# INVESTIGATING LAMINAR BURNING VELOCITY IN AMMONIA-HYDROGEN MIXTURES USING DIFFERENT KINETIC MECHANISMS

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**ABSTRACT**

*Ammonia, considered a promising substitute for fossil fuels, presents significant advantages in terms of zero carbon emissions and ease of storage and transportation. However, ammonia combustion faces substantial challenges, such as $NO_x$ and $N_2O$ emissions, combustion stability within a narrow range of equivalence ratios, and low laminar burning velocity. The present work investigates the kinetic mechanisms in the combustion of ammonia-hydrogen mixtures, using the Cantera to perform detailed thermodynamic simulations. Three kinetic models were evaluated: GRI-Mech 3.0, UT-LCS, and a recent model developed by Zhu et al. The predictions of laminar burning velocity were compared with experimental data available in the literature, revealing significant variations among the models, especially in ammonia-hydrogen mixtures. Sensitivity analysis highlighted the importance of the $H + O_2 \leftrightarrow O + OH$ reaction in determining the laminar burning velocity of $NH_3/H_2$/air. The results indicate that while GRI-Mech 3.0 provides good predictions for pure ammonia combustion, the Zhu et al. model showed a better agreement with experimental data for ammonia-hydrogen mixtures. Results underscore the necessity for additional comparative experimental studies to gather more data. The review of various experiments revealed discrepancies exceeding 30% in the results obtained under identical test conditions but with different combustion systems and diagnostic techniques for measuring laminar burning velocity.*

## 1. INTRODUCTION

Currently, ammonia emerges as one of the most promising substitutes for fossil fuels. Its application in maritime engines and power plants already demonstrates its potential as a low-emission fuel (Kobayashi et al., 2019). Ammonia can also be used in a hybrid configuration with hydrogen for vehicle engines, where hydrogen is instantly generated in an electrolytic cell by the reduction of ammonia (Ezzat & Dincer, 2018). In a notable development, the Chinese company Guangzhou Automobile Group Co., in partnership with the Japanese company Toyota, announced the creation of the world's first car engine powered solely by ammonia. This 2.0-liter, four-cylinder engine can generate up to 161 horsepower, achieving up to a 90% reduction in carbon emissions compared to conventional fossil fuels (Lew, 2023).

Ammonia also stands out as an efficient vector for hydrogen storage and transportation, overcoming significant challenges related to its large-scale use as an energy source. Currently, the production, storage, and transportation of hydrogen face obstacles such as high costs and stringent safety requirements due to the need for storage under high pressure or at extremely low temperatures. Industry and academia are investigating the use of ammonia as a solution to these issues, given its ease of liquefaction and storage under less severe conditions than liquid hydrogen. Additionally, ammonia has a higher energy density (12.7 MJ/L) compared to liquid hydrogen (8.5 MJ/L) and can be stored at -33°C, which is considerably less demanding than the -253°C required for hydrogen.

Ammonia has a promising future due to its carbon-free emissions, potential for renewable production, and relative ease of storage, making it a sustainable alternative to fossil fuels (Kobayashi et al., 2019). Additionally, knowledge regarding the

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utilization, transportation, and handling of ammonia is well established, as this substance is extensively used in the agrochemical industry as a fertilizer. However, the implementation of ammonia-based combustion systems faces significant challenges, including $NO_x$ and $N_2O$ emissions, combustion stability within a narrow equivalence ratio range, low laminar burning velocity, and safety concerns due to its toxicity (Elbaz et al., 2022). Elsewhere the combustion dynamics, one of the major challenges in developing combustion systems using ammonia as fuel is the ability to predict results with chemical kinetic models.

Regarding the challenges in combustion dynamics, the use of an ammonia-hydrogen mixture has been considered a solution to these difficulties. This combination can enhance combustion efficiency and simultaneously reduce $NO_x$ emissions, representing an efficient alternative to improve the performance of combustion systems (Chai et al., 2021). Concerning the challenges associated with chemical kinetic models, it is essential to conduct further studies on the chemical interaction between NH3 and its radicals in combustion environments. Factors such as laminar burning velocity, $NO_x$ formation, and ignition delay time are critical to evaluating the performance of $NH_3$-containing mixtures in combustion. These are considered essential findings to enhance our understanding of working with $NH_3$. Therefore, studying the combustion mechanisms of $NH_3$ is crucial to unravel the complexities in combustion systems, not only under standard atmospheric conditions but also in high-pressure, variable temperature, and different equivalence ratios (Alnasif, Mashruk, Shi, et al., 2023).

