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## 2<sup>nd</sup> Symposium on Ammonia Energy

# Local Curvature and Speed of Turbulent Premixed Ammonia and Blends with Methane and Hydrogen Flames in a Spherically Expanding Configuration

Seif Zitouni <sup>\*a</sup>, Pierre Brequigny<sup>a</sup>, Christine Mounaïm-Rousselle<sup>a</sup>

<sup>a</sup> Université d'Orléans, INSA-CVL, EA 4229—PRISME, 45072 Orléans, France

\* Corresponding author.

e-mail address: seif-eddine.zitouni@univ-orleans.fr

### Topics: Combustion Fundamental

### Introduction

Ammonia (NH<sub>3</sub>) as a fuel boasts several benefits, notably a high volumetric energy density, and is emerging as an efficient zero-carbon Hydrogen (H<sub>2</sub>) carrier. However, there are number of practical combustion challenges hindering wide-spread application, including but not limited to slow burning velocity, long ignition delay times as well as the control and reduction of pollutant emissions (NO<sub>x</sub> and N<sub>2</sub>O). To alleviate these barriers, the use of NH<sub>3</sub> blending with either Methane (CH<sub>4</sub>) and/or H<sub>2</sub> obtained by in-situ NH<sub>3</sub> cracking, seem to be promising solutions to improve NH<sub>3</sub> combustion characteristics, and has gained considerable recent attention, with comprehensive reviews of NH<sub>3</sub> related work undertaken [1]. In literature, the research upon the laminar burning velocity ( $S_L^0$ ), one fundamental physiochemical property of a combustible mixture and a critical step in turbulent flame combustion, of NH<sub>3</sub> based fuels has been increasingly investigated [2]. However, there remains limited peer-reviewed studies regarding the turbulence-flame interaction for NH<sub>3</sub> fuel, more reflective of practical combustion systems. Relative to  $S_L^0$ , the turbulent burning velocity ( $S_T$ ) is enhanced due to flame stretch and wrinkling induced by the turbulence, with potential enhanced mixing resulting in an increase in combustion efficiency. The very different characteristics of NH<sub>3</sub> (low  $S_L^0$  coupled with a large flame thickness ( $\delta_L$ )) relative to hydrocarbons result in significant differences in relative chemical time scales (ratio of  $S_L^0/\delta_L$ ). As a consequence, the turbulent burning of NH<sub>3</sub> leads to higher turbulence Karlovitz numbers (Ka) [3]. Recent turbulent combustion experiments, underline the role of preferential-diffusion and flame stretch upon NH<sub>3</sub> based flames, but understanding of some of the physical phenomena, such as the influence of turbulent wrinkling upon local curvature and local flame speed remains scarce, particularly from an experimental perspective. To that end, the spherically expanding flame configuration coupled with Mie-scattering tomography was employed, facilitating the study of the flame structure and turbulent interaction of NH<sub>3</sub> and NH<sub>3</sub>-based blends. For each stage of the flame development the mean global stretch and mean propagation speed, as well as the local flame speed and curvature are evaluated. Finally, the statistical behaviour of local flame speed in response to curvature is analysed and the influence of preferential-diffusion and flame stretch interaction discussed.

### Materials and Methods

In the present study, a constant-volume vessel was employed, closely mimicking practical situations such as combustion in engines. The vessel is fitted with six-four blade fans, positioned in a regular hexahedral configuration, producing a near-isotropic and homogeneous region within a radius of 20 mm of the vessel, fully described in [4]. Two fan speeds were investigated (0.65 and 0.98 m/s), with the integral length scale of the system ( $L_T$ ) ~ 2.64 mm. Mie-scattering laser tomography was employed, enabling enhanced precision with respect to flame front wrinkling by the turbulence. Details of this optical set-up alongside the employed post-processing techniques can be found in [5]. By assuming a spherical flame, from the binarized flame contour images, the surface equivalent flame radius ( $R_s$ ) and perimeter ( $R_p$ ), defined as  $R_s=(A/\pi)^{1/2}$  and  $R_p=(P/2\pi)$ , where A represents

