Results of turbulent flame speed for H_2-rich and syngas fuel mixtures measured

Deliverable 1.1.4

SEVENTH FRAMEWORK PROGRAMME

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Summary

In the deliverable D1.1.4, the turbulent flame speed (S_T) data for three hydrogen-rich fuel gases are presented. Comparisons with the syngas data previously acquired are also demonstrated. The lean premixed turbulent combustion in a confined jet configuration of three hydrogen-rich fuels (H_2-N_2 70%-30%, H_2-N_2 85%-15%, and H_2 100%; numbers in Vol. %) were investigated at the high-pressure test rig in PSI. Experiments were performed at fixed bulk velocity at combustor inlet (u_{bulk} = 40 m/s) and preheat temperature (T_{in} = 623 K). The pressure and equivalence ratio covered the range of 1-10 bar and 0.31-0.50, respectively.

Data show that for the hydrogen-rich flames, the profile of the averaged flame front generally approaches that of an ideal cone. Thus a simplified approach for estimating the S_T only via the flame length can be applied. To supplement the observations from experiments, combustion properties (e.g. unstretched laminar flame speed S_{L0} and laminar flame thickness D_L) were derived from chemical-kinetic calculations with the implementation of various reaction mechanisms. Distinct allocations of the data points on the regime diagram of premixed turbulent combustion [1] are observed. In general, the recently updated reaction schemes of H_2-O_2 kinetics are considered capable of capturing the fast chemistry of H_2-rich fuel gases more appropriately.

Background

Establishing reliable and clean combustion technologies for undiluted, hydrogen-rich (hereafter abbreviated as "H_2-rich") syngas is the ultimate goal of this sub-project. Due to distinct combustion properties, such as the much higher flame speed of hydrogen compared to methane, challenges emerge when introducing hydrogen to the premixed gas turbine engines that are conventionally fueled with natural gas. Combustion properties of H_2-rich fuel mixtures are thoroughly investigated in work package WP1.1, and this deliverable D1.1.4 addresses specifically the issue of turbulent flame speed (S_T).

Several definitions and procedures for evaluation of turbulent flame speed can be found in the literature [2-7], and one of the most common approaches of evaluating S_T is based on the continuity equation. This methodology provides a direct link of S_T to the mass burning rate, which is a critical parameter for combustor design. The major task then comes to identifying a representative surface of the flame front. A review by Bradley *et al.* [6] addressed the issue of determining S_T in a fan-stirred bomb via the perspectives of flame surface density, turbulent Karlovitz stretch factor, and Markstein number for the flame strain rate. In another study on a similar configuration, the turbulence Reynolds number and the Lewis number were considered essential to derive the correlation for S_T [5]. It is clear that to characterize the turbulent flame speed appropriately, various dimensionless parameters depicting the flow-turbulence-flame interactions have to be incorporated. Research activities on this issue still vigorously proceed in the combustion community.

Despite the quantity of investigations on S_T [8-11], a deficit exists for lean premixed combustion experiments with H_2-rich fuels at gas turbine relevant conditions (high-pressure/-temperature). Characteristics of the turbulent flame speed were investigated for various syngas mixtures (with the maximum H_2 contents of 67 Vol. %) at the pressure up to 20 bar [8]. Recent work from Ichikawa *et al*. [9], Venkateswaren *et al*. [10] and Marshall *et al.* [11] also focused on similar issues with extensive discussions from the perspectives like scale relations [9], stretch sensitivity [10-11], and the concept of leading point [10-11]. Nonetheless, while the H_2 contents in the former [9] were generally not categorized as H_2-rich, the latter studies [9-10] contained few data points at high pressure and were limited to non-preheat conditions. Accordingly, a dedicated investigation on the turbulent flame speed for H_2-rich fuels at gas turbine relevant conditions (elevated pressure, preheated) is imperative for attaining the objectives of SP1.

Turbulent Flame Speed (S_T)

Experiments / Operational Range

The measurement campaign for investigating the flame front characteristics of H_2-rich fuels has been conducted at the high-pressure test rig in PSI. The axial-dump combustor with complete optical access is specifically designed to study turbulent, lean premixed flames (Figure 1). Three H_2-rich fuel gases (H_2-N_2 70%-30%, H_2-N_2 85%-15%, and H_2 100%; numbers in Vol. %) were selected. Experiments were performed at fixed bulk velocity at combustor inlet (u_{bulk} = 40 m/s) and preheat temperature (T_{in} = 623 K). The pressure and equivalence ratio covered the range of 1-10 bar and 0.31-0.50, respectively. Laser diagnostics such as planar laser induced fluorescence of OH radicals (OH-PLIF) was implemented to measure and derive the turbulent flame speed (S_T). For each measuring point, 400 images (instantaneous shots) were acquired (at about 20Hz) to ensure a good statistics. The post processing of the data was performed with a methodology developed in-house and well accepted by the combustion community [8].