It is crucial that kinetic reaction mechanisms accurately replicate experimental measurements across a wide range of operating conditions, including temperature and pressure changes, as well as equivalence ratio and fuel mixture proportions such as $NH_3/H_2$. However, many of the kinetic mechanisms published so far struggle to accurately reproduce these experimental measurements under diverse operating conditions, indicating that a model performing well in one situation may not be ideal for other applications (Duynslaegher et al., 2012). In the realm of chemistry, differences in kinetic reaction mechanisms are clearly evidenced through sensitivity analyses. A detailed study by da Rocha et al., (2019) highlighted variations in the predictions of laminar burning velocity across ten evaluated mechanisms.

Ammonia mixtures with other fuels are a primary focus of several scientific investigations. Research by Alnasif et al. (2023b) showed discrepancies among mechanisms in estimating NO molar fractions. Different reaction mechanisms exhibited significant variations in performance due to proposed NO chemistry. Despite ongoing efforts to improve kinetic mechanisms under various operational conditions to enhance the accuracy of predictions in reproducing experimental measurements for $NH_3/H_2$ flames, they demonstrated low quality in estimating NO molar fractions for all equivalence ratios ($\phi$).

Developing a reliable kinetic model that accurately reproduces experimental results constitutes a significant challenge. The accuracy of these predictions directly depends on the quality and precision of experimental measurements. Therefore, chemical kinetic models need continuous refinement and updates to incorporate new experimental findings. Comparing numerical results with experimental data is complex, as experiments and calculation methods for parameters vary considerably. For example, laminar burning velocity can be determined using different combustion systems, such as combustion chambers or tubes where ignition and flame propagation are analyzed, or a wide range of burners. Additionally, velocity can be measured by various methods, including schlieren techniques, shadowgraphy, or luminescence. Wang et al. (2021) obtained varied results for laminar burning velocity using the same combustion mechanism and optical configuration but differing in how the flame propagation points were measured.

Commonly in the literature, works focusing on experimental measurements of laminar burning velocity (Figueroa-Labastida et al., 2024; Han et al., 2024; Ichikawa et al., 2015; Lhuillier et al., 2020) and the development of chemical kinetic mechanisms (Gotama et al., 2022; Liu et al., 2023; Yin, Xiao, You, et al., 2023; Yin, Xiao, Zhao, et al., 2023) do not discuss the different combustion systems employed in the experiments, the optical setup used for obtaining combustion images, and the speed calculation method. This gap hinders the effective comparison of different experimental results for laminar burning velocity.

Given the lack of literature discussing various methods for calculating laminar burning velocity and the increasing demand for experimental and numerical data on ammonia combustion, this study aims to address this gap. The laminar burning velocity will be calculated using different kinetic mechanisms and the results will be compared with experimental data available in the literature. Additionally, the types of burners and measurement methods employed will be analyzed to provide a comprehensive understanding of the combustion process. For this, three kinetic models will be employed: i) the GRI Mech 3 model, one of the most traditional and widely used in combustion (Smith et al., n.d.); ii) the UT-LCS model, modified to work with ammonia and hydrogen combustion (Otomo et l., 2018); iii) a recent mechanism developed for ammonia and hydrogen analysis (Zhu et al., 2024).

## 2. KINETIC MECHANISMS

The A kinetic mechanism is a set of chemical equations that describe the elementary reactions and their respective rates occurring during a combustion process. This mechanism includes details about the reactants, intermediate products, and final products, as well as the rate constants for each reaction. Such mechanisms are essential for modeling and understanding the dynamics of complex chemical reactions, such as combustion.

In Cantera, the use of different kinetic mechanisms results in varied responses due to the sensitivity of the involved reactions and the inclusion or exclusion of specific intermediate reactions and species. Each kinetic mechanism may incorporate or exclude intermediate reactions and alter the values of reaction rates, directly influencing the predictions regarding combustion behavior. These variations highlight the importance of selecting and validating the appropriate kinetic mechanism for each specific application, ensuring that the models accurately predict the critical combustion properties to optimize efficiency and reduce emissions.

