

**INVESTIGATION OF COMBUSTION
CHARACTERISTICS AND STATIC STABILITY
LIMITS OF HYDROGEN-ENRICHED CH₄/AIR
STRATIFIED FLAMES IN A MODEL GAS-TURBINE
COMBUSTOR**

BY

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In

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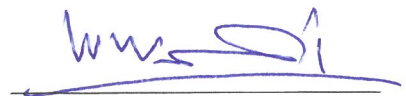
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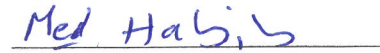
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to

My beloved family

for their endless support

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LIST OF ABBREVIATIONS

AFT	:	Adiabatic Flame Temperature
BLF	:	Boundary Layer Flashback
CH₄	:	Methane
CIVB	:	Combustion-Induced Vortex Breakdown
CO	:	Carbon Monoxide
CO₂	:	Carbon Dioxide
COP21	:	21st Conference of the Parties
Da	:	Damköhler Number
DL	:	Darrieus-Landau
DO	:	Discrete Ordinates
GT	:	Gas Turbine
H₂	:	Hydrogen
HC	:	Hydrocarbon
HE	:	Hydrogen-Enriched
HF	:	Hydrogen Fraction
HDI	:	Hydrodynamic Instability
HRR	:	Heat Release Rate
IDT	:	Ignition Delay Time
IRZ	:	Inner Recirculation Zone
LBO	:	Lean Blowout
LFS	:	Laminar Flame Speed
Le	:	Lewis Number

NH₃	:	Ammonia
NG	:	Natural Gas
NO_x	:	Nitrogen Oxides
Nu	:	Nusselt Number
PD	:	Power Density
POLIMI	:	Politecnico di Milano
Pr	:	Prandtl Number
Re	:	Reynolds Number
RANS	:	Reynolds-Averaged Navier-Stokes
SST	:	Shear Stress Transport
TDI	:	Thermodiffusive Instability
UNFCCC	:	United Nations Framework Convention on Climate Change

ABSTRACT

Full Name : [Ahmed Ibrahim Hassan Mahmoud Abdelhalim]
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Recently, using hydrogen enriched flames has been gaining significant attention as a potential solution for reducing greenhouse gas emissions and improving combustion efficiency in gas turbines for industrial applications. Compared to traditional hydrocarbon fuels, hydrogen has higher combustion energy density and wider flammability range, resulting in more stable leaner flames. The advantages of hydrogen-enriched flames include improved combustion efficiency, reduced emissions of pollutants such as CO₂ and particulate matter, and increased turbine power output. Additionally, hydrogen can be produced from renewable sources, making it a sustainable and environmentally friendly fuel option. However, a main drawback of hydrogen enriched flames is the high temperature produced from hydrogen combustion which leads to increased NO_x emissions. To address this issue, lean combustion technology with swirl stabilization and hydrogen enrichment can be used to improve the stability of the combustion process, enhance combustion efficiency, and reduce emissions. Stratification is a combustion technique that can be employed to improve the static stability of premixed flames, as well. This is accomplished by introducing a non-uniform distribution of equivalence ratio using a hybrid premixed/non-premixed operation. The fuel is divided into two components: a premixed portion which is mixed with the oxidizer upstream of the flame, and a non-premixed

portion which is directly injected into the flame. Overall, the combination of stratification with hydrogen enrichment in lean swirl-stabilized flames is expected to show great potential in improving the performance and environmental impact of gas-turbine and industrial combustion systems. In this study, the stability limits and combustion and emission characteristics of hydrogen-enriched stratified CH₄/air flames were investigated experimentally and numerically in a gas-turbine burner. The primary mixture of CH₄/air was supplied through a swirler in the center of the combustor, while hydrogen was injected as peripheral non-premixed jets around the primary mixture. The effects of hydrogen fractions from 0 to 25% and equivalence ratios up to 0.893 on stability, flame shape, flame speed, flame thickness, temperature, and emissions were studied. The results indicate that employing hydrogen in a non-premixed jet configuration around the primary flame proves to be an effective strategy for reducing elevated nitrogen oxides (NO_x) emissions associated with the high temperatures in hydrogen flames. However, the excessive use of pilot fuel, commonly applied to enhance the lean blowout limit in burners like DACRS burners, does not result in a comparable improvement in the blowout limit when tilted jets are positioned on the outer edge of the flame. This is due to the conflicting effects of the pilot jet, acting both as a stabilizing source by anchoring the flame and as a disruptive force with its high jet momentum dispersing the flame and diminishing stability. Nevertheless, using hydrogen as a pilot fuel leads to an increase in intermediate species like OH, H, and O, contributing to flame stabilization. However, this practice also results in higher carbon monoxide (CO) and unburned hydrocarbons emissions due to the inherent characteristics and heightened reactivity of hydrogen.

ملخص الرسالة

الاسم الكامل: أحمد ابراهيم حسن محمود عبد الحليم

عنوان الرسالة: دراسة خصائص الاحتراق والاستقرار للشعلة الطبقيّة لغاز الميثان/الهواء الغني بالهيدروجين في نموذج موقد لتوربينات الغاز

التخصص: الهندسة الميكانيكية

تاريخ الدرجة العلمية: ديسمبر 2023

في السنوات الأخيرة، اكتسب استخدام اللهب المخصب بالهيدروجين اهتمامًا كبيرًا كحل محتمل لتقليل انبعاثات الغازات الدفيئة وتحسين كفاءة الاحتراق في توربينات الغاز والتطبيقات الصناعية. بالمقارنة مع الوقود الهيدروكربوني التقليدي، يتمتع الهيدروجين بكثافة طاقة احتراق أعلى ونطاق قابلية اشتعال أوسع، مما يؤدي إلى احتراق أصغر حجمًا وأكثر استقرارًا. تشمل مزايا اللهب المخصب بالهيدروجين تحسين كفاءة الاحتراق، وتقليل انبعاثات الملوثات مثل ثاني أكسيد الكربون والجسيمات، وزيادة إنتاج طاقة التوربينات. بالإضافة إلى ذلك، يمكن إنتاج الهيدروجين من مصادر متجددة، مما يجعله خيار وقود مستدام وصديق للبيئة. ومع ذلك، فإن العيب الرئيسي للهب المخصب بالهيدروجين هو ارتفاع درجة الحرارة الناتجة عن احتراق الهيدروجين مما يؤدي إلى زيادة انبعاثات أكاسيد النيتروجين. ولمعالجة هذه المشكلة، يمكن استخدام تقنية الاحتراق الفقير (lean Combustion) مع المثبت الدوامي (Swirler) و إضافة الهيدروجين لتحسين استقرار عملية الاحتراق، وتعزيز كفاءة الاحتراق، وتقليل الانبعاثات. التقسيم الطبقي (Stratification) هو أسلوب احتراق يمكن استخدامه لتحسين الاستقرار الثابت للهب المختلط مسبقًا أيضًا. ويتم تحقيق ذلك عن طريق إدخال توزيع غير منتظم لنسبة التكافؤ من خلال استخدام عملية هجينة مختلطة مسبقًا/غير مختلطة مسبقًا. ينقسم الوقود إلى مكونين: جزء مخلوط مسبقًا يتم خلطه مع المؤكسد قبل اللهب، وجزء غير مختلط يتم حقنه مباشرة في اللهب. بشكل عام، من المتوقع أن يُظهر الجمع بين التقسيم الطبقي وإثراء الهيدروجين في اللهب الهزيل المستقر بالدوامية إمكانات كبيرة في تحسين الأداء والأثر البيئي لتوربينات الغاز وأنظمة الاحتراق الصناعية. في هذه الدراسة، تم دراسة خصائص الثبات والاحتراق للهب خليط طبقي للميثان و الهواء المخصب بالهيدروجين في موقد توربينات غازية تجريبيًا وعدديًا. تم توفير الخليط الأولي من الميثان/الهواء من خلال دوامة في مركز الاحتراق، بينما تم حقن الهيدروجين كنفاثات طرفية غير مختلطة مسبقًا حول الخليط الأولي. تمت دراسة تأثير أجزاء الهيدروجين من 0 إلى 25% ونسب التكافؤ حتى 0.893 على الثبات وشكل اللهب وسرعة اللهب وسمك اللهب ودرجة الحرارة والانبعاثات. تشير النتائج إلى أن استخدام الهيدروجين في تكوين نفاث غير مخلوط مسبقًا حول اللهب الأولي يثبت أنه استراتيجية فعالة لتقليل انبعاثات أكاسيد النيتروجين المرتفعة المرتبطة بدرجات الحرارة المرتفعة في

