Effects of Turbulence Reynolds Number on Structure and Propagation of Turbulent Premixed Flames

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Abstract

The flame structure and propagation characteristics of high-pressure, high-temperature turbulent premixed flames in terms of the effects of turbulent Reynolds number was investigated. OH radical profiles of the turbulent flame, which was stabilized by a nozzle-type burner with a turbulence generator installed in a high-pressure chamber, were taken by planar laser-induced fluorescence (OH-PLIF) method. The OH-PLIF images of turbulent premixed flame were analyzed to find fractal inner cutoff as the smallest scale of flame wrinkles and turbulent burning velocity.

It was found that this fractal inner cutoff first decreases with turbulent Reynolds number based on Tayler microscale, R_λ (=$u'\lambda_g/\nu$, where u', λ_g, and ν are turbulence intensity, Taylor microscale, and kinematic viscosity) , and then becomes almost constant with further increase in R_λ regardless of pressure and temperature of mixture (Fig. 1). In a high-pressure environment, it has been already found that the flame wrinkles becomes very fine [1]. It was conformed that the fractal inner cutoff as the smallest scale of flame wrinkles, ε_i, is strongly correlated with the characteristic scale of flame instability, i.e., Darrieus-Landau instability combined with diffusive-thermal effects, l_i, in a high-pressure and high-temperature environment.

To explore how the small-scale vortex in turbulent flow of an unburned mixture affects flame wrinkles and D-L instability of flame front, precise measurements of energy spectrum of turbulence were performed using a hot wire anemometer (Fig. 2). From this measurement, nondimensional

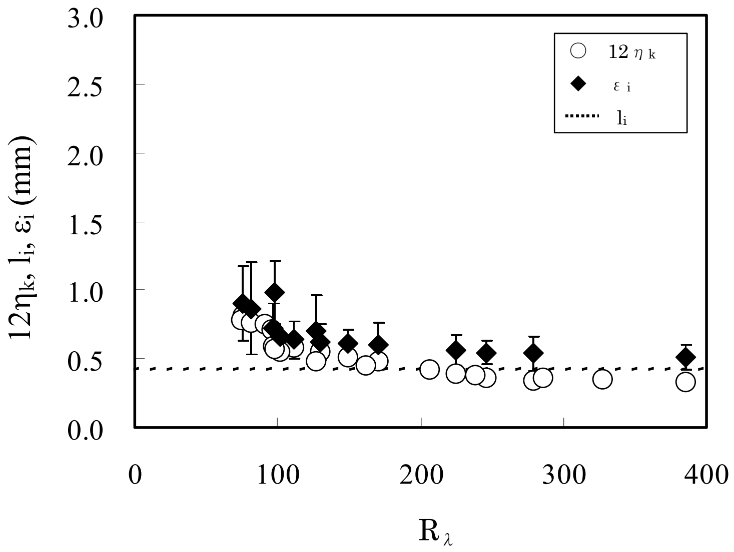

Figure 1. Variations of the average diameter of vortex tube, $12\eta_k$, and fractal inner cutoff, ε_i, with turbulence Reynolds number, R_λ, and comparison with the characteristic scale of flame instability, l_i at 1.0 MPa and 573 K using O.D.20 mm burner for CH_4/air mixture.

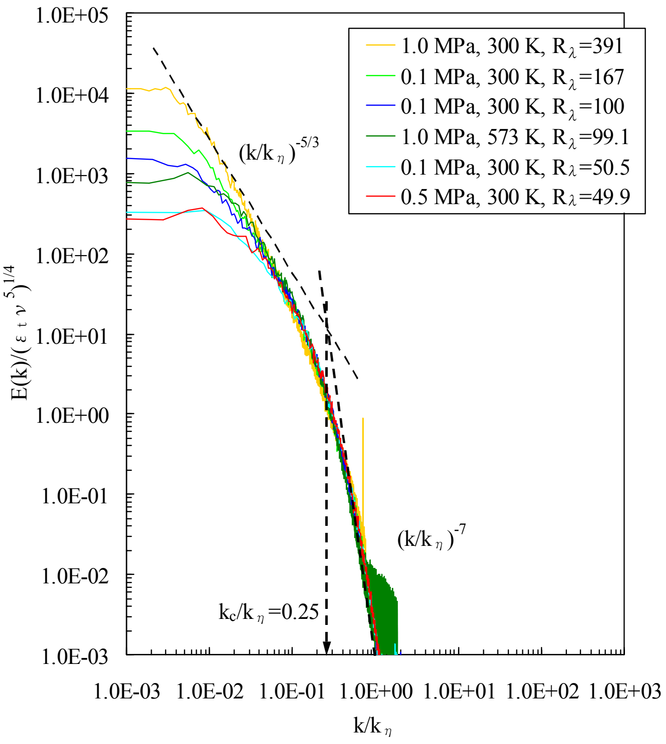

Figure 2. Nondimensional energy spectrum of turbulence at various pressure and temperature.

energy spectrum based on Kolmogorov's similarity law was confirmed and the Kolmogorov wavenumber at the point of intersection of the two lines –5/3 power law and –7 power law was converted to a length scale. The length scale was 12.6 times larger than Kolmogorov scale, η_k.