the burnt gases area and  $P$  the perimeter, were determined. The wrinkling ratio ( $W$ ) was evaluated to be  $W=R_p^2/R_s^2$ . Lastly, the local flame curvature was estimated as follows [6]:

$$h = [x(s)y(s)'' - y(s)x(s)''] / [(x(s)')^2 + y(s)']^{3/2}$$

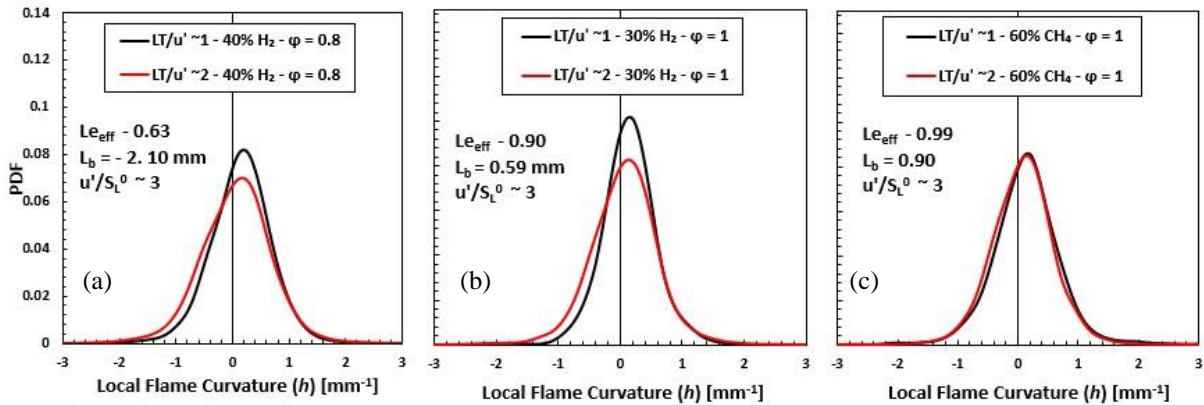
where  $x(s)$  and  $y(s)$  the coordinates on the spline curve and  $s$  the curvilinear coordinate. For positive flame front curvature, the local flame front is convex towards the fresh gases, with negative values to regions convex toward the burnt gases. With respect to blend selection a 60% - 40%  $\text{NH}_3/\text{H}_2$  ( $\Phi = 0.8, 1.0, 1.2$ ) blend (by vol.%) was appraised, as the aforementioned blend exhibits a similar  $S_L^0$  than that of pure  $\text{CH}_4$ , with differences in  $S_L^0 \sim 10\%$ , as well as similar thermo diffusive properties ( $Le = 1$ ), and is currently investigated for gas turbine applications. Moreover, two other blends, stoichiometric 40% - 60%  $\text{NH}_3/\text{CH}_4$  and 70% - 30 %  $\text{NH}_3/\text{H}_2$  were investigated and compared to the 60% - 40%  $\text{NH}_3/\text{H}_2$  ( $\Phi = 0.8$ ) blend, since these three different mixtures exhibit ostensibly similar  $S_L^0$  and flame thickness ( $\delta$ ) but different flame stretch sensitivity (Lewis number, Markstein Length), allowing to gain insight on the effect of flame stretch and wrinkling effect at constant turbulent intensity to laminar flame speed ratio ( $u'/S_L^0 \approx 3$ ) and ratio of the integral length scale and flame thickness ( $L_T/\delta_L \approx 4$ ). Table 1 summarises the mixture properties of the selected blends evaluated.