### 2.1 GRI Mech 3.0 mechanism

GRI-Mech 3.0 is a detailed kinetic mechanism specifically developed to model the combustion of hydrocarbons, with a particular focus on natural gas combustion. This mechanism was created through extensive collaboration between researchers and combustion experts, aiming to provide accurate predictions of the combustion properties of natural gas and air mixtures. GRI-Mech 3.0 includes a comprehensive set of elementary reactions and associated rate constants, covering the oxidation of methane and other minor components of natural gas (Smith et al., n.d.).

The database contains detailed information on 53 chemical species and 325 elementary reactions, encompassing a wide range of temperature and pressure conditions. This mechanism is widely used in the scientific community for combustion simulations due to its proven accuracy and reliability in predicting important characteristics of combustion.

### 2.2 UT-LCS mechanism

The UT-LCS (University of Tokyo - Low Carbon Society) model, proposed by Otomo et al. (2018), is an evolution of the model by Song et al. (2016). The original mechanism is a detailed model that describes ammonia oxidation, encompassing 32 chemical species and 204 elementary reactions. This new model was developed to provide more accurate predictions of the combustion properties of ammonia with hydrogen, including laminar burning velocity and ignition delay time. The improvements introduced in the UT-LCS model include the incorporation of new reactions, adjustment of rate constants, and a preliminary sensitivity analysis to identify reactions that significantly influence laminar burning velocity. The rate constants for these reactions were adjusted based on values obtained from the literature to improve the reproduction of experimental data. The unimolecular decomposition reactions of $NH_3$, $N_2H_2$, and $H_2N2$ were adjusted to include pressure dependence, using Quantum Rice-Ramsperger-Kassel (QRRK) analysis and the master equation (ME). These pressure dependencies were expressed through PLOG functions implemented in CHEMKIN PRO software.

Additional reactions were incorporated into the mechanism, including those involving $NH_2$, HNO, and $N_2H_2$, which are crucial for ammonia oxidation and $NO_x$ formation. The UT-LCS model introduces a series of new or modified reactions, with their respective rate constants adjusted to improve the accuracy of predictions. Some of the most significant reactions are as follows: i) $NH_2 + H \leftrightarrow NH + H_2$, the rate constant was adjusted to improve the prediction of laminar burning velocity; ii) $NH_2 + NO \leftrightarrow NNH + OH$, this reaction was included to better represent NO oxidation; iii) $N_2H_2 \leftrightarrow NNH + H$, the pressure dependence for this unimolecular decomposition was adjusted; iv) $NH + H \leftrightarrow N + H_2$, adjustments based on literature data were implemented to increase the model's accuracy.

### 2.3 Mechanism developed for ammonia and hydrogen

Zhu et al. (2024) developed a detailed kinetic mechanism for the combustion of ammonia/hydrogen ($NH_3/H_2$) mixtures. This study built on previously validated kinetic models and incorporated significant improvements to accurately capture the combustion properties of these mixtures under a wide range of conditions relevant to engines. The detailed kinetic model developed in this study is based on an updated $H_2/O_2$ sub-mechanism from NUIGMech1.3, validated by the Combustion Chemistry Centre at the University of Galway. An important addition to the sub-mechanism was the inclusion of the chain-branching channel $HO_2 + HO_2 \leftrightarrow OH + OH + O_2$, the rate constants for the reactions $H_2 + O \leftrightarrow H + OH$ and $H + O_2 + M \leftrightarrow HO_2 + M$ were updated. The model incorporates high-temperature reactions ($\geq$ 1500 K) and low to medium temperature reactions ($1000 \leq T \leq 1500$ K), covering a full range of temperature regimes relevant to $NH_3/H_2$ combustion.

Unimolecular decomposition and hydrogen atom abstraction reactions play a crucial role in fuel oxidation at high temperatures. For these reactions, rate constants were determined and adjusted based on experimental data and advanced theoretical calculations. For example, the unimolecular decomposition of $NH_3$ (R1) was adjusted by increasing the frequency factor by 30% to better match experimentally measured fuel concentration

profiles. In the low to medium temperature regime, the formation of $HO_2$ radicals and $NO_2$ molecules is favored, enhancing fuel reactivity. These reactions were rigorously evaluated and adjusted to ensure the model accurately captured the experimentally observed behaviors. The formation of intermediates such as $H_2NO$ and their subsequent reactions with $O_2$, $NH_2$, $HO_2$, and $NO_2$ are essential for describing fuel reactivity at low temperatures. Additionally, reactions involving $NH_2$ and NO radicals play a critical role at both high and low temperatures. The $NH_2$ + NO reaction system has two product channels: $NH_2$ + NO ↔ NNH + OH, which increases fuel reactivity, and $NH_2$ + NO ↔ $N_2$ + $H_2O$, which decreases reactivity. The branching ratio of these channels was carefully adjusted based on available experimental and theoretical investigations. The developed model was validated using a wide range of experimental data on ignition delay times (IDTs) and laminar burning velocities of $NH_3/H_2$ mixtures.

