Formation of Turbulent Eddies in Jet Diffusion Flames

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The transition from laminar to turbulent mode of an ethylene jet flame was investigated using the two-dimensional instantaneous photography of turbulent eddies by a laser-light sheeting method. Observations were made of the eddies around the break point in the fuel flow and the flame. The results show that in the laminar region the fuel flow is curved due to instability in the shear layer, whereas the outer soot layer has little curvature because of the high viscosity in the hot layer. In the transient region, eddies generated in the fuel flow deform the outer soot layer. Numerical calculations were performed to predict fluid motions due to interaction between density and pressure gradients in the flame boundary. The results show that the pressure gradient in a medium of varying density generates the vorticity along the flame. Deformation and stretching of the flame boundary take place once the vorticity becomes stronger than the dissipation due to viscosity.

Key Words: Diffusion Combustion, Turbulent Mixing, Flow Visualization, Numerical Analysis, Jet Flame, Turbulent Eddy, Density Gradient

1. Introduction

Jet diffusion flames have long been studied for their practical importance because many items of combustion equipment such as furnaces and boilers tend to use this type of combustion. Flames of this kind significantly rely on turbulent mixing of fuel and air in the shear layer at the jet boundary. In previous studies, turbulent eddies in the shear layer have been visualized using shadowgraphs, schlieren photographs and other optical methods, most of which exhibit a structure of a complicated nature consisting of a number of small scale eddies. The concept of a coherent structure has been proposed to explain mixing of fuel with air which is engulfed intermittently by large-scale eddies produced by fluid shear\textsuperscript{11,22}. There are many other concepts for generation of such an eddy structure; one is the mechanism of selective growth of vortices in a free shear flow\textsuperscript{5b}, and another is that originating from the Kelvin-Helmholtz instability in stratified density fluid flow\textsuperscript{5h}. However, the details of the formation of turbulent eddies in the jet diffusion flame have yet to be fully clarified.

Recently, we applied a laser-light sheeting method (LLS) to visualize the instantaneous turbulent eddies on specified crosssections in free jets and jet diffusion flames\textsuperscript{5a,14}. We found that jet flames are essentially different from ordinary nonreacting free jets in regard to the appearance of turbulent eddies due to a large temperature rise: the flame boundaries are strongly distorted on the horizontal cross section rather than on the vertical cross section, unlike the coherent structure in the shear layer. This suggests that the turbulent eddies on the horizontal plane have much more significant influence on mixing than the eddies on the vertical plane. It was also noted that the turbulent eddies in the jet flame are much coarser than those in a nonreacting jet, where smaller dissipating eddies are no longer observed. These findings present
a very different picture from that suggested by studies on turbulent eddies in jet flames up to now. However, the flow visualization in our previous study was carried out only by using spontaneously forming soot particles as the scatterers, and as a result the details of the flow could not be determined for the region where the laminar to turbulent mode transition took place. For this reason, the effects of combustion on the onset and growth of turbulent eddies have not been clarified in depth.

In the present study, the formation of turbulent eddies around the transition point was investigated in more detail, based again on observations by LLS using titanium oxide particles as tracers for visualization for jets with and without combustion. Furthermore, a numerical calculation was performed by solving the transport equation of the vorticity to predict fluid motions induced by interaction between the gradients of density and pressure in the flame boundary. The results suggest that vorticities may be generated in a region where a pressure gradient exists in a medium of varying density, and that deformation and stretching of the flame boundary may occur once the production rate of vorticity becomes higher than the dissipation rate due to viscosity.

