ON THE THICKNESS OF THE SCALAR SUPERLAYER AND ITS CONTRIBUTIONS TO THE MIXTURE FRACTION PDF IN A JET FLOW

Markus Gampert*[a)], Philip Schaefer*& Norbert Peters*
*Institute for Combustion Technology, RWTH Aachen University, Aachen, 52056, Germany

Summary Based on planar high-speed measurements of the mixture fraction Z in a turbulent round jet with nozzle based Reynolds numbers between $3,600$ and $8,600$, we investigate the scalar superlayer of the flow. Since combustion occurs in the vicinity of the stoichiometric mixture fraction, it is expected to take place largely within that layer. Therefore, profound understanding of this part of the flow is essential for an accurate modeling of turbulent non-premixed combustion. To this end, we first validate a composite model [1] for the pdf $P(Z)$, which turns out to be in good agreement with the measurements. In a second step, we analyze the scaling of the thickness δ of the scalar superlayer, and conclude that $\delta/L \sim Re_\lambda^{-1}$ where L is an integral length scale and Re_λ the local Taylor based Reynolds, meaning that $\delta \sim \lambda$.

INTRODUCTION

In various combustion applications, fuel and oxidizer enter separately into the combustion chamber. They mix and burn there, resulting in so called non-premixed turbulent combustion [2], where the fuel often enters the combustion chamber as a turbulent jet. Mixing occurs in these processes due to continuous interdiffusion of a hydrocarbon fuel with air. The combustion of the former then requires a fuel/air stoichiometric mixture fraction Z_{st} of around 0.06, meaning that combustion occurs at the outer boundary of such a turbulent flow, which is characterized by turbulent regions adjacent to non-turbulent ones. Corrsin and Kistler [3] first termed the layer adjacent to the interface the 'laminar superlayert'. In analogy, we will refer to the region in which the scalar signal changes from turbulent to laminar as the 'scalar superlayert'. These two physically fundamentally different parts of the flow are also of major importance to the modeling of non-premixed combustion, as they manifest themselves in the regularly observed bimodal structure of the scalar probability density function (pdf) in the intermittent region. The idea that the superlayer might represent more than just a thin diffusive layer at the edge of a turbulent flow and that it might have an effect on the statistics well within the turbulent region was already elaborated by Effelsberg and Peters [1]. The latter considered this transition zone between the turbulent and the non-turbulent regions as a separate layer and formulated a model for a composite probability density function (pdf) for a conserved scalar, which takes the separate contributions from the fully turbulent and the superlayer region into account and relates the four parameters of the model to the first four moments of the pdf. The present study continues the investigation of the conserved scalar pdf in the presence of the scalar superlayer as well as analyses the scaling of the thickness of this superlayer by means of an experimental investigation of the mixture fraction field of a turbulent jet flow.

ANALYSIS

The experiments were performed in a co-flowing turbulent jet facility, which consists of a center tube with an internal diameter of 12 mm. The surrounding co-flow tube has a diameter of 150 mm. Research grade propane (99.95% pure) is fed through the center tube and CO_2 was chosen as co-flow gas owing to its larger Rayleigh cross-section, which is necessary to obtain an accurate determination of the scalar superlayer. The Reynolds number Re_D based on jet exit conditions, was varied between $3,000$ and $8,600$ and the corresponding jet exit velocity was between 1.15 and 3.30 m/s. The scalar fields were acquired using high-speed two-dimensional Rayleigh scattering imaging. Two frequency doubled beams ($\lambda = 527$ nm) from a high-frequency dual-head Nd:YLF laser were combined to deliver an energy of about 32 mJ/p at 1 kHz (32 W). The beams were transformed into a collimated sheet using a combination of a Galilean telescope (expansion ratio of 1.5) and a cylindrical lens. The width and the thickness of the resultant beam were approximately 10 mm and 1 mm respectively. Images were acquired at 1 kHz using a high-speed CMOS camera (LaVision HighSpeedStar 6) fitted with a camera lens (Nikon f.l. = 85 mm) stopped at $f/1.4$. The signal-to noise ratio in the pure CO_2 region is over 20 and that in the pure propane region is over 40. The resolution is of the order of the Kolmogorov scale η, thus allowing a detailed investigation of the superlayer. Figure 1 shows a representative measured profile of an intermittent mixture fraction signal. One clearly observes three different regions in the signal, one of which belongs to the fully turbulent part of the flow (A), while the second one (B) describes the two scalar superlayers, where the value of the mixture fraction drops from the turbulent to the outer flow value. In the third part (C), one observes this outer flow with $Z = 0$. As mentioned in the introduction, the stoichiometric mixture fraction of a propane-air mixture is $Z_{st} = 0.06095$ which is clearly located in the scalar superlayer marked by the dashed lines for the present example. Furthermore, a length scale δ is introduced, indicating that the extension of the superlayer can be described by a characteristic thickness, while the fully turbulent part and the outer flow can be arbitrarily long.

