Turbulent/non-turbulent interface and flow topogloy in a temporally evolving mixing layer

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1 Introduction

Scalar mixing is of critical importance in combustion systems, which can greatly affect combustion efficiency. The investigation of scalar mixing in turbulent jets helps to understand the effects of turbulence on scalar evolution. In the turbulent jet, there is a very important interface (i.e., turbulent/non-turbulent interface - TNTI) [1] which has a significant impact on scalar mixing. The TNTI distinguishes the turbulent and non-turbulent regions in the jet, separating the rotation region from the non-rotation region [2]. It is generally accepted that there are two entrainment mechanisms near the TNTI [2], leading to the kinetic energy transport between the turbulent and non-turbulent regions. One is the nibbling mechanism due to small-scale vortex propagation, in which the rotating regions can drive the external non-rotation regions to rotate, causing the external non-rotation regions to gradually evolve into rotating regions. The other is the engulfment mechanism, which is a process of outward growth, caused by the large-scale ingestion of external (usually irrotational) fluid. It is noted that nibbling is a viscous diffusion process that occurs throughout the interface and occurs at smooth interfaces with low curvature. On the other hand, in the engulfment zones, there are large-scale fluctuations of the interface with negative curvature pointing inward.

Previous studies [1-6] found that both the above two menchanisms play important roles in the entrainment of fluid. Nevertheless, the impact of the two mechanisms on scalar mixing are not well documented. Moreover, flow topology analysis [6,8-10] can be used to gain insights into the fluid motion near the TNTI. In this context, this work will investigate the flow topology, and nibbling and engulfment processes in a mixing layer, in order to understand the underlying mechansims of scalar mixing near the TNTI.

2 Numerical method

The Direct numerical simulation (DNS) method is used to perform the simulation of a temporally evolving mixing layer (see Fig. 1). The well-established low-Mach number flow solver NGA [7] is used in this work. To create initial turbulence, a channel flow is calculated with the Reynolds number of 10000. Three passive scalars at the Schmid numbers of 0.1, 1 and 10 are examined to consider different diffusion coefficients. The jet viscosity is set to be that of air. The initial velocity of scalar jet is 108m/s.

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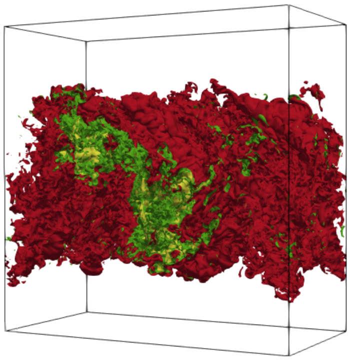

Figure 1: The three passive scalars in a temporally evolving mixing layer, in which the red, green, and yellow colors represent high, medium, and low Schmidt number passive scalars, respectively.

3 Mathmetical method

Flow topology is a mathematical method proposed by Chong [8-9]. The velocity-gradient tensor A has its characteristic equation, from which we can compute three solutions λ1, λ2, λ3 as the eigenvalues of A.

$$\lambda^3 + P\lambda^2 + Q\lambda + R = 0$$

where P, Q, and R are the first, second and third invariants of A, which can be given as

$$P = -S_{ii} = 0$$

$$Q = Q_S + Q_W = -S_{ij}S_{ji}/2 + W_{ij}W_{ji}/2$$

$$R = \left(-S_{ij}S_{jk}S_{ki} - 3W_{ij}W_{jk}W_{ki}\right)/3$$

where Sij = (Aij +Aji)/2 is the strain tensor while Wij = (Aij −Aji)/2 is the rotation tensor. It is noted that P is close to zero since the flow is incompressible. Hence, it is simple to discuss in the Q-R space. First, the discriminant of the first equation can be written as

$$\Delta = \left(27R^2 + 4Q^3\right)/108$$

The space can be divided into two regions at Δ = 0 by r_{1a} and r_{1b}, which is given by

$$r_{1a} = -2(-3Q)^{3/2}/27$$

$$r_{1b} = +2(-3Q)^{3/2}/27$$

Moreover, the Q-R space can be divided by another line, r_2, which is the set that makes the equation has only purely imaginary roots and is given by PQ − R = 0. Since P = 0, it can be simplified to R = 0. Hence, the Q-R space can be divided into four spaces by r_{1a}, r_{1b}, and r_2, which is shown in Fig. 2. Each zone corresponds to a topology and represents a different physical mechanism.