## 3. EXPERIMENTAL METHODS FOR DETERMINING LAMINAR BURNING VELOCITY

As mentioned in the introduction, there are various methods to calculate the laminar burning velocity. The purpose of this section is not to discuss all the methods available in the literature but to focus on the methods employed in studies that use ammonia as fuel. The laminar burning velocity data from these methods will be used in the present study for comparison with velocities obtained by different kinetic mechanisms.

In the study by Ronney (1988), the laminar burning velocity of ammonia-air mixtures under various conditions was determined using a detailed method based on closed-vessel experiments. The procedure involved using a cylindrical constant-volume combustion vessel equipped with a spark generator capable of producing controlled ignitions in terms of duration and energy. Flame propagation was monitored using fine-wire thermocouples aligned along the cylinders axis and visual records obtained by a motion picture camera. The burning velocities were calculated from the flame propagation speeds observed in the film records and corroborated by the thermocouple temperature data.

Kumar and Meyer (2013) investigated the burning velocities in $H_2$–$NH_3$–air mixtures using a laminar jet burner. The laminar burning velocity measurements were obtained through the natural chemiluminescence of the flame. A heat loss model was implemented to correct the experimental measurements, considering the significant heat losses observed under high equivalence ratio conditions. The results showed that heat loss corrections are essential to align the experimental burning velocities with the modeled predictions.

Li et al. (2014) employed a premixed flame burner mounted inside a 3-liter stainless steel chamber. The Bunsen burner method was used to measure the burning velocity. The burning velocity was calculated from the total mass flow rate existing the burner's outlet and the flame area surface, as measured from photographs of the flames chemiluminescence. In this method, a premixed $H_2$–$NH_3$–air flame flows through a tube, and the flame is stabilized at the tubes exit rim.

Ichikawa et al. (2015) used a constant-volume combustion chamber to study premixed ammonia/hydrogen/air flames. The constant combustion chamber configuration is cylindrical, with a volume of 23 liters. The fuel-oxidizer mixture is ignited by a centrally located spark using a capacitive discharge ignition (CDI) system. The flame speed was measured using the Schlieren technique, observing the spherical propagation of the flames. The flame propagation speed was determined by calculating the rate of change of the flame radius over time.

Han et al. (2019) determined the laminar burning velocity of premixed ammonia and other fuel flames using the heat flux method. This method is based on an adiabatic, unstretched flat flame, providing consistent data with very low experimental uncertainties, around ±1 cm/s. The method involves measuring the temperature profile of the burner surface plate, which is used to determine the inlet flow velocity that matches the laminar burning velocity.

Lhuillier et al. (2020) used an outwardly propagating spherical burner to investigate the laminar burning velocities of ammonia/hydrogen/air mixtures. The measurements included the laminar burning velocity, obtained through the outwardly propagating spherical flame method at atmospheric pressure. The flame images were captured using the Schlieren technique. The measurements were conducted for unburned gas temperatures ranging from 298 to 473 K, hydrogen fractions in the fuel ranging from 0% to 60%, and equivalence ratios in the range of 0.8 to 1.4.

Wang et al. (2021) compared three methods to calculate the laminar burning velocity from the image of a flame kernel ignited by a laser. Shadowgraphy images were analyzed to determine the velocity using different image analysis methods. Method 1, which uses the equivalent area of the burned zone, showed the smallest variations and standard deviations, being considered the most consistent and reliable. Method 2 measures the distance between the top and base of the flame kernel, showing moderate variations and a higher standard deviation. Method 3 calculates the curvature radius at specific points on the flame surface, presenting the largest variations and a relatively higher standard deviation. Thus, the authors conclude that Method 1 is the most suitable for

determining the laminar burning velocity due to its higher accuracy and lower variability.

