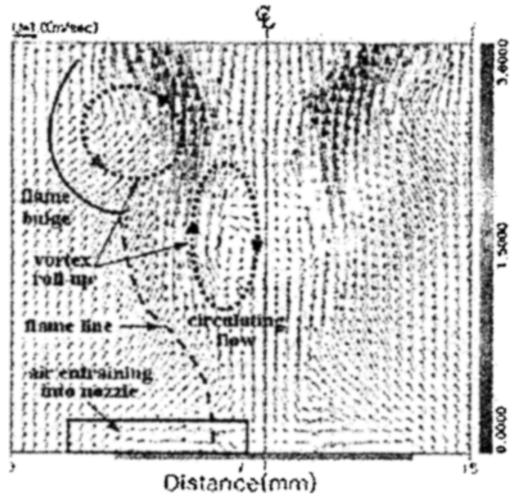
the in-burning flame is sucked-back deep into the jet nozzle, causing a partially premixed flame to be formed in the jet nozzle. Thus, by using the PIV system, we could discern the air entrainment behavior in the elongated and in-burning flames.

Fig. 6 shows the vorticity and velocity fields of the elongation flame measured with PIV near the jet nozzle. These images show the entrainment of the surrounding air into the jet nozzle and the upward vortex roll-up, which causes circulating flow of forced fuel in the inner jet flow. Inspection of the fields also confirms that the co-flowing air jet flow accelerates on passing through the flame sheet and that only the upper vortex is observed, which appears as a counter-rotating pair of vortices, due to the negative part of forcing flow on the fuel branch. In this case, although there is a positive part of the forcing flow, it is sufficiently feeble that the downward vortex roll-up motion cannot be discerned. The left-upper corner image of Fig. 6 shows an instantaneous direct photo of these vortices and velocities scale.

Fig. 7 shows the vorticity and velocity fields of the in-burning flame, which apparently seemed to occur as a re-turnabout of vortex roll-up. Due to the higher forcing amplitude applied in this system, the instantaneous velocities were very fast, up to values on the order of 3 m/s, and the vorticity strength was also stronger than for the elongated flame. As a result, in the in-burning flame not only can we detect the upper vortex that was observed in the elongated flame, but



(a) Vorticity field (vorticity contour)



(b) Velocity field (unit scale is 1 m/s)

Fig. 7. Vorticity and velocity fields of the in-burning flame measured with PIV (270° phase). Small image in the left-lower corner shows an instantaneous direct photo image of the flame from which the vorticity and velocity fields were measured.

also the lower vortex just underneath the fuel branch. This lower vortex was not observed in the direct photos and high speed motion images in Figs. 3, 4 and 5. Moreover, the velocity profile obtained from the PIV data shows a re-circulating flow of the inner forcing fuel arising from the strong suck-back flow. Again, this re-circulating flow could not be seen in any of the other images. Owing to the roll-up motions of the upper and lower vortices, the forced jet flame becomes a partial premixed flame and shows a high velocity on passing the flame sheet.

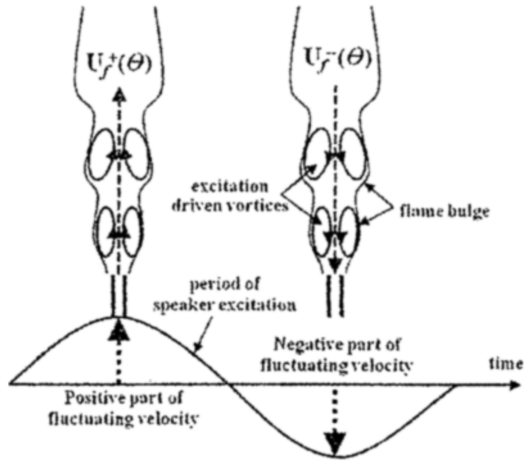


Fig. 8. The direction of vortex roll-up considering the fluctuating velocity components only.

3.2 Mechanism of the turnabout of vortex roll-up

In general, the instantaneous velocity of a forcing jet, u, can be decomposed into a long-time mean velocity u_m and a periodic component of fluctuating velocity $u_f(\Theta)$, that is,

$$u = u_m + u_f(\Theta) \tag{1}$$

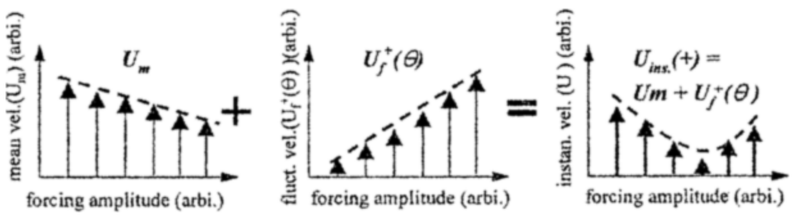
The fluctuating velocity $u_f(\Theta)$, in turn, can be decomposed into a positive velocity $u_f^+(\Theta)$, which corresponds to the push effect on the forcing jet flow, and a negative velocity $u_f^-(\Theta)$, which corresponds to the pull effect. These fluctuating velocity components are pointed in opposite directions but have the same amplitude, which increases linearly with increasing forcing amplitude.