لهب الهيدروجين. ومع ذلك، فإن الاستخدام المفرط للوقود المعزز، الذي يتم تطبيقه عادة لتعزيز حد الانفجار الهزيل في الشعلات مثل مواقع DACERS، لا يؤدي إلى تحسن مماثل في حد الانفجار عند وضع النفاثات المائلة على الحافة الخارجية للهب. ويرجع ذلك إلى التأثيرات المتضاربة للنفاثات المعززة، التي تعمل كمصدر استقرار من خلال تثبيت اللهب وكقوة تخريبية مع زخمها النفاث العالي الذي يؤدي إلى تشتيت اللهب وتقليل الاستقرار. استخدام الهيدروجين كوقود داعم يؤدي إلى زيادة في الجذور الوسيطة مثل OH و H و O ، مما يساهم في تثبيت اللهب. ومع ذلك، تؤدي هذه الممارسة أيضًا إلى ارتفاع انبعاثات أول أكسيد الكربون (CO) والهيدروكربونات غير المحترقة بسبب سرعة تفاعل الهيدروجين.

CHAPTER 1

INTRODUCTION

Recently, the palpable effects due to changes in global climate have manifested in various facets of our surroundings. To alleviate the lasting negative consequences, there is a need for a shift toward carbon-free fuels without compromising the essential requirements of global energy production and consumption [1]. Burning fossil fuels remains a prominent participant to the release of various emissions, comprising detrimental pollutants such as NO_x, CO, and CO₂. Therefore, a crucial and necessary approach involves adopting alternative fuels, such as hydrogen, which stands out for its inherent lack of carbon content [2]–[4]. This fundamental change is essential for effectively addressing the challenges posed by climate change.

Electricity generation facilities are significant consumers of fossil fuels, accounting for approximately 80% of their usage [5]. In response to the imperative to regulate and curtail greenhouse gas emissions, the Paris Agreement was established in 2015 during the COP21 at the UNFCCC [6]. This global agreement's main objective is to collectively tackle the issue of global warming. It aims to restrict the rise in the worldwide average temperature to a level significantly below the 2 °C threshold from pre-industrial levels. Accomplishing this mission necessitates an adoption of carbon-free fuels in both industrial and power sectors to mitigate CO₂ emissions. According to the IEA 2022 report [7], global energy-related CO₂ emissions experienced a growth of 0.9%, equivalent to 321 Mt, in 2022,

reaching a record high exceeding 36.8 Gt. Emissions from energy combustion showed an increase of 423 Mt, while emissions from industrial processes decreased by 102 Mt. The most significant rise in emissions in 2022 occurred in the electricity and heat generation sector, with emissions increasing by 1.8%, totaling 261 Mt. Notably, global emissions from coal-fired electricity and heat generation witnessed a growth of 224 Mt or 2.1%, primarily led by emerging economies in Asia. Controlling carbon emissions in the environment can be accomplished through diverse methods, such as enhancing the efficiency of industrial plants, curbing fuel consumption, and decreasing the fuel's level of carbon [8], [9]. The adoption of hydrogen fuel presents a notable advantage in this regard, owing to its classification as a zero-carbon fuel.

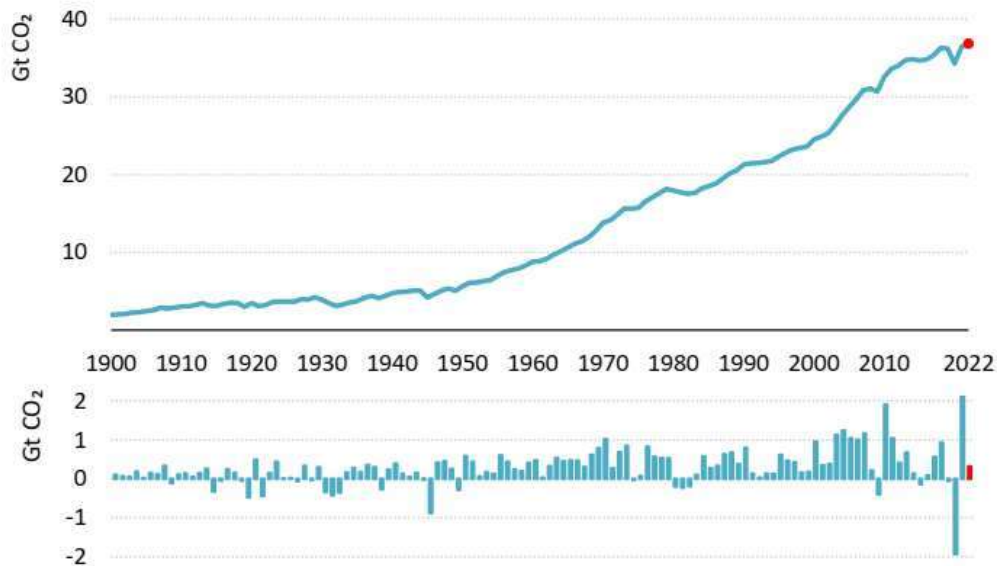


Figure 1: The global carbon dioxide emissions stemming from energy combustion and industrial processes, presenting their annual variations from 1900 to 2022. [7]

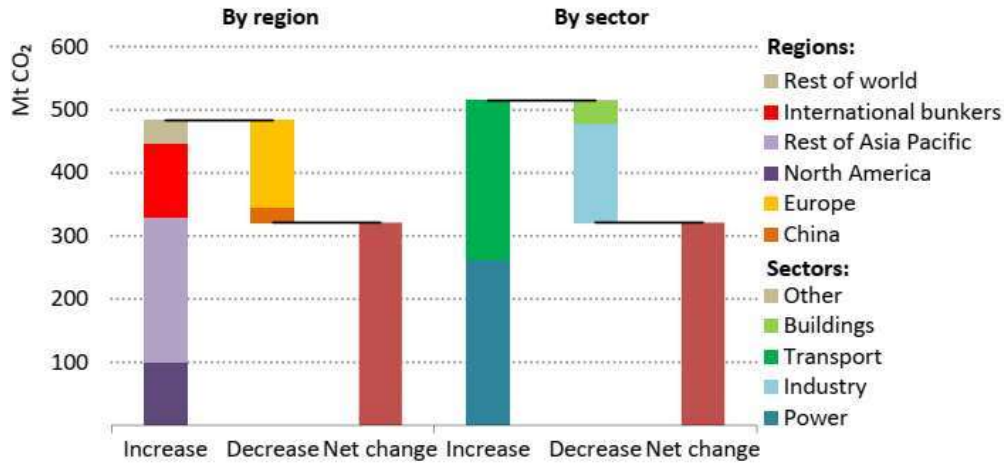


Figure 2: the change in carbon dioxide (CO₂) emissions by region and sector during 2021/ 2022. [7]