## 4. RESULTS AND DISCUSSIONS

Numerical calculations and experimental data were obtained under atmospheric pressure and ambient temperature conditions, with ammonia burning in atmospheric air. The numerical calculations were performed using a freely-propagating flame reactor. The numerical calculations were performed using the freely-propagating flame available in Cantera. Figure 1 presents the laminar burning velocity calculated by three kinetic mechanisms, compared with experimental data from three different sources. Among the numerical data, the lowest values were obtained by GRI-Mech 3.0. The UT-LCS and Zhu et al. methods exhibited similar values in the equivalence ratio range of 0.6 to 0.9; however, beyond this point, the Zhu et al. method predicted higher laminar burning velocities. Additionally, the maximum laminar burning velocities differed among the three methods, with a shift towards richer combustion conditions in the methods predicting higher velocities. Overall, both the experimental and theoretical values do not exceed 9 cms-1.

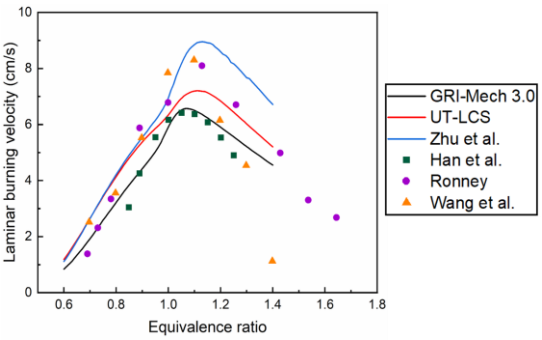


Figure 1 - Laminar burning velocity as a function of the equivalence ratio ($\phi$). Ammonia burning with atmospheric air. The symbols correspond to experimental data, and the lines represent numerical data.

The experimental data show a 30% difference in the maximum laminar burning velocity values between the data from Wang et al. and Han et al. for an equivalence ratio of 1.1. The experimental results obtained from different studies indicate that different types of burners can influence the laminar burning velocity and the equivalence ratio range. Ronney, using a constant volume cylindrical burner, obtained a variation of $0.69 \leq \phi \leq 1.64$. On the other hand, Han et al. used a heat flux burner, resulting in a smaller range of $0.85 \leq \phi \leq 1.25$. Analyzing the maximum velocities and the equivalence ratio range of Han et al. and Wang et al., similar results are observed. Both used combustion chambers and spherical flames, with Ronney employing CDI for ignition, while Wang et al. used a laser. The results indicate that the laminar burning velocity may be lower with the use of burners, and the equivalence ratio range may be more restricted. However, for a more in-depth analysis of ammonia combustion, more experimental data are needed. In the comparison between experimental and numerical data, it can be observed that the GRI-Mech 3.0 mechanism closely approximates the results obtained by Han et al., indicating that this mechanism predicts experimental results obtained with a burner with high accuracy.

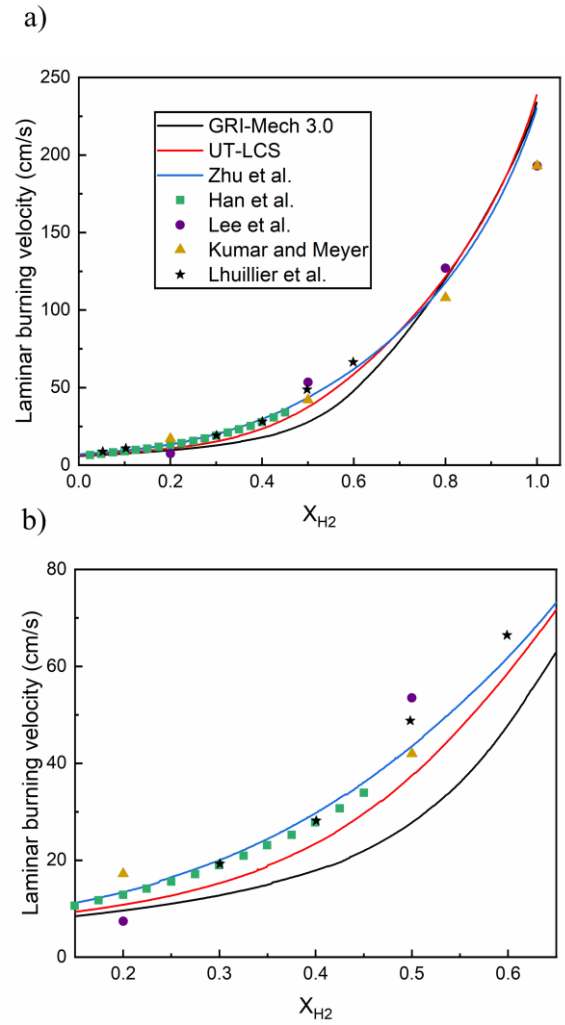


Figure 2 - Laminar burning velocity as a function of the hydrogen percentage in the fuel.

