

Mixedness Measurement in Gaseous Jet Injection

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Abstract

In turbulent non-premixed combustion applications, such as diesel and direct injection engines, the mixedness of the injected fuel with oxygen and the working fluid inside the combustion chamber is a crucial parameter since it can significantly affect the ignition behavior. In this study, a comprehensive method for investigating mixedness, defined by spatial variation and scalar dissipation, is implemented to assess the turbulent injection of hydrogen into mixture of oxygen with nitrogen, argon, and xenon. Evaluating both criteria reflects the mixture homogeneity as well as local gradients, which aids in discriminating scalar distributions with identical homogeneity and different patterns. The results indicate that replacing nitrogen with argon as the working fluid can provide more suitable ignition conditions for the hydrogen jet.

Keywords: *Mixedness, Scalar Dissipation, Spatial Variation, Gaseous Injection*

1.0 Introduction/Background

Measuring mixedness has always been of great interest due to many relevant applications, including turbulent non-premixed combustion. For instance, in diesel and direct injection engines, an increase in mixing rate of the fuel and the working fluid can improve the combustion quality and the engine efficiency. However, understanding the mixedness concept and developing a comprehensive method to measure the mixing rate is not a straightforward exercise. To investigate the behavior of a turbulent jet, two different length scales should be understood: (1) the integral length scale (δ), which is the large length scale and relates

to convection, and (2) the strain-limited length scale (λ_D), which is the small length scale and corresponds to diffusion.

$$\frac{\lambda_D}{\delta} = \Lambda Re^{-3/4} Sc^{-1/2} \quad (1)$$

Equation 1 shows the relationship between these length scales. Λ is the scale constant, Re is the integral Reynolds number of the jet, and Sc is the Schmidt number which approximately equals unity for gaseous jets [1]. Chemical reactions between fuel and oxidizer occur at the smallest length scales. However, the turbulent mixing process is important and plays a key role since it implicitly contributes to the scalar variance and molecular

mixing [2]. The rate of the scalar mixing at molecular level is called the scalar dissipation, which is the most fundamental parameter in non-premixed turbulent combustion and is described by Equation 2. ξ is a conserved scalar (e.g., temperature or mixture fraction), D is the scalar diffusivity, and χ represents the scalar dissipation [3].

$$\left(\frac{\partial}{\partial t} + u \cdot \nabla - D \nabla^2 \right) \frac{1}{2} \xi^2 = -D \nabla \xi \cdot \nabla \xi = -\chi \quad (2)$$

Several investigations have been carried out on mixedness measurement [4-6]. However, most of them only consider the scalar population and do not provide information about the scalar distribution patterns. In this study, a comprehensive method for measuring the mixedness [7] is selected and implemented on a turbulent gaseous injection into a constant volume combustion chamber to understand the effect of the working fluid on the gaseous fuel mixing rate, which is a critical parameter in assessing the non-premixed combustion quality.

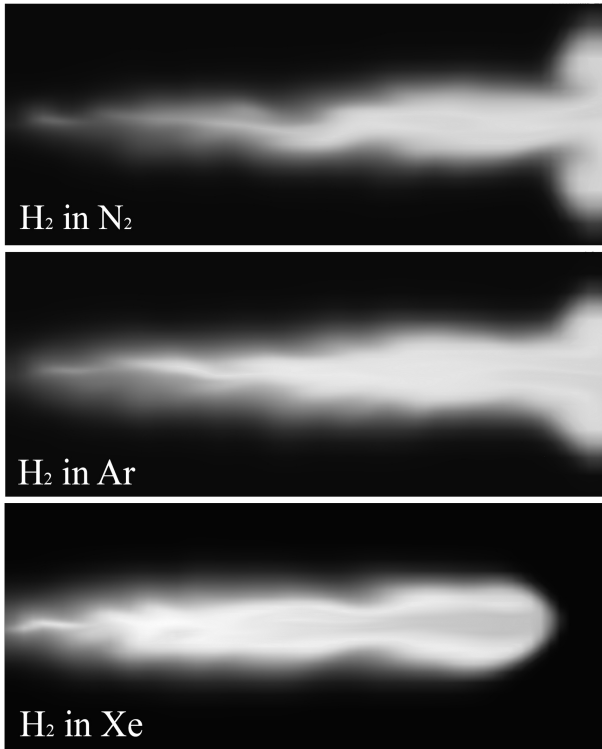


Figure 1. Mixture fraction distribution for hydrogen into nitrogen, argon, and xenon at 6 ms after injection.

2.0 Data/Formulation/Methodology

Numerical data from the turbulent injection of hydrogen into a mixture of oxygen and different working fluids (nitrogen, argon, and xenon) were utilized to measure the mixedness of the gaseous fuel and the environment in order to compare the effect of different working fluids. For details of the numerical setup and data refer to [8].

Figure 1 shows the scalar distribution of the hydrogen jet into different working fluids at 6 ms after the injection. The bright areas with higher pixel intensities involve more hydrogen concentration compared to the dark areas which mainly contain the working fluid. Here, $\xi_{i,j}$ is defined as the pixel intensity at i^{th} row and j^{th} column of the image.