Based on this physical interpretation of an intermittent signal of a conserved scalar, [1] formulated a composite model for the pdf of such a quantity. The latter calculates pdfs for the superlayer $P_s(Z)$ and the fully turbulent part $P_t(Z)$ separately which are then used to formulate a composite pdf. To this end, the authors used the first four moments of the scalar pdf and

[a)] Corresponding author. E-mail: m.gampert@itv.rwth-aachen.de

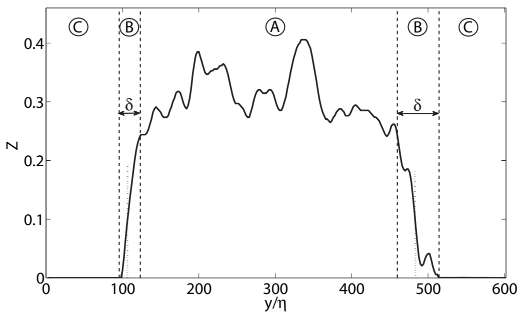

Figure 1. Measured profile of the mixture fraction Z at $x/d = 10$ and $U_j = 2.26$ m/s, shown over an arbitrary coordinate y/η.

relate them to the model parameters. We measure $P(Z)$ and calculate its first four moments $Z_1 - Z_4$, for mathematical details please refer to [1]. Based on this input, we can calculate a composite pdf $P_c(Z)$. A representative result for the mixture fraction pdf together with its model parameters is shown in Fig. 2 (a), where we observe a very good agreement between the measured and the modeled pdf. It is noteworthy that we find relatively large values of s even for values of the intermittency factor γ close to one, thereby indicating that even close to the centerline of the jet a considerable part of the signal stems from a transition between the fully turbulent region and the scalar superlayer. The separation into two sub-pdfs indicates that the flow in the region of stoichiometric mixture is dominated by the superlayer rather than by the fully turbulent part of the flow. Furthermore, it is obvious from Fig. 2 (a) that the composite model is well suited to reproduce $P(Z)$ even in a very intermittent sheared region of the flow where it is of major interest for modeling of non-premixed combustion. Finally, we observe an almost constant mean mixture fraction value Z_t in the fully turbulent part at fixed axial and different radial location as well as varying γ, $P_t(Z)$ thus being of non-marching character [4].

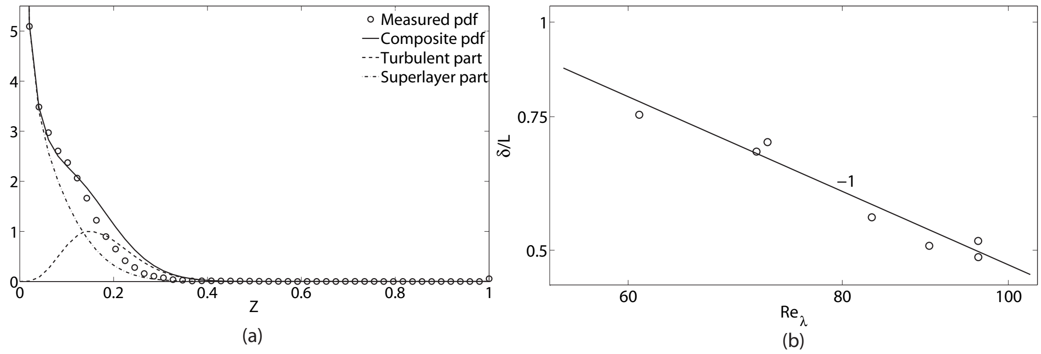

Figure 2. (a) Comparison between measured and approximated pdfs at $x/d = 20$ and $\tilde{r} = 0.17$ with $Re_D = 8,610$, $\gamma = 0.751$. (b) Scaling of the non-dimensional thickness of the scalar superlayer δ/L as a function of the Taylor-based Reynolds number.

In a next step, we will investigate the scalar superlayer of the jet and in particular its thickness δ in more detail. The value of the mixture fraction drops in this part of the flow from its turbulent value to zero, based on which Prasad and Sreenivasan [5] developed a method to detect the location of the superlayer which is also applied in the present study. Based on the high-speed measurements we analyze the position of the superlayer and the profile of the mixture fraction in the superlayer normal direction to analyze its spatial extension δ, where we observe a steep scalar drop across the superlayer. The resulting values normalized with a local integral scale L, where $L = 0.7 * r_{1/2}$ [6] (note that any integral scale serves our purpose), are shown in Fig. 2 (b) as a function of the local Taylor based Reynolds number in a double logarithmic plot. Da Silva and dos Reis [7] postulated for the thickness of the superlayer in the presence of a mean shear a scaling according to $\delta/L \sim Re_L^{-1/2}$, where Re_L is a Reynolds number based on the integral scale L. This translates in terms of the Taylor based Reynolds number into $\delta/L \sim Re_\lambda^{-1}$. Based on the present results, we can confirm this relation as all experimentally determined data points clearly scatter around the included line with a slope of minus one. Hence, $\delta \sim \lambda$ meaning that the superlayer is neither purely dominated by viscous nor by inertial length scales.

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