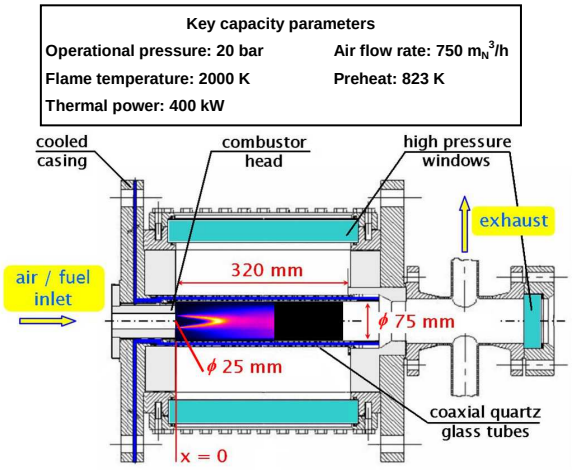


Figure 1

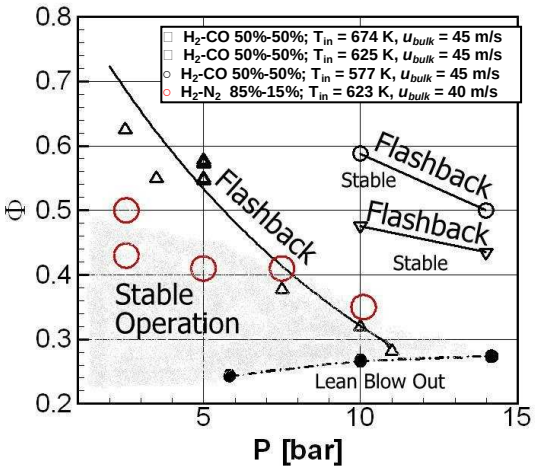
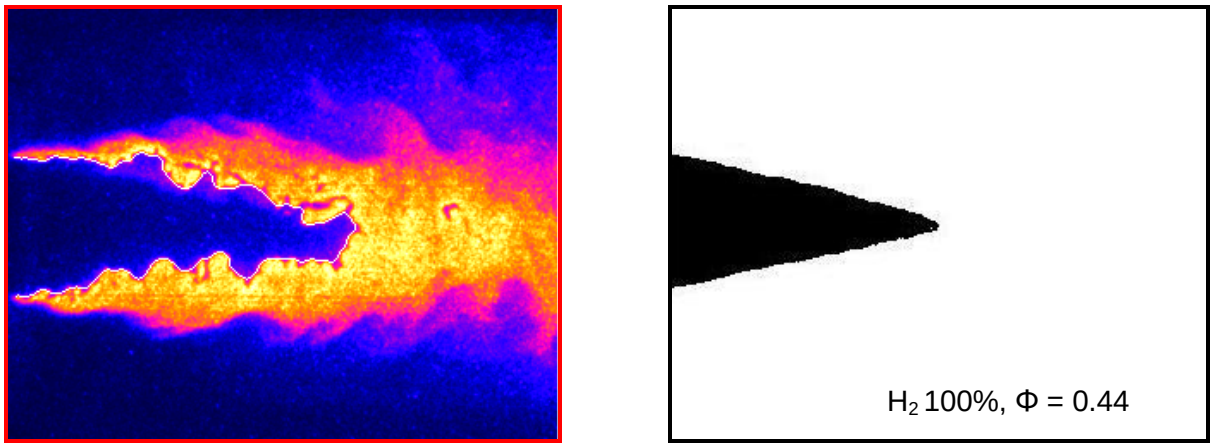


Figure 2

Five representative data points collected for the fuel mixture H_2-N_2 85%-15% (hereafter mentioned as “H85N”) are marked as red circles in Figure 2. The figure is based on the operational window of a syngas mixture (H_2-CO 50%-50%) [12], and is demonstrated in terms of the equivalence ratio Φ versus pressure. The solid lines represent the limit above which flashback occurs for the syngas at various preheat temperatures. For safety concerns the flashback limit was not specifically determined for the three H_2-rich mixtures. Nonetheless, based on the operational experience with the current configuration of the facility, burning these mixtures at Φ = 0.5 has almost been the richest boundary that is

manageable at 2.5 bar. The flame length reaches roughly twice the diameter of the combustor inlet (d), and flashback occurs if the fuel flow is further increased. At higher pressure levels, the flames reach a similarly short length to that of the aforementioned boundary at much leaner stoichiometric ratios, which are also represented by the red circles. Accordingly, it is believed that the H_2-rich fuel gases behave similarly to the syngas, of which the operational window is drastically narrowed down at elevated pressure [12]. Since reducing the preheat temperature has proved to be capable of expanding the operational window for syngas (as shown by the points at higher pressure), the same approach seems applicable for the H_2-rich fuels. Nonetheless, the tested preheat temperature (T_{in} = 623 K) is already low as viewed from the standard of gas turbine operations. Modifications to the current premix-tube/burner configuration are hence necessary to proceed the measurements at even higher pressure with a practical level of preheat.