3.0 Analysis

The scalar dissipation (Equation 2) is discretized for the numerical calculation as shown in Equation 3. The value of the scalar dissipation at each cell (pixel) is calculated based on the neighbor cells. Δ is the pixel to pixel distance [7].

$$\begin{aligned} \chi &= D (\nabla \xi \cdot \nabla \xi)_{i,j} \\ &= -D \left[\frac{1}{4\Delta} (\xi_{i+1,j} - \xi_{i-1,j}) + \frac{1}{8\Delta} (\xi_{i+1,j+1} + \xi_{i+1,j-1} \right. \\ &\quad \left. - \xi_{i-1,j+1} - \xi_{i-1,j-1}) \right]^2 \\ &\quad - D \left[\frac{1}{4\Delta} (\xi_{i,j+1} - \xi_{i,j-1}) + \frac{1}{8\Delta} (\xi_{i+1,j+1} + \xi_{i-1,j+1} \right. \\ &\quad \left. - \xi_{i+1,j-1} - \xi_{i-1,j-1}) \right]^2 \end{aligned} \quad (3)$$

The scalar dissipation is then normalized by the mean pixel intensity (ξ_m) and averaged on an N by P pixels region to obtain a single value, χ_m , called the mean scalar dissipation as described in Equation 4.

$$\chi_m = \frac{1}{NP} \sum_{i,j} \frac{(\nabla \xi_{i,j} \cdot \nabla \xi_{i,j})}{(\xi_m / \lambda_D)^2} \quad (4)$$

Furthermore, the spatial variation which corresponds to the scalar population is calculated based on the value of the mean scalar and averaged on the N by P pixels region. Equation 5 shows the

formulation for calculation of the mean spatial variation.

$$\frac{\sigma}{\xi_m} = \frac{\left\{ \left[1 / (NP) \right] \sum_{i,j}^{N,P} \left[\xi_{i,j} - \xi_m \right]^2 \right\}^{1/2}}{\xi_m} \quad (5)$$

4.0 Results and Conclusions

Using Equation 5, the mean spatial variation is calculated at every 0.25 ms, giving 24 values for each case. It is then plotted versus the mean scalar dissipation, evaluated by Equation 4, for the same cases as illustrated in Figure 2. Both mean spatial variation and mean scalar dissipation decrease over time. Technically, it is perceived that the closer the data point is to the origin, the better mixing rate. According to this concept, hydrogen injection into xenon shows a better mixing rate at the very early time steps compared to nitrogen and argon. Since xenon has a higher molecular weight (131 g/mole) compared to nitrogen (28 g/mole) and argon (40 g/mole), it shows a higher resistance against the hydrogen jet penetration. Therefore, the region is mainly filled with xenon (dark areas). For the later time steps, a closer observation to the plot is required, which is shown in Figure 3.

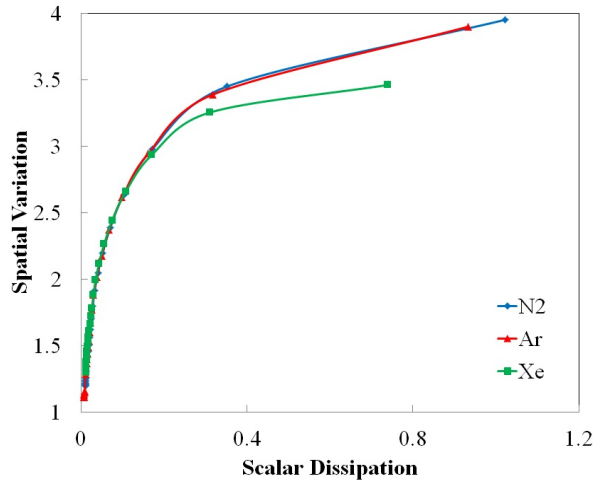


Figure 2. Spatial variation vs. scalar dissipation.

At the later time steps, argon indicates the best mixing progress and xenon demonstrates the least mixedness. Figure 1 shows that hydrogen jet into nitrogen and argon has approximately an identical behavior at 6 ms after the injection. In both cases, the jet hits the end wall which causes it to be

propagated toward the side walls. Yet, the wall impingement does not occur in the xenon case.

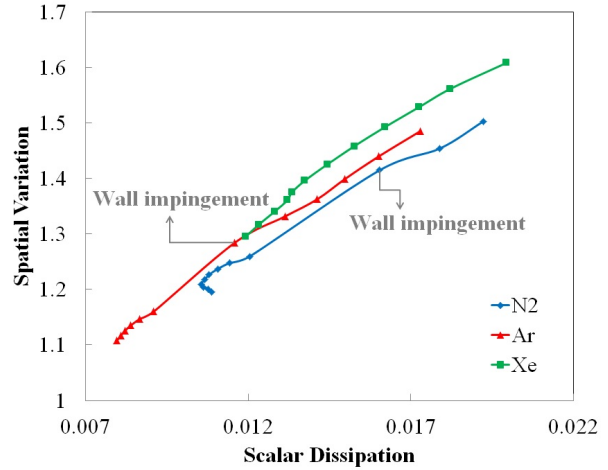


Figure 3. Spatial variation vs. scalar dissipation between 3 ms and 6 ms after injection.

Moreover, Figure 3 suggests that wall impingement can result in a severe increase in mixing process. The relatively long distance between the wall impingement data point and the next time step proves this idea.

Table 1. Diffusion coefficients at 100°C, 1 atm.

Mixture	$D_{12}/\text{cm}^2\text{s}^{-1}$
H ₂ - N ₂	1.162
H ₂ - Ar	1.228
H ₂ - Xe	0.890

Table 1 shows the diffusion coefficients for the mixtures of hydrogen and different working fluids at a constant temperature and pressure. Hydrogen-argon mixture has the greatest diffusion coefficient, which means that hydrogen can diffuse more easily into argon rather than nitrogen and xenon. This observation can be a reason for the higher mixedness of the hydrogen jet into argon at late time steps after injection, when the jet has filled the chamber and diffusion plays a more important role in mixedness rather than advection.

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