When this length scale is smaller than characteristic scale of flame instability, D-L instability had great effect on flame wrinkles. It has been recently revealed by DNS (Direct Numerical Simulation) that the average vortex-tube diameter is 10 to 12 times larger than the Kolmogorov scale. Average vortex-tube diameter in turbulent flow 12 times larger than Kolmogorov scale has great effect on flame wrinkles and D-L instability. When the fractal inner cutoff decreases with R_λ, the fractal inner cutoff scale becomes almost equal to 12 times Kolmogorov scale, $12\eta_k$. When the fractal inner cutoff, ε_i, becomes constant with a further increase in R_λ, the scale is almost equal to characteristic scale of flame instability, l_i. This relationship between fractal inner cutoff, Kolmogorov scale, and the characteristic scale of flame instability, was confirmed even at atmospheric pressure using a larger burner to realize large turbulence Reynolds number and another kind of mixture (Fig. 3).

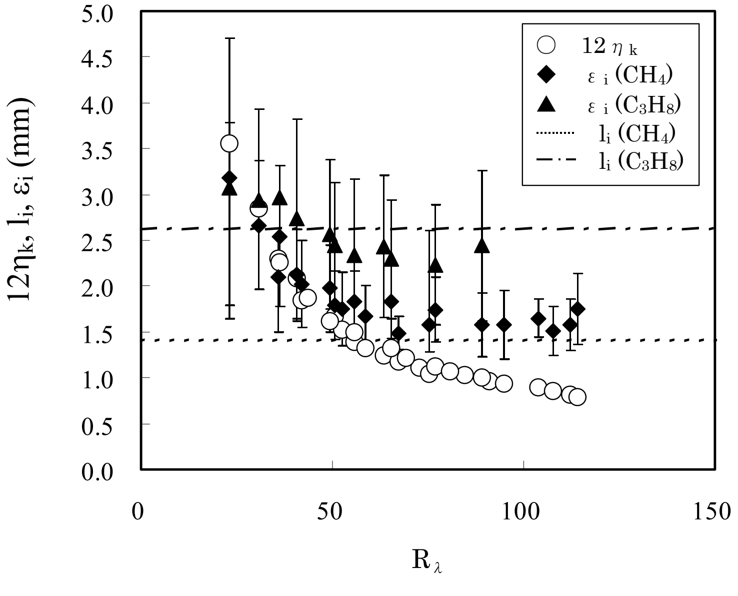

Figure 3. Variations of the average diameter of vortex tube, $12\eta_k$, and fractal inner cutoff, ε_i, with turbulence Reynolds number, R_λ, and comparison with the characteristic scale of flame instability, l_i at 0.1 MPa and 300 K using O.D.60 mm burner.

The turbulent burning velocities, S_T, were measured using the angle method and the area method for the mean flame cone and the mean progress variable based on OH-PLIF images, $<\bar{c}>$.

From $<\bar{c}>$ profiles, it was found that, in some experimental conditions, $<\bar{c}>$ constant images have no clear cone angle the area method was suitable. The mean flame cone [2] was almost equal to the $<\bar{c}>= 0.5$ position, so that both turbulent burning velocities determined using these two methods were equal. The bending of S_T/S_L curves, where S_L is laminar burning velocity, was seen for any $<\bar{c}>$ over the wide range of experimental condition. The R_λ at which S_T/S_L gradually bends corresponded to the R_λ at which the fractal inner cutoff becomes almost constant (Fig. 4). The best correlation between u'/S_L and S_T/S_L derived from $<\bar{c}>= 0.1$ position was $S_T/S_L \propto [(P/P_0)(u'/S_L)]^{0.38}$ regardless of mixture temperature, and the exponent 0.38 of this relation was equal to that of the relation derived from the mean flame cone previously [2, 3].

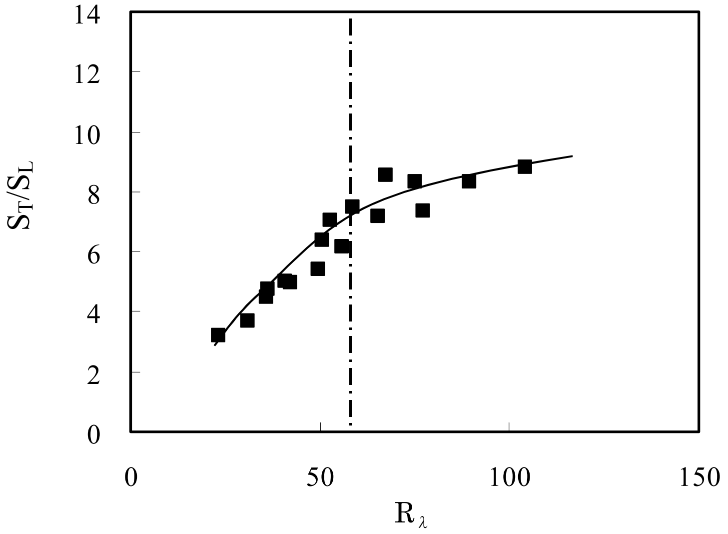

Figure 4. Variations of turbulent burning velocity with turbulence Reynolds number, R_λ, at 0.1 MPa and 300 K using O.D.60 mm burner for CH_4/air mixture.

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