While hydrogen stands as the most widespread element in our universe, it is not found as free molecules on Earth. Instead, it is found within compounds containing other atomic species, such as H₂O or HCs like CH₄. The extraction of pure hydrogen involves separating it from these molecules. Presently, the global demand for hydrogen stands at approximately 70 million tons per annum, with nearly 90% sourced from NG or coal, predominantly through processes of reforming [10]. One such method is steam CH₄ reforming (SMR), generating "blue hydrogen" from CH₄ and H₂O. However, this process emits about 9.5 kg of CO₂ for every kg of H₂ produced, underscoring the imperative of employing carbon capture, utilization, and storage (CCUS) techniques to enhance sustainability. An alternative "green hydrogen" production method is electrolysis of water, considered environmentally cleaner and utilizing renewable energy sources [11], [12]. Recent advancements in technology include various of biogas generation methods like gasification and pyrolysis [13], [14]. In addition, advances in microorganism-based biomass fermentation have garnered attention [15], [16]. Furthermore, new techniques such as thermo-chemical processes and photo-electrochemical, including microbial electrolysis, aim to reduce the energy input needed for water splitting compared to conventional

electrolysis methods [17], [18]. To meet the large-scale hydrogen demand for decarbonizing the thermo-electric generation sector, “blue hydrogen” is still necessary, using the SMR process with CO₂ capture techniques. Considering the features of current CCS technologies [19], [20], a centralized production system seems more feasible, as it offers higher volumes and lower capture costs.

Table 1: H₂ properties compared with CH₄, C₃H₈ [21]–[23]

	CH₄	H₂	C₃H₈
Molecular Weight [g/mol]	16.04	2.016	44.097
Density at NTP [Kg/m ³]	0.6512	0.0838	1.87
Self-Ignition T [K]	813–905	845–858	760–766
Minimum Ignition energy [mJ]	0.29–0.33	0.02	0.26–0.305
Flammability range in Air [vol%]	5–15	4–75	2.1–10
Flammability range [ϕ]	0.4–1.6	0.1–7.1	0.56–2.7
St. Composition in air [vol%]	9.48	29.53	4.02
AFT [K]	2158–2226	2318–2400	2198–2267
Lower Heating value [MJ/Kg]	50	118.8–120.3	46.35
Higher Heating value [MJ/Kg]	55.5	141.75	50.4
Lower Heating value [MJ/m ³]	35.8	10.78	91.21
Higher Heating value [MJ/m ³]	39.72	12.75	99.03

The combustion of hydrogen with air presents a distinctive environmental advantage by avoiding the generation of CO₂ emissions, a major contributor to the greenhouse effect. In its exothermic reaction with air, the resulting products primarily consist of H₂O, inconsequential portions of OH, H, and O, along with a measured quantity of NO_x emissions. Significantly, hydrogen combustion diverges from the production of typical HC reaction intermediates, such as CO, and avoids the formation of more complex, potentially

harmful molecules [1], [24]. However, harnessing the full potential of GTs at elevated hydrogen concentrations requires specialized combustion systems tailored to the unique attributes of this fuel. The combustion characteristics of hydrogen deviate notably from those of NG, with key distinctions summarized in Table 1.

The utilization of hydrogen in GTs presents several distinctive characteristics that impact both combustion efficiency and design considerations. In comparison to CH_4 , hydrogen exhibits a higher AFT, a parameter crucial for defining combustion efficiency and liner cooling requirements in GT design [25]. This elevated AFT, however, poses challenges, potentially leading to increased NO_x levels. The introduction of hydrogen into conventional fuels can mitigate CO emissions due to reduced carbon input at a constant value of equivalence ratio, enhancing the oxidation of CO and CO_2 through higher quantities of H and OH radicals [26]. Nonetheless, working with excessively lean mixtures may decrease temperature and increase CO emissions [21]. Hydrogen has a lower calorific value than NG, about one-third on the volume basis. This means that fuel supply systems need to deliver higher volumes of hydrogen to achieve the same energy output [27]. Hydrogen's reactivity, flame speed, and IDT differ significantly from NG, with hydrogen-rich mixtures exhibiting higher LFS and increased risks of dynamic instabilities and thermo-acoustic instabilities [28]–[33]. Despite ongoing research, the comprehensive resolution of combustion instabilities remains elusive, prompting reliance on empirical methods [34]–[36]. Lean hydrogen flames, characterized by pronounced wrinkles, possess higher turbulent flame speeds compared to other lean mixtures [37]. Additionally, hydrogen combustion produces dim flames, with most energy transmitted through convection and sensible heat in the exhausted gas [38].

1.1 Objectives

This work aims to evaluate the impact of hydrogen enrichment in stratified combustion through a combined experimental and numerical approach. Experimental assessments will be conducted utilizing the facilities at the Clean Combustion Laboratory in KFUPM. In this configuration, CH_4/air constitutes the primary premixed swirl-stabilized mixture, with hydrogen introduced as non-premixed jets around the CH_4/air flame. Concurrently, numerical simulations will be executed using the ANSYS Fluent commercial code, employing large eddy simulations to model stratified $\text{H}_2/\text{CH}_4/\text{air}$ flames in a full 3-D domain of the model combustor with a fixed inlet speed of 6 m/s for the primary mixture. The objectives of this study are as following:

1. Conduct experimental assessments to record Lean Blowout (LBO) limits, visual appearances, and temperature distributions of stratified $\text{H}_2/\text{CH}_4/\text{air}$ flames.
2. Develop a computational model for simulating stratified combustion and validate the numerical model by comparing the simulation results with available experimental data.
3. Conduct a comprehensive numerical exploration into the intricate combustion characteristics, encompassing parameters such as flame Temperature, velocity contours, Flame speed and flame thickness, Critical strain rate, Progress variable and Product formation rate, along with a detailed examination of Species Distributions and emissions.

CHAPTER 2

LITERATURE REVIEW

In the domain of combustion research, hydrogen has garnered significant attention as a fuel source, presenting a nuanced interplay of advantages and challenges. On the positive side, hydrogen combustion stands out for its notable virtue in yielding minimal greenhouse gas emissions, directly addressing environmental concerns associated with conventional fuels. The elevated AFT and reactivity inherent to hydrogen combustion contribute to heightened combustion efficiency and flame speed, making it an appealing prospect for specific applications. Additionally, the utilization of hydrogen holds potential benefits in alleviating static instability, particularly in the context of LBO limits.

However, this seemingly advantageous fuel alternative is not exempt from inherent challenges. Foremost among these challenges is the potential escalation in NO_x levels, necessitating strategic interventions for effective mitigation. Furthermore, the deployment of hydrogen necessitates specialized combustion systems and heightens the risk of flashback, demanding meticulous engineering considerations. The combustion of hydrogen introduces intricate instabilities, including intrinsic and dynamic (thermo-acoustic) instabilities, requiring nuanced scrutiny in both design and operational realms. This comprehensive assessment underscores the nuanced nature of hydrogen's utilization as a combustion fuel, emphasizing its dualities in both environmental and operational contexts.

2.1 Advantages of Hydrogen Combustion

2.1.1 Improving Flame Speed and Reaction Kinetics

Hydrogen fuel has very distinguished properties which made it one of the most promising fuels. Hydrogen has a very low molecular weight which helps in its diffusion easily among other fuels and reacting with its oxidizer very fast [39]. Besides, it has a high calorific value which makes it produce a high-temperature flame. All of these make hydrogen combust very fast with a high flame speed and produce many radicals which assist in flame stability and make reaction kinetics so fast. Because of its rapid flame speed, hydrogen is a very efficient fuel, which is why it is used in many applications, such as rocket engines, fuel cells, and industrial processes. However, it is also important to handle hydrogen with care because of its high reactivity and flammability. Hydrogen combustion kinetics, explored since the early 20th century however, precise reaction mechanisms and rate parameters details remain unknown. Recent years have seen new reaction steps proposed [40]. Table 2 summarizes the most recent reaction kinetics models used for hydrogen combustion.