Evaluation of S_T



(a) (b)

Figure 3. Output from the post processing of raw PLIF images. (a) Raw PLIF image with the trace of flame front. (b) Binary image of the averaged flame front profile (c = 0.05).

Based on the methodology depicted in [8], the averaged flame front profile was derived from 400 instantaneous, planar contours of OH-PLIF. With these data, a progress variable (c) approach can be introduced. Figure 3 shows an example of the output from the procedure. In this work an iso-contour of c = 0.05 was selected as representative of the combustion wave, where c = 0 and c = 1 correspond respectively to the fresh mixture and the completely burnt gas. Selecting the progress variable closer to the fresh mixture side retains the consistency with the definition of the unstretched laminar flame speed (S_{L0}), which is an

important combustion property that facilitates the characterization of S_T. The three-dimensional flame front surface is obtained by rotating the iso-contour line (c = 0.05) about the x-axis assuming axial-symmetric flames. Solving the continuity equation for the combustor inlet and the flame front surface allows the evaluation of the turbulent flame speed. For convenience, the axial position at which the c = 0.05 contour crosses with the centerline is defined as the "flame tip" ($F_L^{<c>=0.05}$).

Turbulent Flame Speed Data for H_2-rich flames

According to the averaged flame front shown in Figure 3 (b), it is obvious that the profile is essentially an ideal cone. The phenomenon is further confirmed via evaluating the S_T for several representative data points from the mixture H85N. The turbulent flame speed S_T is plotted against the normalized flame tip location $F_L^{<c>=0.05}/d$ in Figure 4, where d is the diameter of the combustor inlet (d = 25 mm). Data from the measurements on syngas mixtures and CH_4 [8] are shown in grey for reference, while those from the mixture H85N are again marked as red circles. The dashed curve "S_T (ideal cone)" indicates the turbulent flame speed with the corresponding tip location if the average flame profile is exactly an ideal cone. Generally, the hydrogen flames exhibit extremely short flame length compared to syngas, and they are approaching the ideal cone condition very closely. Thus it is feasible to implement a simplified approach for evaluating the turbulent flame speed of hydrogen-rich fuel gases via using only the flame tip location as the differentiating parameter.

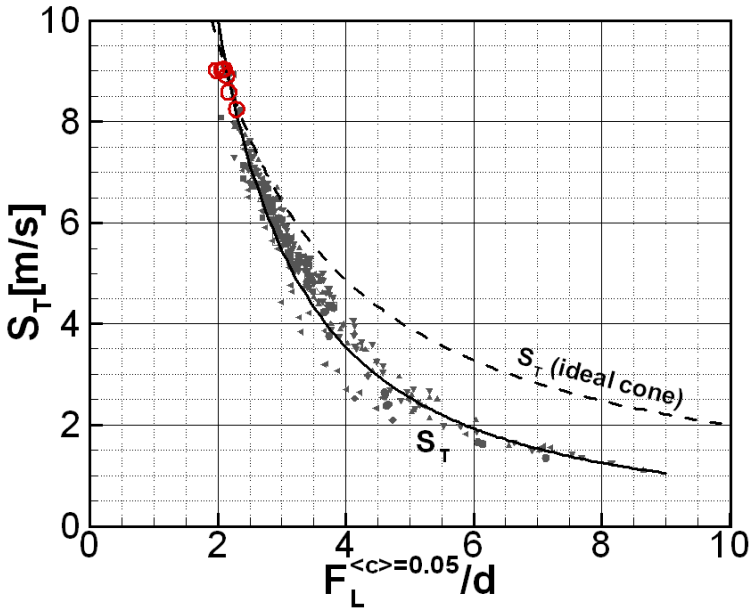


Figure 4

Figures 5, 6, and 7 present the turbulent flame speed evaluated for all collected data points in this deliverable. It is plotted against the normalized flame length ($F_L^{<c>=0.05}/d$), the equivalence ratio (Φ), and the adiabatic flame temperature (T_{ad}), respectively. In Figure 5, the solid curve again indicates the S_T with the corresponding tip location for an ideal "conic" flame. It should be noted that a ±10% error is expected for all absolute S_T values reported.