Figure 2 compares three numerical calculations with four experimental studies for the laminar flame speed as a function of the molar percentage of hydrogen $X_{(H2)}$. Figure 2a) shows the speed varying from $0 < X_{(H2)} < 1$. A convergence is observed at the extremes of the hydrogen percentage for all numerical models and experimental data. The discrepancy occurs in the range of $0.2 < X_{(H2)} < 0.7$

(Fig. 2b), where the numerical models show more variation among themselves than the experimental results obtained by different methods. The agreement between numerical and experimental results was observed by Han et al., using a flat flame burner, compared to the most recent model proposed by Zhu et al., specifically developed for this combustion region. The values obtained by Lhuillier et al. and Han et al. are very close. While Han et al. used a burner, Lhuillier employed a combustion chamber with a spherical flame. These close values indicate that the difference in experimental laminar burning velocity data, when burning only ammonia and using different combustion systems (Fig. 1), tends to decrease. It is noted that the GRI-Mech 3.0 model, which provided the best predictions for pure ammonia combustion, performed the worst in the combustion of the ammonia-hydrogen mixture.

Accurate analysis of this region is a challenge. From an engineering perspective, it represents the potential combustion region for engine operation. From a green economy perspective, both pure hydrogen and ammonia are carbon-free. However, in the production of blue fuels, where hydrogen is produced from wind energy and synthesized into ammonia for transport, an engine operating with 100% hydrogen requires that all transported ammonia be converted back into hydrogen, making the process more energy-expensive. Combustion dynamics problems, such as the low flame speed of pure ammonia, will only be resolved with the addition of hydrogen in combustion with air. Therefore, finding a mixture with high energy efficiency and economic viability represents a significant challenge for ammonia and hydrogen-based combustion systems.

To better evaluate the region of interest, the sensitivity analysis of the different chemical kinetic mechanisms employed in the study will be analyzed. In the graph, the x-axis represents the partial derivative of the laminar burning velocity concerning each kinetic parameter, indicating the sensitivity of the burning velocity to changes in these parameters. The higher the value on the x-axis, the greater the influence of the respective parameter on the final simulation result. Negative values mean that increasing the rate of this specific reaction decreases the laminar burning velocity. Figure 3 shows the sensitivity for two input conditions, with $\phi$=1 for a flame burning only with ammonia and air and another of interest for engines with $X_{(H2)} = 0.5$.

The analysis of the three sensitivity mechanisms: GRI-Mech 3.0, UT-LCS, and Zhu et al. reveals similarities in the combustion of $NH_3/H_2$/air, with the chain-branching reaction $H + O_2 \leftrightarrow O + OH$ contributing approximately half of the total sensitivity value to increase the laminar burning velocity. However, the differences in the predicted values for the laminar burning velocity can be attributed to the reactions that contribute secondarily to the increase in velocity, which vary from model to model. For pure ammonia combustion, the three mechanisms present different reactions as the most important. In GRI-Mech 3.0, the most significant reaction is $HNO + OH \leftrightarrow H_2O + NO$, while in the UT-LCS mechanism, the primary reaction is $H + O_2 \leftrightarrow O + OH$, the same as for ammonia combustion with hydrogen. In Zhu's model, the most important reaction for pure ammonia combustion is $NH + NH_2 \leftrightarrow H + N_2H_2$.