Table 2: The most recently reaction kinetics models used for hydrogen combustion.

Kinetic model	Fuel Studied	Model Overview
GRI-Mech 3.0 [41]	Detailed kinetic mechanism for CH ₄ /air combustion	The model comprises 53 species and 325 reactions, assembled without specific optimization for hydrogen combustion but rather relying on the authors' expertise in the field.
Konnov [42], [43]	H ₂ /O ₂	The outcomes of the calculations conducted in this study, employing the revised mechanism, exhibit commendable quantitative concordance with ignition experiments

		spanning temperatures ranging from 950 to 2700 K and encompassing sub-atmospheric pressures up to 87 atm.
Alekseev et al. [44]	H ₂ /O ₂	The investigation employed an updated Konnov reaction mechanism to examine the impact of temperature on adiabatic burning velocities in diluted hydrogen flames.
Kéromnès et al. [45]	H ₂ /CO/O ₂ /N ₂ /Ar mixtures	The study encompassed pressure levels ranging from 1 to 70 bar, exploring a temperature span of 914–2220 K and considering equivalence ratios within the range of 0.1 to 4.0.
Hong et al. [46]	H ₂ /O ₂	The revised mechanism is informed by the outcomes of recent rate coefficient studies, enhancing its reliability. This validation suggests that the updated mechanism is well-suited for robust performance across a spectrum of reactant concentrations, stoichiometries, pressures, and temperatures, spanning from 950 K to beyond 3000 K.
Wang [47]	H ₂ /CO/C1-C4 HCs	A skeletal mechanism comprising 56 species and 428 reactions has been derived from a more comprehensive mechanism, which originally consisted of 111 species and 784 elementary reactions.
Powell et al. [48]	Hydrogen and C1–C3 HC	The assembled chemical mechanism has undergone comparison and validation against existing data documented in the literature.
Li et al. mechanism [49], [50]	H ₂ /O ₂	The study encompassed a broad range of conditions, including temperatures ranging from 298 K to 3000 K, pressures spanning from 0.3 atm to 87 atm, and equivalence ratios (ϕ) extending from 0.25 to 5.0.
Burke et al. mechanism [51]	H ₂ /O ₂	An enhanced kinetic model has been developed, drawing its foundation from the work of Li et al. [49], [50].
CRECK modeling	H ₂ /CO mixtures	The model is comprised of 21 species and 62 reactions.

group at Politecnico di Milano [52]–[54]		
Zhang et al. [55]	H ₂ /O ₂	Incorporating updated transport parameters, new rate coefficients, and chemically termolecular reactions significantly improves predictions for LFS and structure. This mechanism excels in high-pressure lean H ₂ flames (up to 25 atm) but struggles with accuracy under negative pressure conditions.
optimized mechanisms		
Davis et al. [56]	H ₂ –CO	The construction of the model involves a review of recent kinetics literature, incorporating a substantial set of GRI 3.0 rate parameters.
Varga et al. [57], [58]	Syngas mixture	An optimization was conducted on the hydrogen combustion mechanism proposed by Kéromnès et al. [45], spanning extensive ranges of temperature (800 K–2300 K), pressure (0.1 bar–65 bar), and equivalence ratio ($\phi = 0.2$ –5.0).
Slavinskaya et al. [59]	H ₂ /CO	The validation and optimization of a syngas combustion model were undertaken using a data-centric infrastructure referred to as the Process Informatics Model.
Wang et al. [60]	H ₂ /O ₂	The chemical kinetic model for H ₂ oxidation, comprising 19 reactions, underwent optimization accompanied by uncertainty quantification.

Flame speed is influenced by the way chemical reactions occur and the presence of radicals like OH and H in the flame. When it comes to hydrogen flames, the interactions between reaction processes and these radicals are of significant interest. By delving into these complexities, we aim to gain a deeper understanding of how hydrogen flames behave. This

knowledge is pivotal for optimizing the utilization of hydrogen as a supply for energy, with the goal of making it more efficient and environmentally friendly. A widely recognized observation in laminar premixed hydrogen/air flames is their significantly faster propagation compared to HC flames. Figure 3 [61], [62] compares time-sequences of spherically expanding flames. All flames are shown at the same radii, with times relative to ignition indicated. Hydrogen flames are roughly ten times faster than CH_4 flames. Intrinsic flame instabilities, which will be discussed in section 2.2.3.1, are observed in both stoichiometric and lean hydrogen flames, while the CH_4 flame surface remains smooth.

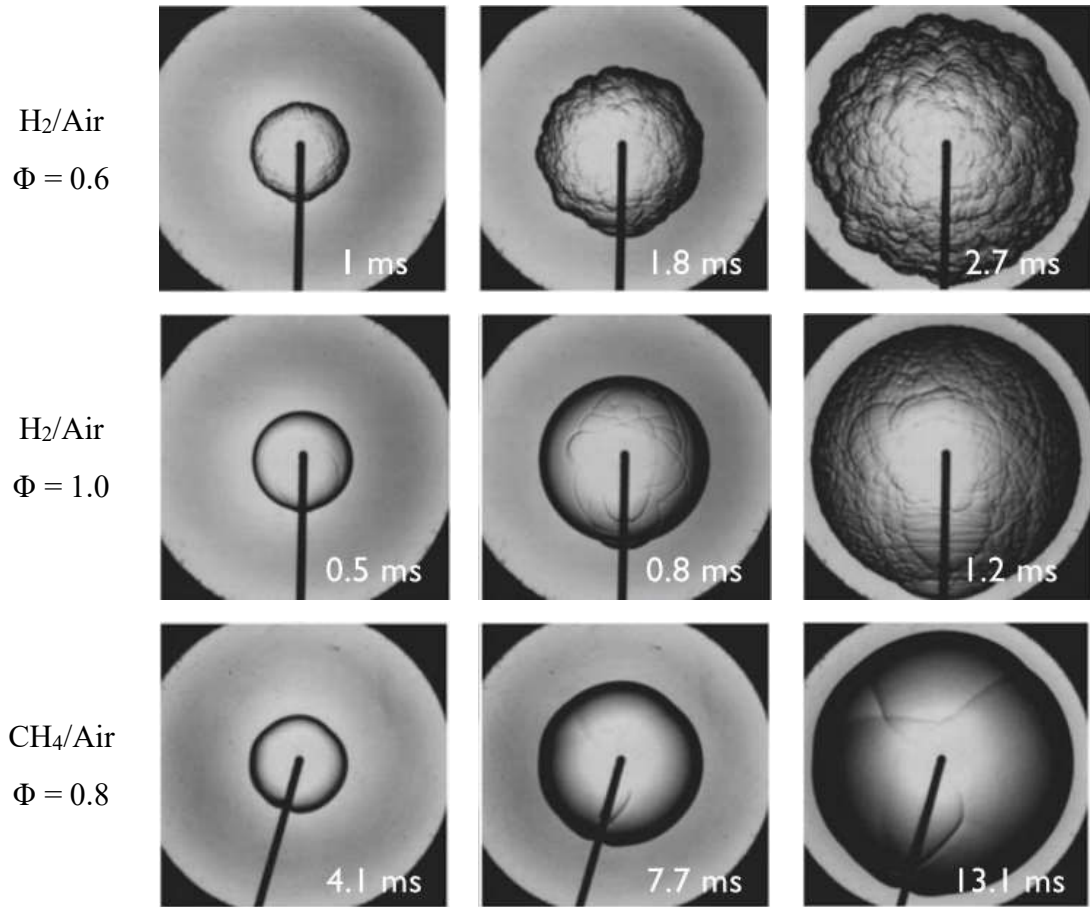
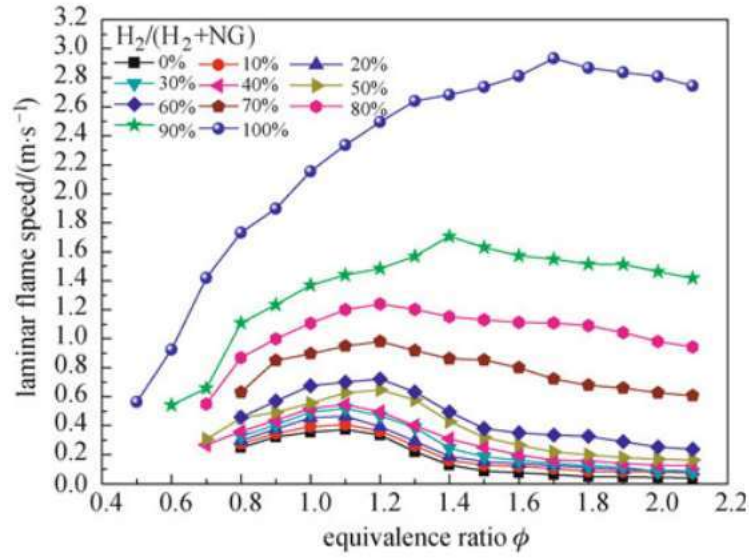