**Table 1:** Mixture properties of selected blends

Blends Denomination ( $\Phi$ )	$S_L^0$ (m/s)	$L_b$ (mm)	$Le_{\text{eff}}$	$\delta_L$ (mm)	$\sigma$ (-)	Ka	Da	$u'/S_L^0$
60% $\text{NH}_3$ - 40% $\text{H}_2$ (0.80)	<b>0.218</b>	<b>-2.09</b>	<b>0.63</b>	0.72	0.154	2.69 – 4.97	0.82 – 1.23	<b>2.98</b>
60% $\text{NH}_3$ - 40% $\text{H}_2$ (1.0)	<b>0.326</b>	<b>0.050</b>	<b>0.94</b>	0.60	0.140	1.34 – 2.48	1.46 – 2.20	/
60% $\text{NH}_3$ - 40% $\text{H}_2$ (1.2)	<b>0.292</b>	<b>0.960</b>	<b>0.96</b>	0.65	0.142	1.64 – 3.05	1.21 – 1.83	/
70% $\text{NH}_3$ - 30% $\text{H}_2$ (1.0)	<b>0.241</b>	<b>0.587</b>	<b>0.90</b>	0.84	0.138	2.49	1.17	<b>2.70</b>
40% $\text{NH}_3$ - 60% $\text{CH}_4$ (1.0)	<b>0.210</b>	<b>0.868</b>	<b>0.99</b>	0.69	0.135	2.79	1.23	<b>3.10</b>

## Results and Discussions

With respect to the examined 40% - 60%  $\text{NH}_3/\text{H}_2$  mixture, an increase in turbulent intensity resulted in an increase in the turbulent flame propagation, similar in magnitude for the lean ( $\Phi = 0.8$ ) and stoichiometric cases, whilst nominal change was observed for the rich case ( $\Phi = 1.2$ ), in spite of displaying a much higher  $S_L^0$  than the lean case. This is presumably due to the thermo-diffusive and stretch behavior of the flames, with the lean case exhibiting a negative Markstein Length (-2.09 mm) and  $Le$  below 1 (0.63), consequently enhancing turbulent flame propagation, with the rich case exhibiting a positive Markstein length and  $Le$  equal to unity. This difference in response to turbulence is also reflected in the wrinkling ratios, with the rich case displaying higher wrinkling ratios than the lean and stoichiometric case. It is interesting to note that both the lean case and rich case are located within the thin reaction zone regime on the Borghi diagram, however the lean case crosses the Damköhler limit = 1 ( $Da < 1$ ), whilst the rich case does not, which may potential result in different eddy turbulent flame interaction, and thus turbulent flame propagation rate. However, this effect was only partially observed in the local curvature PDFs, with all three  $\Phi$  evaluated displaying similar distributions. On the other hand, various blends were evaluated at constant  $u'/S_L^0$  ( $\sim 3$ ) with selected fundamental combustion properties of mixtures located in Table 1. As can be seen from Fig. 1, the PDFs of curvature at a fixed eddy turn over time, distinctively spread towards greater negative curvatures with a decreasing  $Le$  and Markstein length, underlining the role of flame stretch interaction on turbulent  $\text{NH}_3$  flames, with this behavior invariably impacting practical combustion systems.



**Fig. 1** – Curvature PDFs of (a) 60%NH<sub>3</sub> - 40%H<sub>2</sub> ( $\Phi = 0.80$ ), (b) 70%NH<sub>3</sub> - 30%H<sub>2</sub> ( $\Phi = 1.0$ ), (c) 40%NH<sub>3</sub> - 60%CH<sub>4</sub> ( $\Phi = 1.0$ ) as a function of eddy turn over time ( $L_T/u'$ )

## Conclusions

To enhance knowledge of turbulent-flame interaction of NH<sub>3</sub> based flames, global and local flame structure analysis was conducted upon spherically expanding flames, for different stages of flame development. When the ratio of the turbulence intensity to laminar flame speed is constant ( $u'/S_L^0 \approx 3$ ) as well as the ratio of the integral length scale and flame thickness ( $L_T/\delta_L \approx 4$ ), the thermo-diffusive and stretch behaviour have an influence both on the global parameters, such as the turbulent flame propagation and local flame structure such as the local flame curvature. Indeed, differences are observed between the various blends due to different reaction to flame stretch. Consequently, to evaluate a fuel in terms of burning speed, particularly for NH<sub>3</sub>-based blends, flame stretch sensitivity has to be considered.

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