In Fig. 8, we can see the change in the direction of vortex roll-up according to the phase (positive or negative) of the fluctuating velocity in the periodic tone excitation. While the positive part of the fluctuating velocity promotes downward vortex roll-up as the convective motion of the mean flow, the strong negative part of the fluctuating velocity induces a suck-back flow that promotes vortex roll-up in an upward direction. On the other hand, the vortex roll-up is formed by the shear force, which is proportional to the velocity difference between the jet flow and the surrounding flow, that is, the shear force is proportional to $(u - u_\infty)$. Hence, the shear force of the forced jet flow must be considered to be comprised of a positive (push motion) and a negative (pull motion) phase within each the periodic cycle. Therefore, the velocity difference of the shear force can be expressed as follows:

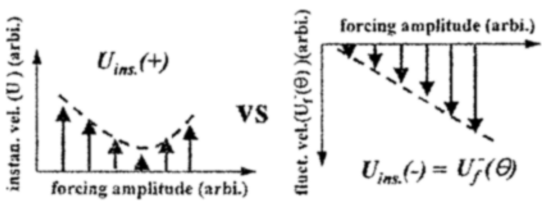
$$\text{Positive part}: \quad u_m + u_f^+(\Theta) - u_\infty$$
$$\text{Negative part}: \quad u_f^-(\Theta) - u_\infty \qquad (2)$$

where u_∞ is the velocity of the surrounding air (which is negligible) and $u_f^+(\Theta)$ and $u_f^-(\Theta)$ are as in Eq. (1).

Then, as the forcing amplitude is increased, the amplitude of the fluctuating velocity $u_f(\Theta)$ increases linearly, whereas the long-time mean velocity u_m decreases. Given that the positive part of the forcing velocity is a like co-flowing condition, the shear force during the positive phase (push motion) is proportional to the difference between the mean velocity u_m and the positive fluctuating velocity $u_f^-(\Theta)$. This means that there is a turning point in the difference between the mean velocity and positive fluctuating velocity at the positive phase of the periodic excitation cycle. That is, the positive part of the instantaneous velocity of the forced jet decreases at the start and then increases after passing the turning point. The negative part of the fluctuating velocity, however, increases linearly with forcing amplitude. To aid in understanding the decomposition of the shear force of



(a) Velocity difference of positive part that presents a shear force which is proportional to the difference between the mean velocity and positive fluctuating velocity



(b) Shear force scale (arbitrary) which is proportional to the instantaneous velocity, of the positive and negative part in the forced flame

Fig. 9. Schematic showing the positive and negative velocity parts and their instantaneous velocity amplitudes of the forcing flow, which can be expressed as a shear force.

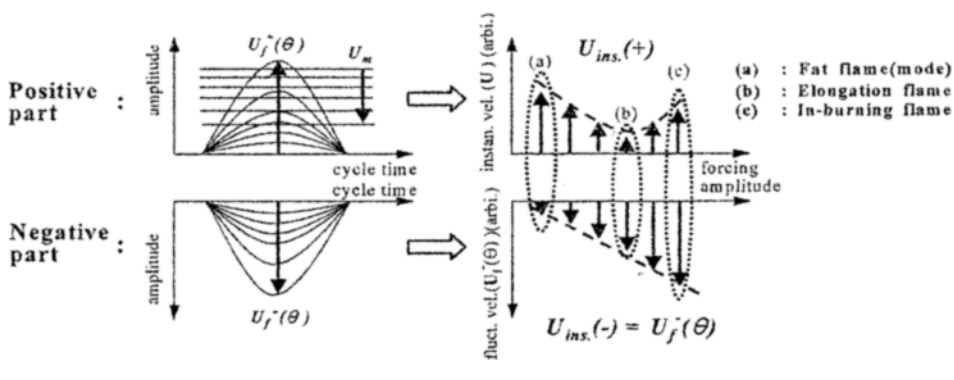


Fig. 10. Schematic diagram of the mechanism of the vortex turnabout phenomenon.

the forcing jet, Fig. 9 shows a schematic diagram of the characteristics of the above velocities.

The mechanism of the vortex turnabout phenomenon can be more easily understood by considering the positive and negative velocity amplitudes about the instantaneous velocity of the forcing flow, as shown in the in Fig. 10. The positive part increases at low forcing amplitude but decreases on increasing the forcing amplitude; by contrast, the negative part is feeble at low forcing amplitude but increases linearly with increasing forcing amplitude. On account of these different trends, the turnabout phenomenon of vortex roll-up occurs in the forced jet flame when a moderate amplitude is applied. The first turnabout occurs at the elongated flame mode. Since the negative part is larger than the positive part, apparently the vortex roll-up looks upward, so it posits in disadvantageous position on the entrainment of surrounding air. If the forcing amplitude increases continuously, a second outward turnabout phenomenon will occur at the in-burning flame mode. That is, the inward roll-up vortex (i.e., the upper vortex) is nearly parallel to the fuel stem similar to being merged into the fuel, such that the clearance between the fuel branch and stem becomes very narrow, and is elongated considerably.

Eventually, at high forcing amplitude, the outward roll-up vortex (i.e., the lower vortex), which was too weak to be observed at the elongated flame mode, appears as a strong vorticity; the occurrence of this outward vortex roll-up in a downward direction is as if a re-turnabout phenomenon occurs.

4. Conclusion

In the present work we used various optical measurement techniques to study forced jet diffusion flames under a range of forcing amplitudes at a fixed resonant frequency. The following conclusions can be drawn from our results.

1) The variation in flame length as a function of forcing amplitude is a direct consequence of the evolution process of the inner flow structure and vortex roll-up turnabout. The negative phase of the tone-excited cycle causes the shapes of the fuel stem and fuel branch part and even the direction of vortex roll-up to change dramatically. As evidence of this phenomenon, the velocity profile determined by PIV showed re-circulating flow of the inner forcing fuel due to the strong suck-back flow; this re-circulating flow has not been seen in previous studies.

2) We present a schematic diagram that allows easy understanding of the mechanism underlying the observed vortex roll-up turnabout. This diagram explains why the forced flame is elongated when subjected to a moderate forcing amplitude and then shortens again on further increase of the forcing amplitude. The present work represents the first report of such an explanation.

Acknowledgments

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