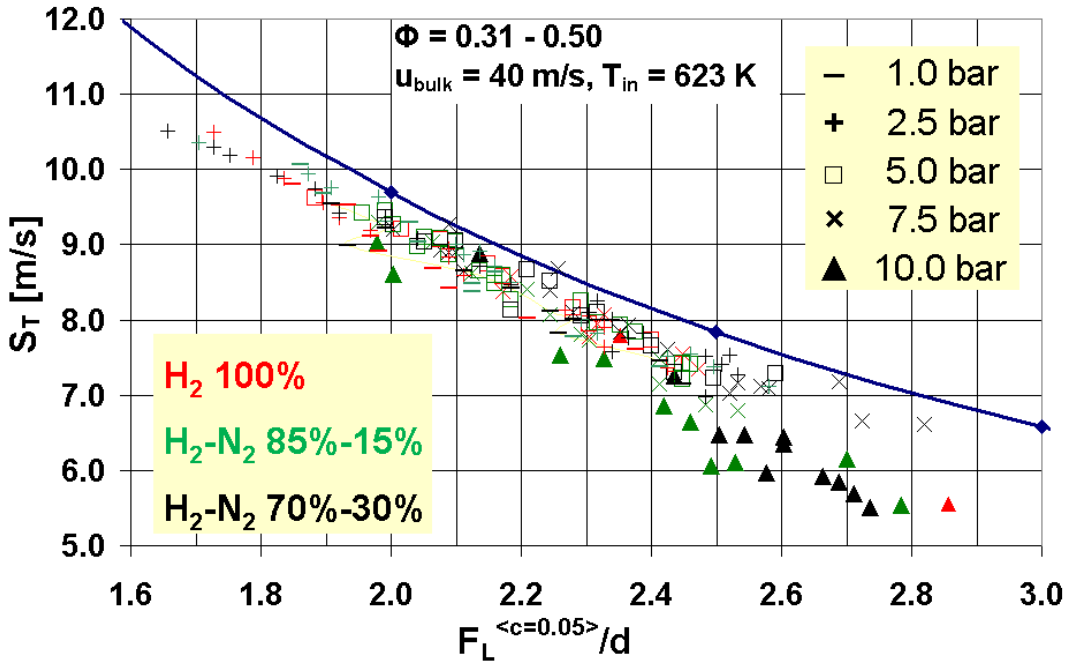


Figure 5

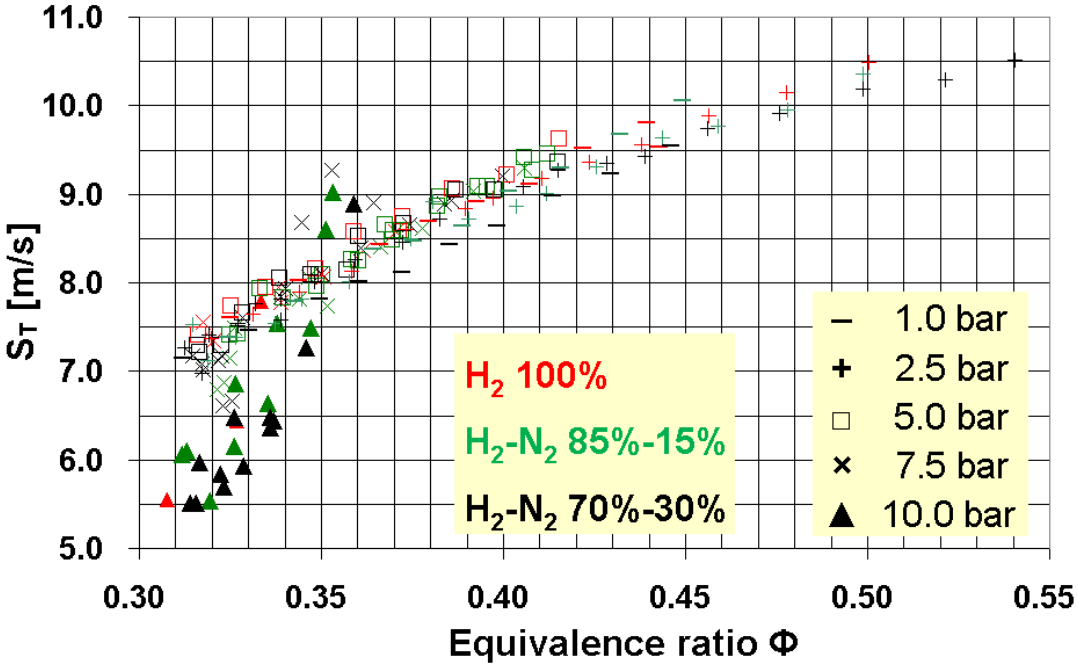


Figure 6

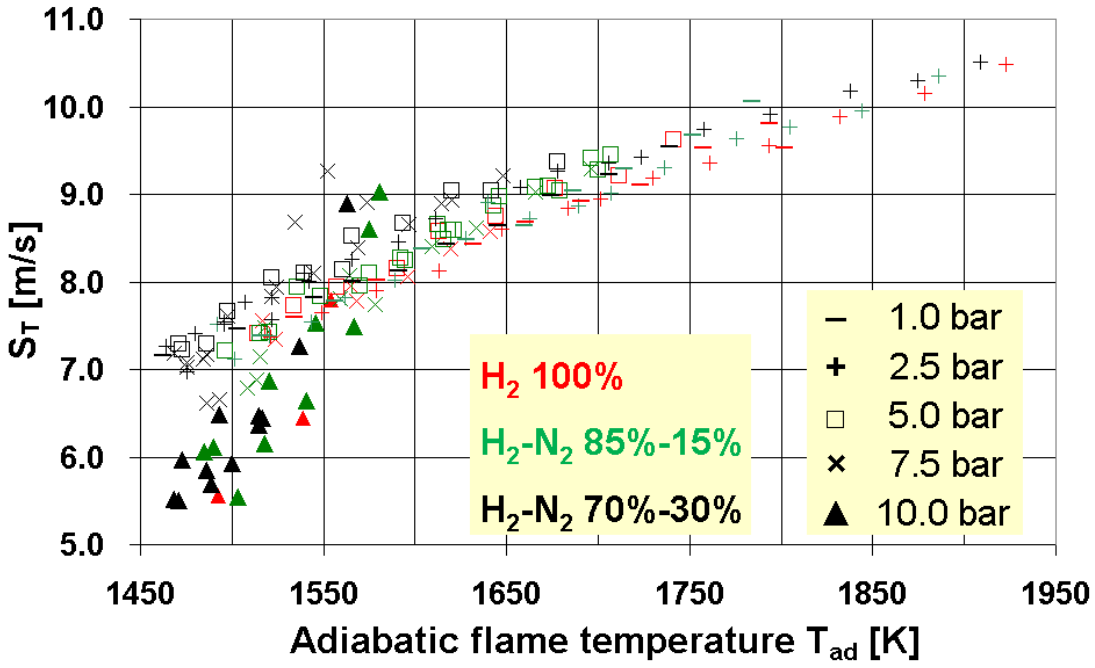


Figure 7

Discussions

To facilitate the analysis and interpretations on the collected S_T dataset, combustion properties (e.g. unstretched laminar flame speed S_{L0} and laminar flame thickness D_L) were derived from chemical-kinetic calculations for freely-propagating, one-dimensional, adiabatic, laminar premixed flames. Various reaction mechanisms were implemented, including the GRI-Mech 3.0 [13] ("GRI"), the model by Li *et al*. [14] (hereafter mentioned as "Li"), an updated version of "Li" by Burke *et al.* [15] (hereafter mentioned as "Burke"), and the "NUI" mechanism recommended by other project partners in SP1 [16].

Based on the S_{L0} and D_L derived from each of the aforementioned reaction mechanisms, distinct allocations of the data points on the regime diagram of premixed turbulent combustion [1] are observed. The L_T (integral length scale) values were retrieved from a separate measurement on the turbulence properties in the test rig. Figure 8 shows a representative dataset for the fuel mixture H_2-N_2 85%-15% (H85N). The range of the equivalence ratios covered are 0.32-0.41 and 0.31-0.35 at 5.0 and 10.0 bar, respectively. The distinction is most explicitly revealed for the data collected at 10.0 bar, even though all data points still exhibit the general characteristics of the thin reaction zone regime. While those normalized with the properties derived from "GRI" (data points in orange) approach the

broken reaction zones, those evaluated via the “Li” model (data points in green) completely lie across the border of Da = 1 and toward the corrugated flamelets. This is consistent with the fact that the “Li” model is generally considered capable of capturing the fast chemistry of hydrogen-rich fuel gases more appropriately. The other two recently updated mechanisms (“Burke” and “NUI”) provide similar predictions on combustion properties to those from “Li,” and the deviations in the allocation of data points on the regime diagram are insignificant. The observation indicates that caution should be taken when selecting reaction mechanisms for interpretating the combustion characteristics of hydrogen (-rich) flames.