Figure 3: Effect of fuel type and equivalence ratio on flame propagation and intrinsic instability for H_2/Air and CH_4/Air mixtures, pressure = 2.5 bar and initial temperature = 373 K. [61], [62]

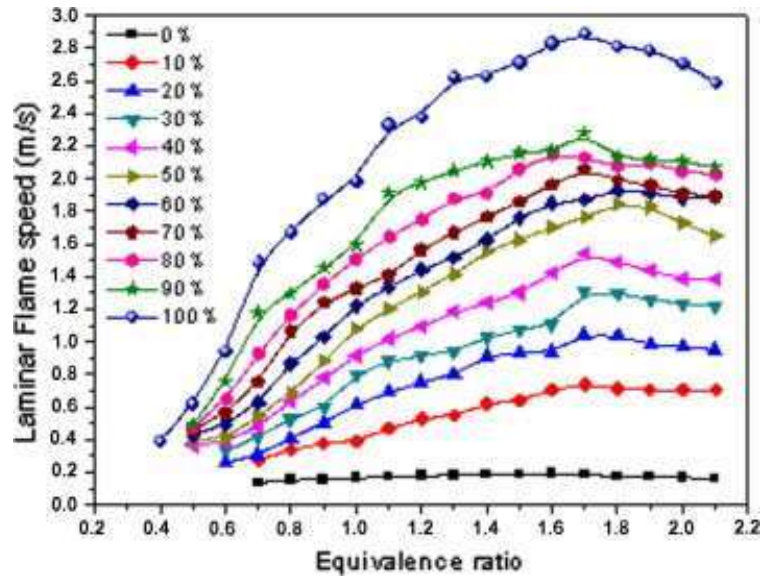
Enhancing combustion characteristics is achievable by integrating hydrogen as a catalyst with various fuels. Introducing hydrogen into a fuel mixture holds the promise of improving flame propagation speed, reducing ignition delay duration, and enhancing reaction kinetics. Numerous studies have been conducted to investigate the impact of hydrogen addition on the LFS of various HC fuels, including CH₄ [63]–[74], propane [63], [75], butane [76], n-decane [77], [78], dimethyl-ether [79] and acetylene [80]. These studies have employed a diverse range of experimental and numerical methodologies encompassing a wide spectrum of fuel compositions and equivalence ratios. The observed augmentation in flame propagation speed is ascribed to the promotion of reaction R1: $\text{H} + \text{O}_2 \rightleftharpoons \text{OH} + \text{O}$, which becomes more clearly by increasing hydrogen content [63], [81].

Dong et al. [82], [83] conducted a comprehensive investigation to show hydrogen enrichment impact on CH₄/H₂ flames. Their study involved the measurement of LFS for CH₄/H₂ and H₂/CO mixtures across a wide range of hydrogen fractions, spanning from 0% to 100% (Figure 4). Hydrogen/air mixture has a maximum LFS of value 2.933 m/s at an equivalence ratio equal to 1.7 while CH₄/air mixture has a maximum value of 0.374 at a 1.1 equivalence ratio. Shang et al. [84] examined experimentally and numerically the LFS in CH₄/H₂/Air mixtures with varying proportions of diluents such as CO₂ and N₂. They used a wide range of HF (0% to 75% by volume) and CO₂/N₂ dilutions (0% to 67% by volume) in the fuel over a range of equivalence ratios between 0.8 and 2.0. At lower hydrogen fractions (HF ≤ 50%), increasing the hydrogen content in H₂/CH₄/air mixtures led to a linear increase in LFS. This increase was due to the greater presence of OH radicals produced by key oxidation reaction, $\text{H} + \text{O}_2 = \text{O} + \text{OH}$, which enhanced CH₄ conversion. As the hydrogen fraction continued to rise, the combustion process shifted from CH₄-

dominated to hydrogen-dominated, resulting in a significant, non-linear increase in LFS. CO_2 had a more pronounced effect on reducing LFS compared to N_2 due to its higher chemical kinetics and heat capacity. When CO_2 was added, it intensified the competition for H radicals through reactions like $\text{CO} + \text{OH} = \text{CO}_2 + \text{H}$ and $\text{H} + \text{O}_2 = \text{O} + \text{OH}$, leading to a more significant decrease in the LFS of the mixtures.



a)



b)

Figure 4: Laminar flame speed versus equivalence ratios, a) CH_4/H_2 and b) H_2/CO mixtures [82], [83]

2.1.2 Improving Static Blowout Stability Limits

Flame blowout is a phenomenon that occurs in combustors, leading to the extinguishing of the flame. This happens due to an imbalance between the flame velocity and the reactants from the opposing side. Under very lean operating conditions, the flame speed decreases, causing the reactants stream to convect the flame downstream, weakening it and leading to its extinction. This phenomenon presents a challenge to operating combustors under very lean conditions, which have significant advantages, such as high efficiency and lower emissions. Numerous studies have attempted to extend the LBO limits by employing various approaches. A viable strategy entails the incorporation of hydrogen into the fuel composition. The conclusions of numerous studies [30], [38], [85]–[94] revealed that lean blow out flame extinction occurs at lower equivalency ratios for greater H_2 mole fraction fuel mixtures which makes the combustor works at lower temperatures as well as emissions.

Schefer et al. [30] and Schefer [85] studied the structure of flames near to the LBO limit for CH_4 /air mixtures enriched with hydrogen and stabilized by swirl. They demonstrated that the addition of hydrogen into the mixture elevated the concentration of OH radicals within the flame, thereby yielding a more concise and resilient flame. This, in turn, led to a decrease in the lean stability limit. For additions of up to 20% hydrogen by volume, a significant improvement in LBO limit was observed. Specifically, at an input velocity of 20 m/s, the LBO limits decreased by 10.4% and 16.6% for 10% and 20% hydrogen fractions, respectively. These findings were also replicated by Griebel et al. [86] and Boschek et al. [88]. Another study [95] demonstrated that when the HF reaches 20%, the range of stable combustion becomes somewhat wider, and the LBO

limit is enhanced by almost three times (Figure 5). In addition, the inclusion of hydrogen aids in the resolution of the problem of difficult ignition and failure to sustain stable CH_4 combustion under certain lean conditions. Strakey et al. [96] showed that increasing hydrogen fraction from 0% to 80% for a lean swirled NG/air mixture lowered the LBO limit from 0.46 to 0.3. while combustor pressure (increased from 1 to 8 atm) and jet velocity (increased from 40 to 80 m/s) has little impact on LBO limit.