2. Experimental Apparatus

Experiments were performed at atmospheric pressure on a diffusion type burner for both axisymmetric round nonreacting free jets and ethylene jet flames. These jets were formed upward in the vertical direction by a straight nozzle with an inner diameter of \( d = 4 \) mm and a rim thickness of 0.5 mm. The optical arrangement is shown in Fig. 1. A Spectra Physics model DCR 11 Nd / YAG pulse laser, having a pulse width of about 10 ns and a light energy of 150 mJ per pulse, was used as the light source for LLS. The laser light beam was focused into a sheet of 0.05 mm thickness by means of convex and cylindrical lenses. The images of scattered light were taken in a direction perpendicular to the light sheet using a Hamamatsu Photonics model C2925 image intensifier and a 35 mm still camera. The effect of flame luminosity was eliminated partly by inserting an interferential filter with a wavelength of 532 nm in the optical path, and partly by closing the shutter of the image intensifier when the laser light was off.

3. Experimental Results

3.1 Laminar-to-turbulent transition in non-reacting jets

Firstly, the formation of turbulent eddies at the transition point of cold jets was observed by LLS, for different exit Reynolds numbers \( Re \). In Fig. 2, the distance between the nozzle exit and the transition point, that is the break point length \( h \), is shown against \( Re \) for nitrogen and helium jets, where the break point represents the position at which turbulence is initiated. In both cases, increasing \( Re \) decreases \( h \) quickly but continuously until a certain value of \( Re \) at which \( h \) discontinuously drops to a low value. For the same \( Re \) the helium jet has much smaller break point length than the nitrogen jet. Also, the helium jet has smaller \( Re \) at which \( h \) suddenly decreases. These differences are due to the fact that helium has a kinematic viscosity eight times higher than those of air and nitrogen. To investigate the sudden change of the break point length, we compared several flow images for different values of \( Re \) shown as A through F in Fig. 2. Figure 3 shows the corresponding LLS images, where photographs A, B, D and E are cases of Reynolds numbers lower than that which produces a sudden fall off of \( h \), showing that turbulence begins to develop on a curved jet core. This pattern resembles a pattern of instability associated with a helical vortex structure which is often observed in low Reynolds number flows. Turbulent eddies are generated in staggered positions along the jet core and finally develop to form strong turbulent vortex motions. Photographs C and F are cases of a Reynolds number higher than that which produces

Fig. 1 Optical arrangement for laser light sheet method

Fig. 2 Break point length \( h \) of nonreacting jets against exit Reynolds number \( Re \)
a sudden fall off of \( h \). They both indicate that the onset of turbulence takes place after the expansion and shrinkage of the jet body. This instability might be induced by a pumping effect due to pressure oscillation in the nozzle. Turbulent fluctuations are observed at symmetric positions on the jet core and in the downstream the flows exhibit random eddies.

3.2 Formation of turbulent eddies in jet diffusion flames

Next, we observed the onset of the flow instability of jet diffusion flames. Figure 4 shows LLS images taken at different positions from the nozzle \( x \), together with direct photographs with 0.25 ms exposure, for two cases of (a) \( Re = 3000 \) and (b) 6000, corresponding to nozzle exit velocities of \( u_e = 6.0 \) m/s and 12.0 m/s respectively. For obtaining LLS images, titanium oxide particles are seeded in the nozzle flow, and they appear as many small dots in fuel flow in contrast to continuously dispersed soot clouds over the flame zone. Visual inspection showed the break

![Image](image_url)

**Fig. 3** LLS images of turbulent eddies around the break point [A-F are shown in Fig. 2]

![Image](image_url)