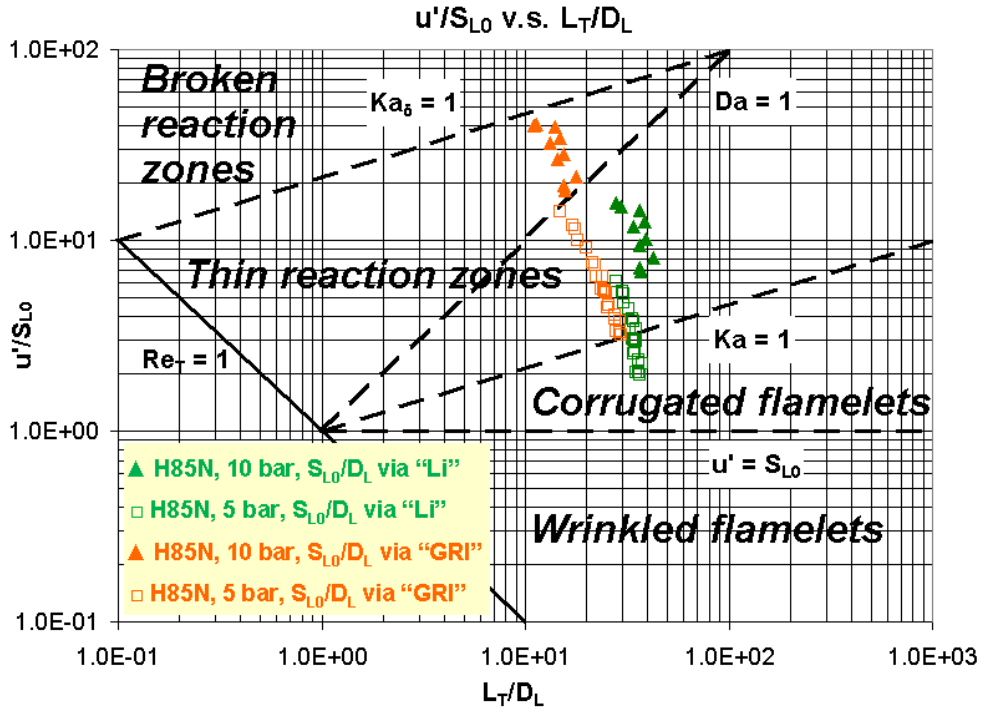


Figure 8. Representative datasets for the fuel mixture H_2-N_2 85%-15% plotted on the regime diagram of premixed turbulent combustion [1].

On the other hand, the general trend of S_T/S_{L0} versus u’/S_{L0} (u’: the turbulence intensity measured at the flame tip location) with both linear and bending features still holds for the H_2-rich fuel gases (Figures 9-12). Again the ranges of the parameters S_T/S_{L0} and u’/S_{L0} differ due to the distinct laminar flame speeds derived from various reaction mechanisms. But generally the values of S_{L0} from the more updated reaction schemes of H_2-O_2 kinetics, e.g. the “Li,” “Burke,” and “NUI” models, are quite consistent. The connection between the combustion regimes and the behavior of the linear-to-bending transition on normalized S_T is still to be established. Appropriate time/length scales capable of depicting the characteristics of flame-turbulence interaction are currently under investigation.

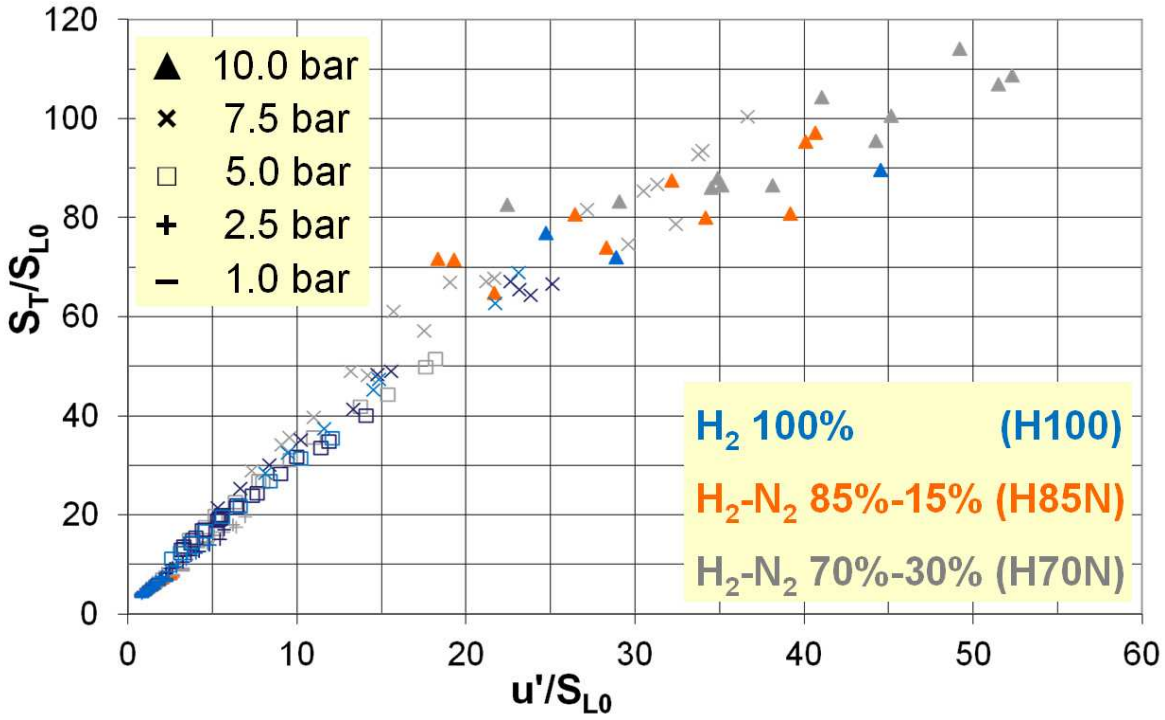


Figure 9. S_T/S_{L0} versus u'/S_{L0} for all the data collected up to 10.0 bar. The values of S_{L0} are derived from GRI-Mech 3.0.