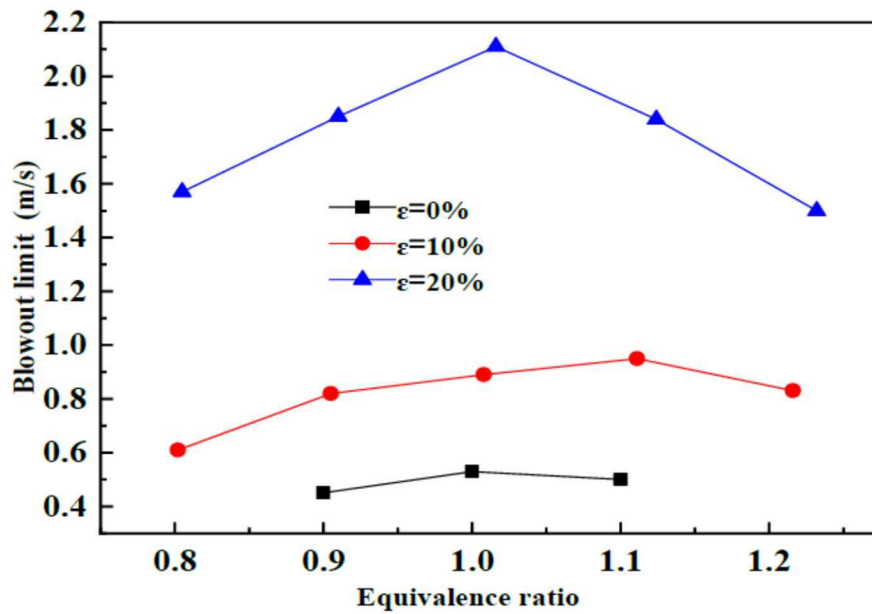


Figure 5: lean blowout limit for fully premixed hydrogen enriched- CH_4 fuel in micro-planar combustor. [95]

Due to its increasing significance, the assessment of stability margins and prediction of LBO have become crucial areas of focus. Huelskamp et al. [97] employed a dataset of 1100 points obtained from published literature to establish a correlation (Equation 1) capable of accurately predicting lean blowout equivalence ratio. Their study involved various fuels including CH_4 , propane, gasoline, hopane, King-JP4, and AFRL. To create their correlation model, they incorporated several factors such as temperature, pressure, oxygen level in oxidizing gas, the ratio of nozzle diameter to brink velocity, and hydrogen-to-carbon ratio

of the fuel. The resulting R-squared value was 0.873, indicating a high level of accuracy. The researchers concluded that an increase in pressure, temperature, hydrogen-to-carbon ratio in the fuel, and oxygen ratios would lower the LBO limit. The studied parameters affected the Da, in which higher hydrogen-to-carbon ratios indicate higher cetane numbers and shorter ignition delay times, which is a suitable representation of the chemical timescale. On the other side, the ratio of nozzle diameter to brink velocity was identified as the fluid mechanic timescale. To obtain more accurate predictions with a smaller dataset, they replaced all the parameters with the ratio of nozzle diameter to its brink velocity and the IDT in the correlation, which resulted in an improved R-squared value of 0.918.

$$\phi_{LBO \text{ predicted}} = \frac{1.02 \times 10^3}{P^{0.2612} T^{0.8416} \left(\frac{D}{U}\right)^{0.1464} \left(\frac{H}{C}\right)^{0.2130} O_2^{1.131}} \quad (1)$$

Many studies [21], [98]–[105] use the Da as a scaling parameter to successfully estimate the blowout conditions for various fuels. The Da is a dimensionless parameter that represents the ratio of the time scale for mixing to the time scale of chemical reaction in a combustion system. Noble et al. [105] have showed that LBO limit permanently occurred at constant Da number of value equals 0.82, regardless of the fuel composition being used H₂/CO/CH₄, for hydrogen fractions less than 50%. They define Da number as following;

$$Da = \frac{t_{res}}{t_{chem}} = \frac{S_L^2 d}{\alpha U_{ref}} \quad (2)$$

Where S_L , α , U_{ref} and d are LFS, thermal diffusivity, reference velocity (function of upstream velocity and temperature of reactants and products) and recirculation zone length.

At higher hydrogen fractions, Da number decreases due to preferential diffusion effects of

hydrogen which affect flame diffusivity and flame turbulent speed. When they recalculated Da number based on local equivalences to take into consideration these effects, they found that LBO limit is at constant Da number of values equals 0.21 for all hydrogen fractions [106]. Figure 6 shows the difference between Da and local Da to predict the LBO limit. On the other hand, Li et al [102] found that Da number at LBO is dependent on inert content for syngas combustion. They generate a correlation (eq. 3) to capture thermal chemical effects of inert dilation.

$$T_{flame}^* = -0.123 \times \ln(Da) + 0.9539 \quad (3)$$

$$T_{flame}^* = \frac{T_{LBO}}{T_{st.}} \quad (4)$$

Where T_{LBO} , $T_{st.}$ are the AFTs at LBO and stoichiometric conditions, respectively. Other correlations based on Da number are generated by Rasmussen and Driscoll [104], [107], Strakey et al. [96] and Zhang et al. [103]. However, all these models are sensitive to the fuel composition, combustion characteristics and definition of Da number parameters.

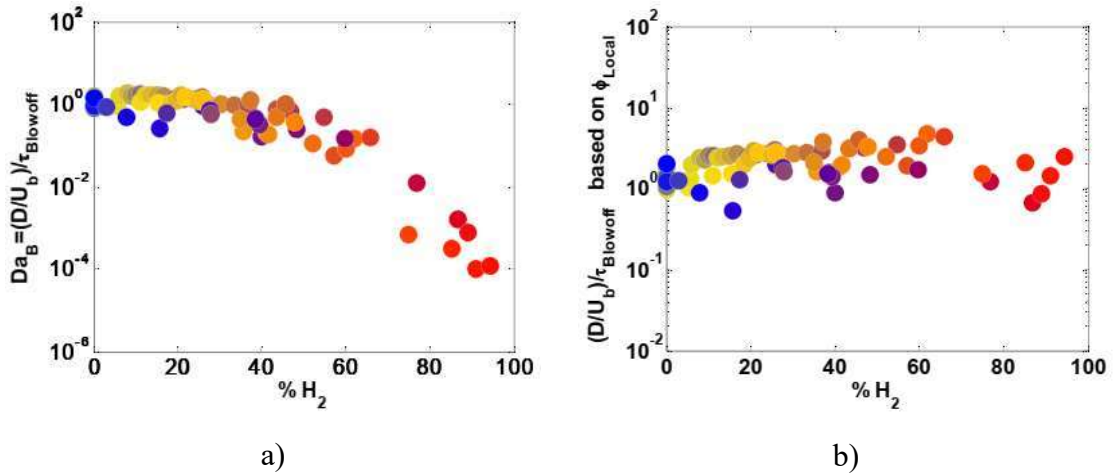


Figure 6: Da number at blowout a) mixtures at $T = 300$ K, $P = 1.7$ atm and $V_{in} = 59$ m/s, b) mixtures based on adjusted local equivalence ratio at $T = 458$ K, $P = 4.4$ atm and $V_{in} = 59$ m/s. [106]