**Fig. 4** Direct photographs and LLS images on vertical and horizontal cross sections in the case of fuel flow seeded with TiO\(_2\) particles
point length to be $h=100\,\text{mm}$ for case (a) and $h=40\,\text{mm}$ for case (b). At these positions, however, the fuel stream appears turbulent and curved, similar to the case of the cold jet at lower Reynolds number. Such a curving flow develops along the fuel flow, finally forming larger eddies and reaching a soot layer near the break point. The eddies make the soot layer penetrate the fuel stream, thereby stretching and folding the soot layer into a thin sheet several times not only on the axial plane but also on the azimuthal plane. In summary, turbulent motions arising within the fuel stream distort the flame front and turn it into air engulfing eddies. To explore the effect of combustion on the formation of turbulent eddies, close-up photographs of the nonreacting ethylene jets are compared with the corresponding reacting cases for the same exit Reynolds numbers, see Fig. 5. It is noted that small turbulent eddies are formed in axisymmetric positions in the nonreacting case, while a curved stream having a relatively low spatial frequency is formed in the reacting case. This corresponds fairly well to the change which occurs when the Reynolds number is lowered at a free jet, as has been noted in the previous section. It follows that combustion may increase the kinematic viscosity in the periphery of the jet due to temperature rise and may suppress generation of small scale eddies. To ascertain whether there is a viscous layer in the periphery of the jet flame, measurements were made to determine the average distribution of spatial temperature using a 0.3-mm diameter Pt–Pt·Rh 13% thermocouple. In Fig. 6, results are given for two cases of different exit Reynolds number. In both cases, the temperature exceeds 1 000 K in the jet boundary even close to the nozzle exit. This suggests that the presence of a highly viscous layer confines a less viscous fuel flow and retards fuel-air mixing considerably.

4. Discussion of the Mechanism of Generating Turbulent Eddies

4.1 Vorticity formation due to density gradient

As has been noted from the experiments on flow visualization, the onset of turbulent eddies in a jet flame significantly differs from that in the nonreacting jet. As may be seen from Fig. 4 (a), the fuel stream close to the nozzle exit is curved similar to the case of the nonreacting jet; nevertheless the outer soot sheath appears less deformed because of the hot viscous layer. In spite of this, large scale eddies are formed at the positions of $x$ greater than 40 mm not only on the axial plane but also on the azimuthal plane. This suggests the likelihood of the vorticity formation due to density fluctuation resulting from a certain coupling effect of density gradient and pressure gradient, rather than the onset of turbulence due to ordinary velocity shear.

To see whether the mechanism of turbulence initiation due to such a density effect is plausible, a theoretical prediction was made using a two dimensional transport equation for vorticity in a variable density flow field. Denoting the density and the pressure as $\rho$ and $p$, respectively, we have the vorticity transport equation

$$\frac{D\omega}{Dt} = \frac{1}{\rho} (\nabla \rho \times \nabla p) - \omega (\nabla \cdot u) + \nu \nabla^2 \omega, \quad (1)$$

where $\omega$ denotes the vorticity, $t$ the time, $u$ the velocity and $\nu$ the kinematic viscosity. The first term of the right-hand side of the above equation represents the production of vorticity due to misalignment of pressure gradient and density gradient, the second term the decrease of vorticity due to dilatation, and the third term the diffusion of vorticity due to viscosity. If the first term is greater than the second and
third terms, then the production of either positive or negative vorticity may occur. In the vicinity of the flame front, there is a very large change in density. If there is a curved flow near the flame front as shown in Fig. 7(a), the pressure gradient might be formed in a direction perpendicular to the density gradient, thereby producing vorticities denoted as $P, P', N$ and $N''$. The vortices thus produced might stretch the flame front in the manner shown in Fig. 7(b), and at the same time they may bring the surrounding air into the fuel stream. The fact that there is a curved flow approaching the flame front in the upstream of the visible break point in Fig. 4 has been noted already. This suggests the contribution of the first term to the production of vorticity.

4.2 Numerical calculation of vorticity formation

A numerical calculation has been conducted using a method proposed by Ashurst for a simplified case where in the initial stage there is a planar flame front in the fuel-air interface on the $y$-axis in the $x, y$ plane and also a circulation in the fuel side at a distance $d_0$ from the origin on the $x$-axis, as shown in Fig. 8. The circulation produces a pressure gradient along the flame front, thereby inducing vortices and increasing the deformation as time goes by. The time evolution can be obtained by solving simultaneously the continuity equation, the transport equation for fuel concentration and the transport equation for vorticity. The concentration is described on the assumption of a