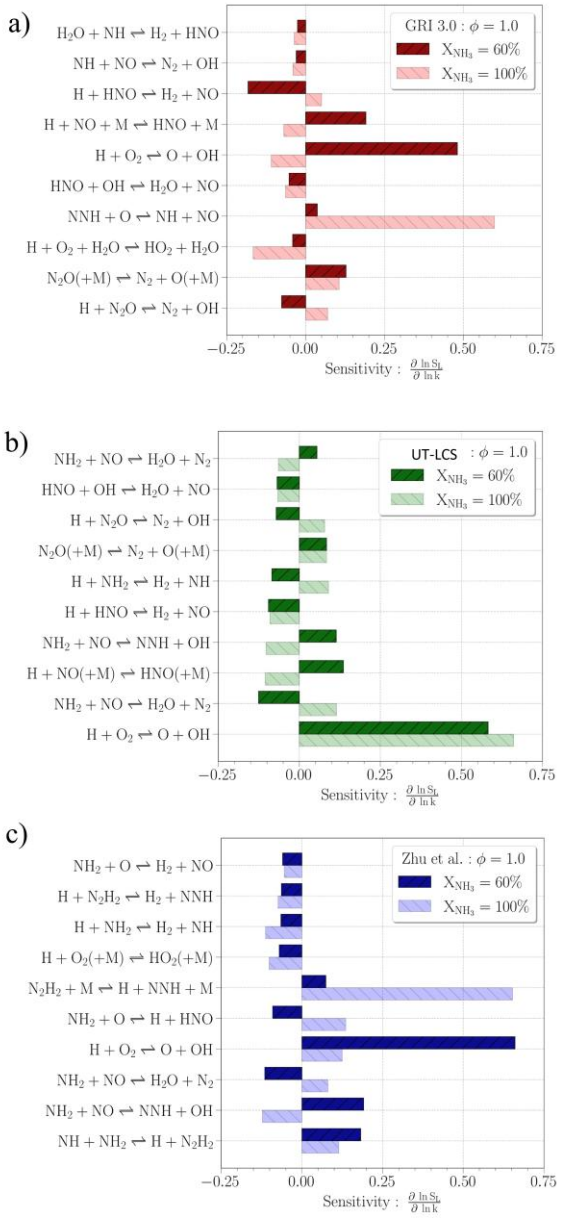


Figure 3 - Sensitivity analysis. a) GRI-Mech 3.0, b) UT-LCS, and c) Zhu et al.

The most significant reaction for increasing the laminar burning velocity is $H+O_2 \leftrightarrow OH+O$, as expected for H-O-C systems, given that, under certain conditions, a significant acceleration of this reaction can lead to explosions. However, ammonia has a laminar burning velocity approximately one-

third of that observed in hydrocarbons. Thus, some reaction occurring during combustion must contribute to the reduction of this velocity. Analyzing Figure 3, it is observed that the reactions with the highest negative sensitivity values that is, those that decrease the burning velocity are $H+HNO \leftrightarrow H_2+NO$ for the GRI 3.0 mechanism, $NH_2+NO \leftrightarrow H_2O+N_2$ for the UT-LC mechanism, and $NH_2+O \leftrightarrow H+HNO$. Unlike positive sensitivity, which promotes the increase in burning velocity, the negative sensitivity reactions do not exhibit individual contributions greater than 0.20. On the other hand, for positive sensitivity values, this contribution can reach up to 0.70, as observed in the GRI 3.0 mechanism.

Another relevant point is the lack of convergence regarding which reaction is the most important in reducing the laminar burning velocity. Each mechanism presents a reaction with the highest sensitivity in this aspect. This highlights the need for further studies to fully understand the kinetic mechanisms of ammonia combustion, particularly regarding the reactions that contribute to the reduction of laminar burning velocity.

## 5. CONCLUSIONS

Based on the analysis of the GRI-Mech 3.0, UT-LCS, and Zhu et al. kinetic mechanisms, it can be concluded that while all share similarities in the combustion of $NH_3/H_2$/air, consistently highlighting the $H + O_2 \leftrightarrow O + OH$ reaction as highly influential on the laminar burning velocity, there are significant differences in the combustion of $NH_3$/air. The analysis of the different burners used in the experimental studies, such as constant volume cylindrical burners and heat flux burners, shows that they primarily influence the laminar flame speed for pure ammonia, but this difference tends to decrease when using an ammonia-hydrogen mixture. The GRI-Mech 3.0 mechanism showed the best results for pure ammonia combustion, while the Zhu et al. mechanism showed the best results when compared with experimental data for the ammonia-hydrogen mixture. The analysis in this study indicated that new mechanisms tend to better reproduce experimental data for ammonia and hydrogen combustion, demonstrating an improvement in numerical models. However, there is a lack of information in comparative experimental studies using different combustion systems, with this study indicating that differences in laminar flame speed are obtained due to the use of different combustion systems. Therefore, for a more comprehensive and accurate understanding, more comparative experimental studies considering a variety of burner configurations, operational conditions, and diagnostic systems are necessary.

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