2.2 Challenges of Hydrogen Combustion

2.2.1 Higher NO_x Emissions

The distinctive properties of hydrogen, rendering it a prominent fuel source, are accompanied by notable challenges, with one of the most significant being the propensity for elevated NO_x emissions. The enrichment of hydrogen, while concurrently augmenting free radicals' number, also raises flame temperature, thereby enhancing chemical reactions and NO_x production. Effectively addressing and mitigating NO_x emissions necessitates a deep grasp of the intricate mechanisms behind their formation and the nuanced impact of hydrogen addition on these mechanisms. NO_x formation typically occurs through four mechanisms: thermal, prompt, nitrous oxide (N₂O), and NNH. Thermal mechanisms predominate in high-temperature combustion scenarios, while prompt mechanisms depend more on radical concentration than temperature [108]. Nitrous oxide mechanisms manifest in very lean, low-temperature combustion, whereas NNH mechanisms dominate in rich combustion conditions [109], [110]. Various investigations have explored the influence of hydrogen enrichment on NO_x emissions in different combustors, as delineated in Table 3. Computational and practical investigations focusing on CH₄ enriched with hydrogen in a diffusion mode, conducted by three studies [111]–[113], unequivocally demonstrate an rising in NO_x emissions attributable to the elevated temperatures for the flame. In hydrogen-CH₄ combustion, thermal and prompt NO_x mechanisms emerge as dominant factors while thermal mechanism dominates in hydrogen combustion. Two additional studies [114], [115] explore the impacts of H₂ enriching to CH₄ under MILD burning conditions, encompassing oxygen percentages ranging from 3% to 9%. Despite the lower temperatures associated with MILD technology, hydrogen addition paradoxically increases

overall NO_x emissions. The specific influence of each NO_x mechanism is contingent upon the percentage of oxygen in the mixture. Notably, for low oxygen percentages (ranging from 3% to 6%), hydrogen addition enhances NNH mechanisms while suppressing prompt and N₂O mechanisms, with the thermal route's contribution being limited as a reason for lower temperature. Interestingly, investigations conducted by Ali et al. [115] demonstrate that N₂O mechanisms dominate in NO_x formation under low oxygen combustion, whereas Gao et al. [114] emphasize the dominance of NNH and prompt routes. An additional two studies [116], [117] under MILD conditions reveal that NNH and N₂O routes prevail, providing nuanced insights into the dynamic relationship between hydrogen addition and NO_x formation mechanisms across diverse combustion scenarios.

Table 3: Various investigations have explored the influence of hydrogen enrichment on NO_x emissions in different combustors.

Main fuel	% HF	ϕ	Flame Type	Combustor Type	Emissions	study
CH ₄	0 and 45%	—	lean, premixed	swirl flame	The addition of hydrogen does not impact NO _x levels.	Experimentally 2002, [30]
CH ₄	0 and 29%	0.52	lean premixed	—	The introduction of hydrogen leads to an increase in NO _x emissions.	Numerically 2004, [118]
CH ₄	0 - 100%	—	diffusion	—	The inclusion of hydrogen results in elevated levels of both NO _x and CO emissions.	Numerically 2005, [112]
CH ₄	0 - 40%	less than 0.7	Lean-premixed	—	Hydrogen addition raises NO _x emissions at a consistent equivalence ratio.	Numerically 2005, [119]
CH ₄ and C ₃ H ₈	0 - 40%	—	premixed	swirl flames	Hydrogen addition reduces NO _x and CO emissions.	Experimentally 2006, [120]

CH ₄	0 - 35%	0.7 - 1.4	premixed	perforated plate	NOx remains unaffected by hydrogen addition in the lean side, while it decreases in the rich side.	Experimentally and Numerically 2007, [121], [122]
CH ₄	0 - 9%	0.62 3 - 0.65 5	lean, premixed	swirl flames	At small swirl angles, augmenting hydrogen addition leads to a reduction in NO emissions, whereas at larger angles, hydrogen addition results in an increase in NO emissions.	Experimentally 2007, [27]
CH ₄	0 - 40%	1	premixed	_____	Hydrogen addition has a minimal impact on NO formation.	Numerically 2009, [123]
CH ₄	0 - 50 %	_____	diffusion	Free jet	The introduction of hydrogen leads to elevated levels of both NOx and CO emissions.	Experimentally 2010, [111]
CH ₄	11 - 30%	_____	diffusion, MILD combustion with oxygen percentage 3 - 9%	_____	The addition of hydrogen results in an increase in NOx emissions.	Numerically 2009, [124]
CH ₄ /CO ₂ /N ₂	0 - 20%	0.7 - 1.3	premixed at high pressures (1 - 5 bar)	_____	The introduction of hydrogen, along with a rise in pressure, leads to an increase in NOx emissions.	Experimentally 2014, [125]
NH ₃	33.3 - 60%	1 - 1.25	premixed	Tube type burner	The introduction of hydrogen increases NOx emissions, while an increase in ϕ correlates with a decrease in NOx concentration.	Experimentally 2014, [126]

CO/CO ₂ /CH ₄ (syngas)	38.5 - 90%	0.5 - 1.1	premixed	swirl flames	The inclusion of hydrogen results in a reduction of NO _x emissions on a per kWh basis across all equivalence ratios.	Experimentally 2016, [127]
NG	15% & 20%	0.7 - 1	diffusion	—	The introduction of hydrogen leads to elevated NO _x emissions, accompanied by a simultaneous decrease in CO and CO ₂ emissions.	Experimentally 2016, [113]
NH ₃	50%	0.3 - 1.2	premixed	swirl flames	High NO _x emissions are observed when the equivalence ratio exceeds 0.5.	Experimentally 2017, [128]
C ₂ H ₄ and CH ₄	0 - 30%	0.69 -0.81	lean partially premixed	bluff-body combustor	Hydrogen addition leads to an increase in NO _x emissions.	Experimentally 2019, [129]
CH ₄	0 - 90%	—	rich/quench /lean	Can combustor	The addition of hydrogen results in a reduction of NO _x and CO emissions at a constant velocity.	Numerically 2019, [130]
CH ₄	20%	0.6 - 0.74	lean, premixed at high pressures (up to 7 bar)	counter flow burner	The introduction of hydrogen, along with a rise in pressure, contributes to an increase in NO _x emissions, whereas a reduction in the equivalence ratio (ϕ) leads to a decrease in NO _x levels.	Experimentally and Numerically 2019, [131]
CH ₄ / CO ₂	0 - 60%	1.2	premixed	—	Hydrogen addition leads to an increase in NO _x emissions.	Experimentally and Numerically 2020, [132]

CH ₄	0 - 60%	0.8	MILD combustion with oxygen percentage 3 - 9%	————	Hydrogen addition leads to an increase in overall NOx emissions.	Numerically 2020, [115]
NH ₃	50 - 100 %	0.4 - 1.05	premixed	swirl flames	Under conditions of very lean combustion, NO emissions remain at low levels.	Experimentally 2021, [133]
CH ₄ /C ₃ H ₈	0 - 100 %	0.55 - 0.65	Lean-premixed	Micromixer	NOx is not affected by the addition of hydrogen.	Experimentally 2021, [134]
NH ₃ /N ₂	0 - 100 %	0.2 - 1.6	lean, premixed at high pressures (up to 5 bar)	swirl flames	Under extremely lean conditions, NO emissions are low.	Experimentally 2021, [135]
NH ₃ /N ₂	21% and 45%	0.3 - 1.1	premixed mixture	————	In lean conditions, an increase in fuel leads to higher NOx emissions, whereas in rich conditions, the lack of oxygen decreases NOx. The maximum NOx levels are observed at $\phi = 0.8$.	Numerically 2021, [136]
CH ₄	0-30%	0.565 - 0.609	lean premixed at high pressures	————	The addition of hydrogen and an increase in pressure lead to elevated NOx emissions.	Numerically 2021, [137]
CH ₄	0 - 100%	0.8	lean	Nozzle burner	The introduction of hydrogen results in an increase in NOx emissions.	Experimentally 2021, [138]
NH ₃	40 - 80%	0.6 - 1.2	premixed	micro combustor	The addition of hydrogen leads to a decrease in NOx	Numerically 2021, [139]

					emissions, with a concurrent reduction in NOx concentration under lean combustion conditions.	
CH ₄	0 - 100 %	0.6 - 1.4	premixed	—	The introduction of hydrogen increases NOx emissions, and a notable reduction in NO emissions can be achieved by decreasing the equivalence ratio from 1.2 to 0.6.	Numerically 2022, [140]
Biogas	0 - 50 %	0.2 – 0.5	non-premixed	can-type combustor	Operating under extra-lean conditions ($\phi = 0.5$ to 0.2) with the inclusion of hydrogen reduces thermal NOx formation.	Numerically 2022, [141]
C ₃ H ₈	0 - 90 %	0.2 – 0.5	non-premixed	can-type combustor	Increased equivalence ratios along with a high-volume percentage of hydrogen led to higher levels of NOx.	Numerically 2023, [142]
CH ₄	0 - 80 %	— —	Partially premixed	Three-stages axial swirler and a one-stage radial swirler	The addition of hydrogen results in an increase in NOx emissions.	Numerically 2023, [143]