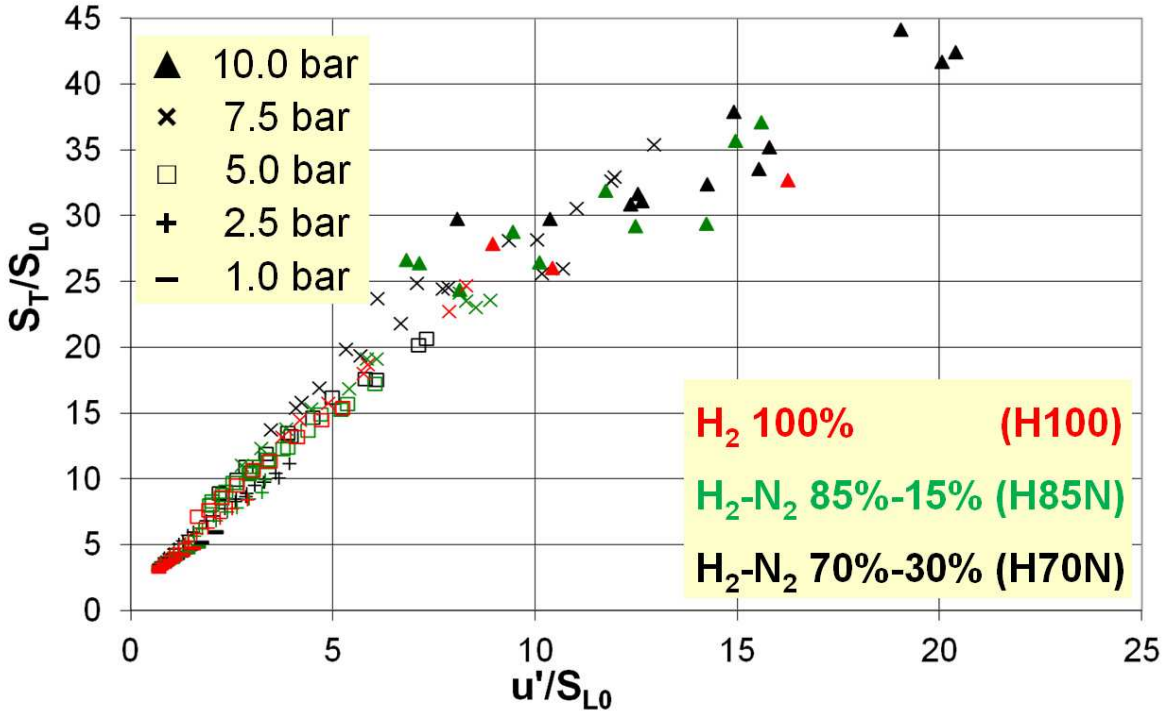


Figure 10. S_T/S_{L0} versus u'/S_{L0} for all the data collected up to 10.0 bar. The values of S_{L0} are derived from the "Li" mechanism.