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**Fig. 7** Deformation of flame boundary due to vorticity generation

**Fig. 8** Schematic of numerical model

**Fig. 9** Distributions of $u, v$, and flame front
flame sheet model using the mixture fraction \( Z \), where \( Z = 0 \) represents pure air and \( Z = 1 \) pure fuel. \( Z \) is often employed in the theoretical approach for non-premixed combustion. The boundary conditions imposed are as follows: the temperature is ambient at \( Z = 0 \) and \( Z = 1 \) and is equal to the adiabatic flame temperature \( T_{ad} \) at \( Z = Z_{ad} \) where \( Z_{ad} \) is the stoichiometric mixture fraction. It is assumed that the Lewis number is one. Furthermore, to avoid an unrealistically large density gradient, it is assumed that diffusion of mixture fraction proceeds within the first 10 ms without a change in the flow field. Subsequently, a vorticity \( \omega \) having a circulation of \( 6.27 \times 10^{-3} \) and a Gaussian profile with standard deviation of 1 mm is placed at the position \( \delta = 8 \) mm on the \( x \)-axis. Calculations were made for a rectangular region having side lengths of \( x = \pm 150 \) mm, \( y = \pm 25 \) mm. The boundary conditions are \( u = 0 \) for both the ends of \( x \) and periodic for \( y \). Assuming an ethylene jet flame, the following values were used: \( Z_{ad} = 0.058 \), ambient temperature \( T_0 = 300 \) K and \( T_{ad} = 2000 \) K for the case of combustion. In Fig. 9, the obtained spatial distribution of velocity \( u \) and vorticity \( \omega \) are shown, together with the profile of the fuel-air interface, for the cases with and without heat release. In the case with heat release, vorticities having positive and negative values are formed which develop from time to time, and finally formed air entraining eddies, consistent with Fig. 7. In the case without heat release, no new vortices are produced and only a slight deformation of the boundary is seen due to the presence of circulation. This is because both the first and second terms in the right hand side of Eq. (1) are zero. In the reacting case, it should be noted that in the case of small pressure and density gradients, the vorticity generation may be suppressed due to the effect of dilatation and viscous diffusion. Nevertheless, it can be safely concluded that the flame front can be stretched considerably when a large heat release occurs.

## 5. Conclusions

Nonreacting free jets and ethylene jet flames were visualized using the laser light sheet method to clarify the onset of the turbulence in the laminar-to-turbulent mode transition. Also, the motion of the flame front caused by the presence of a single vortex was studied theoretically. The results obtained are summarized as follows.

1. For a nonreacting jet, the break point length at which the transition from laminar to turbulent flow takes place decreases with the exit Reynolds number until a certain value at which a sudden discontinuous drop of the break point length occurs. At exit Reynolds numbers lower than this value, the flow approaching the break point is curved, whereas at exit Reynolds numbers higher than this value, axisymmetric turbulent eddies are formed due to pumping.

2. In a jet diffusion flame, the fuel stream is curved even close to the nozzle and the curvature increases with the distance from the nozzle towards the soot layer near the visible break point, finally forming air-entraining eddies.

3. In the periphery of the jet diffusion flame, a hot viscous layer is formed due to combustion which confines a less viscous and turbulent fuel flow. This suppresses the formation of small-scale eddies, and at the same time retards the fuel-air mixing.

4. A fuel flow having a curvature inside the fuel stream produces a pressure gradient which may be coupled with the density gradient to generate a vorticity. The produced vorticity may stretch the flame front and finally grows to form air entraining eddies.

The authors wish to thank Mr. T. Yamaguchi, a graduate student of Kyoto University, for his laboratory work. This study was supported by a Grant-in-Aid for Scientific Research (No. 03452130) obtained in 1991 from the Ministry of Education, Science and Culture of Japan. All numerical calculations were carried out on the FACOM M-1800 computer in the Data Processing Center, Kyoto University.

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