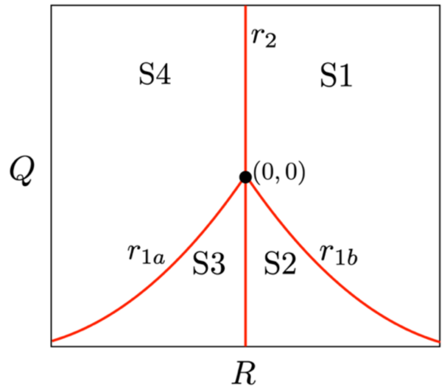

Figure 2: Different topological zones in the Q-R plane

4 Results

To understand the entrainment mechansims near the TNTI, the flow topology conditioned on the TNTI is analyzed in this section. It is noted that the TNTI is identified using a vorticity criteria [1] in this work. Figure 3 shows the joint probability density function (JPDF) of the second and third invariants of velocity gradient tensor near the TNTI. It is seen that S2 and S3 topology structures mainly affect fluid transport near the TNTI, while S1 and S4 topology structures have a negatigble impact. This suggests that the main factor influencing TNTI evolution is the shear deformation of fluid elements, and that the influence of vortex is very small. In this context, we can infer that the viscous shear plays an important role in the TNTI, instead of vortex diffusion.

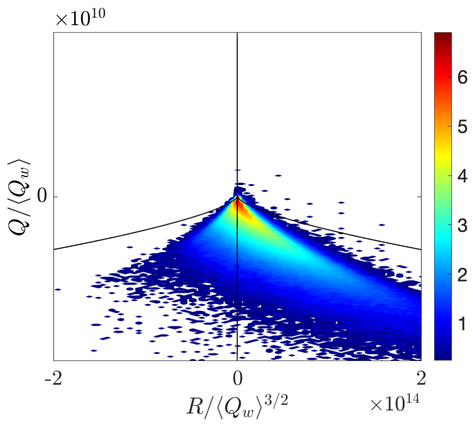

Figure 3: JPDF of R-Q conditioned on the turbulent/non-turbulent interface

To further understand the entrainment mechanisms near the TNTI, the JPDF of mean curvature (κ_m) and gauss curvature (κ_g) conditioned on the TNTI is shown in Fig. 4. It is found that the TNTI exhibit the high probability of flat shape, i..e, low-curvature structure. Given that low curvatures are associated with the nibbling process, the results suggest that the nibbling dominates over the engulament in the entrainment.

It is noted that the above flow topology and curvature analyses mainly investigates the structure of TNTI. In the future, the impact of flow topology and nibbling/engulament on scalalr mixing well be examined.

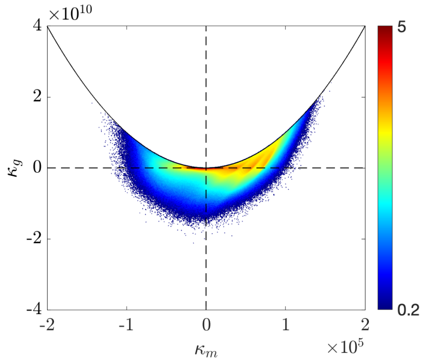

Figure 4: JPDF of κ_m-κ_g conditioned on the turbulent/non-turbulent interface.

5 Conclusion

In this work, a temporally evolving mixing layer is simulated using the direct numerical simulation method. Three passive scalars are considered to understand the scalar mixing process in turbulent jets. Currently, the flow topology and curvature conditioned on the turbulent/non-turbulent interface (TNTI) are investigated. It is found that the S2 and S3 topology structures mainly affect fluid transport near the TNTI, which suggests that the main factor influencing TNTI evolution is the shear deformation of fluid elements, instead of vortex diffusion. Furthermore, the results indicates that the nibbling dominates over the engulament in the entrainment. In the future, the impact of flow topology and nibbling/engulament on scalalr mixing well be examined.

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