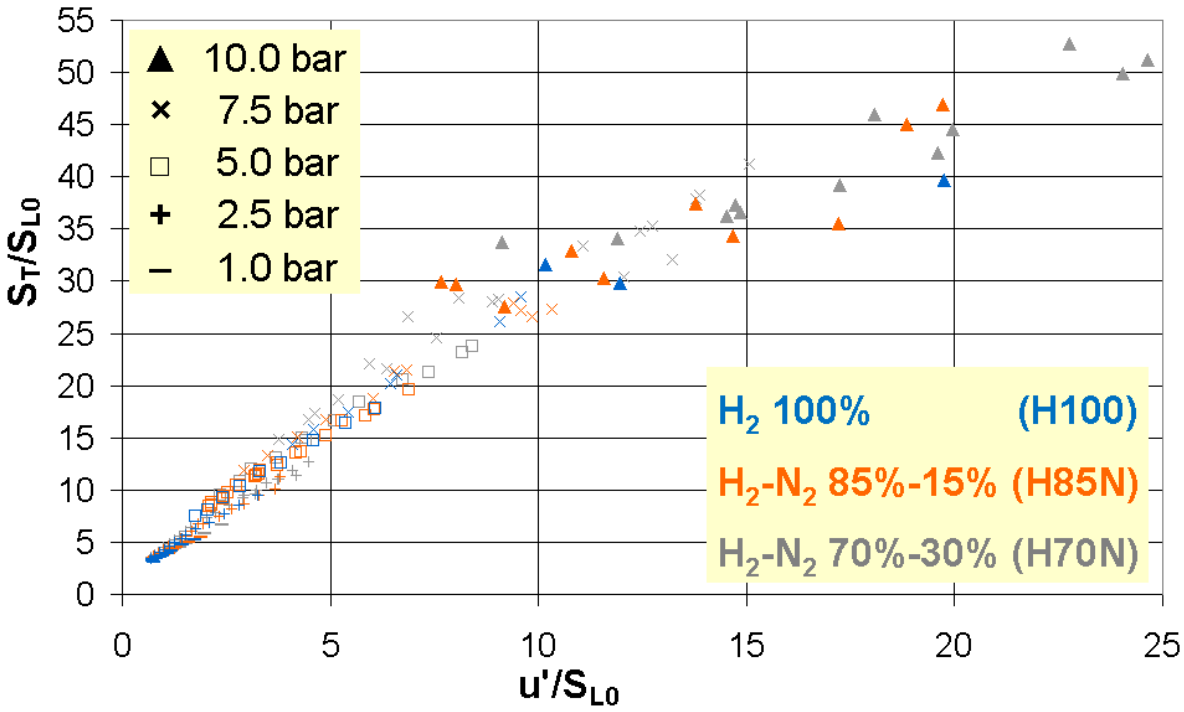


Figure 11. S_T/S_{L0} versus u'/S_{L0} for all the data collected up to 10.0 bar. The values of S_{L0} are derived from the "Burke" mechanism.

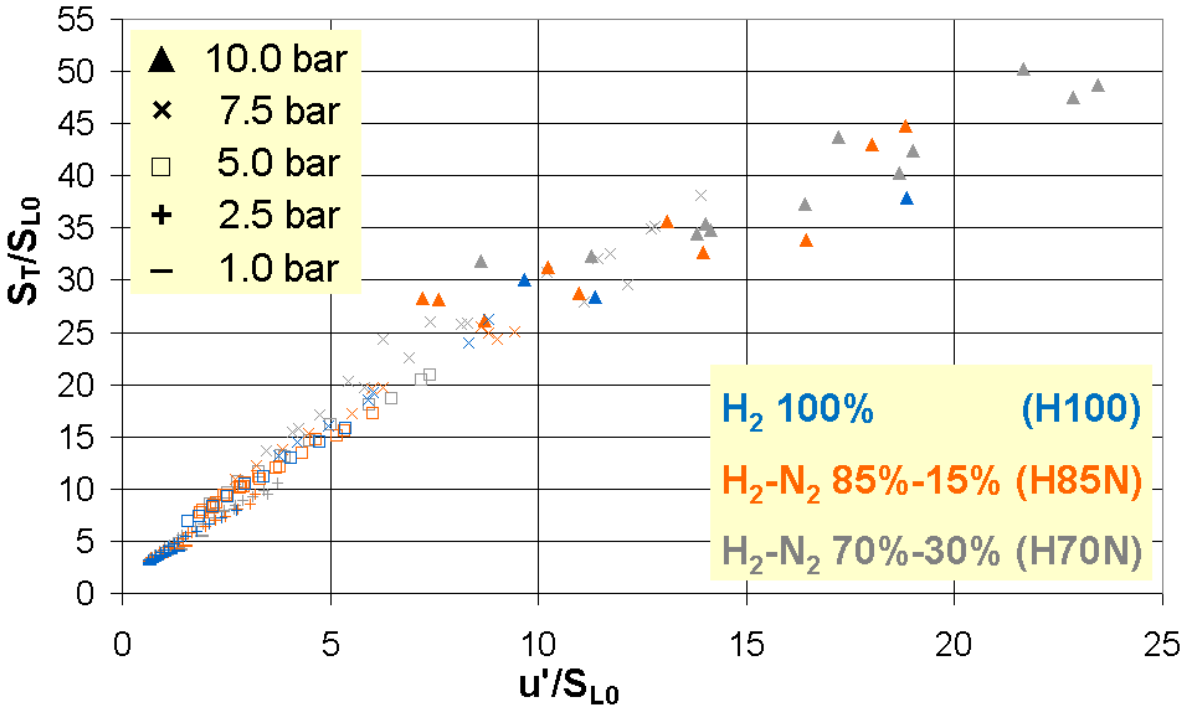


Figure 12. S_T/S_{L0} versus u'/S_{L0} for all the data collected up to 10.0 bar. The values of S_{L0} are derived from the "NUI" mechanism.

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