Numerous investigations have explored the influence of enrichment of hydrogen in premixed combustion scenarios, highlighting the great reliance of NOx emissions on factors such as equivalence ratio and hydrogen fractions. A specific study [129] delves into hydrogen enrichment influence in a lean partial premixed mixture involving two distinct fuels, namely CH₄ and ethylene. The findings reveal an augmentation in NOx emissions

with hydrogen addition, concomitant with a reduction in CO₂ emissions, as depicted in Figure 7. Li et al. [126] have examined the ramifications of hydrogen addition in an ammonia premixed mixture, focusing on the rich region. Despite the improvements in combustion properties attributable to hydrogen addition, it is noted that this enhancement coincides with increased NO_x emissions. The study elucidates that the peak concentration of NO_x occurs at stoichiometric conditions, decreasing as the equivalence ratio rises. Substantiating these outcomes for the lean side, Medina et al. [128] conducted both computational and experimental analyses, establishing that NO_x emissions escalate significantly when the ϕ surpasses 0.5, primarily due to elevated concentrations of OH and O radicals. In contrast, Han et al. [139] present divergent findings, indicating a reduction in NO_x emissions with escalating hydrogen fractions.

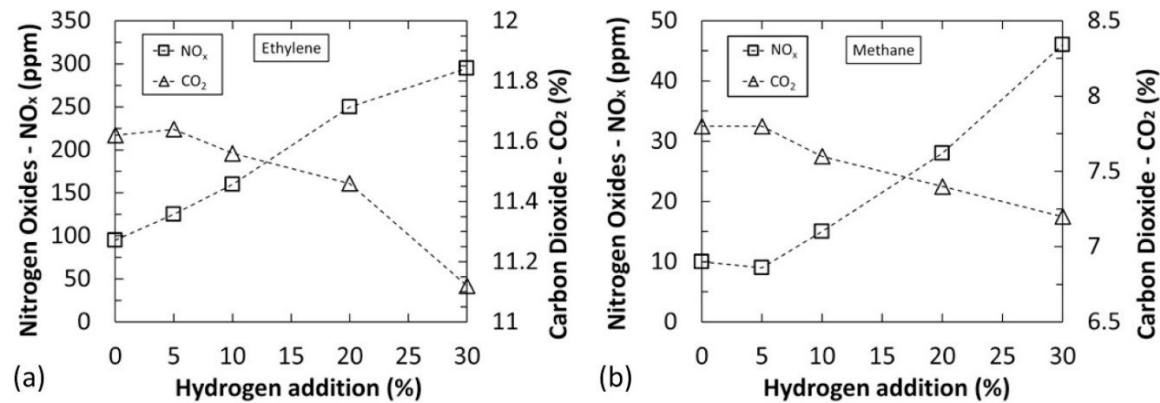


Figure 7: Emission changes (NO_x – ppm and CO₂ – %) with varying hydrogen fractions in (a) ethylene flames and (b) CH₄ flames. [129]

The influence of operating pressure on NO_x formation emerges as a noteworthy factor, as demonstrated by Persis et al. [131] in their study on lean premixed CH₄/H₂ mixtures. Their findings assert that heightened pressure and equivalence ratios play a pivotal role in enhancing NO production. Notably, when the hydrogen percentage reaches 20%, the NO percentage undergoes a twofold increase. This is due to the elevated flame temperature,

favoring the thermal route while concurrently diminishing the N_2O route. Figure 8 provides a comprehensive visualization of the contribution of each route, both with and without hydrogen addition, across distinct pressure values. Figure 9 additionally delineates operating pressure and equivalence ratio influence on the various routes involved in NOx formation. Parallely, Park [137] presents analogous results, though he posits that prompts and NNH routes exert a more pronounced influence than thermal and N_2O routes within the confines of his study range.

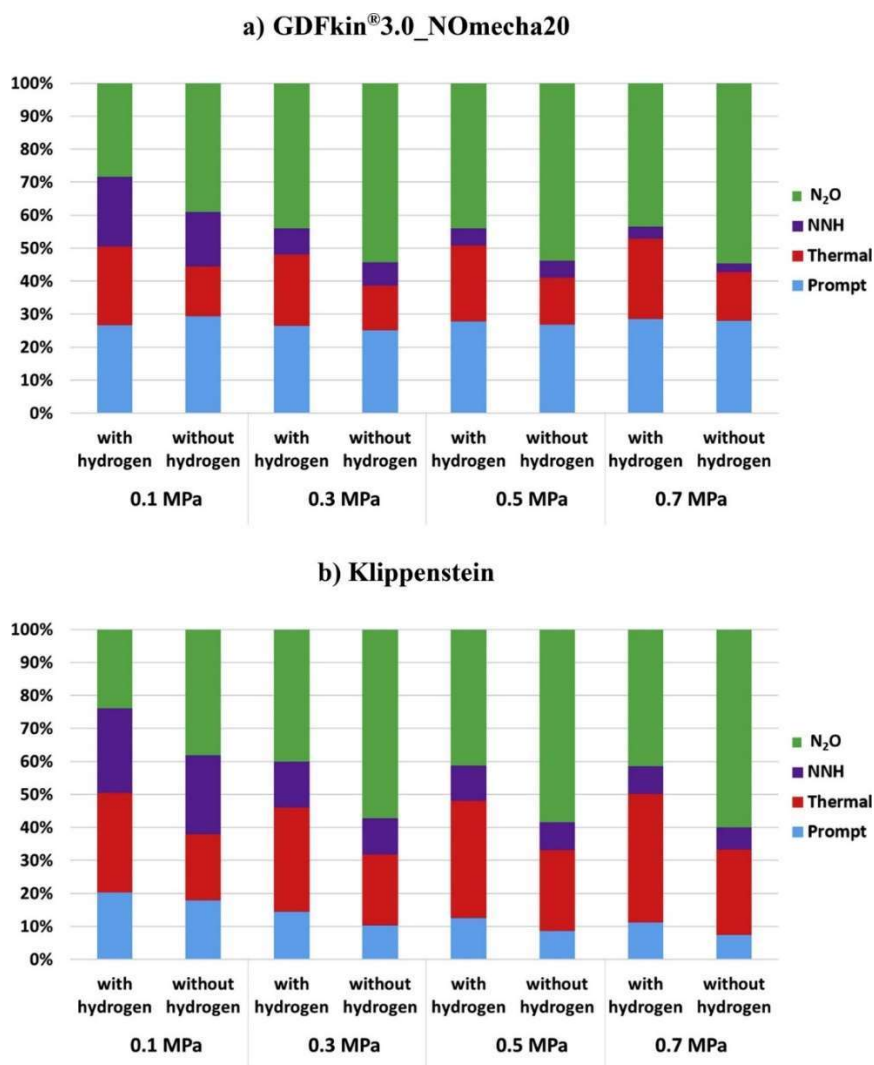


Figure 8: Influence of operating pressure on the varying significance of NO formation routes for CH_4 and H_2/CH_4 (20% hydrogen fraction) ($\phi = 0.74$), using a) “GDFkin@3.0_NOmecha2.0” and b) “Klippenstein mechanism” [131].

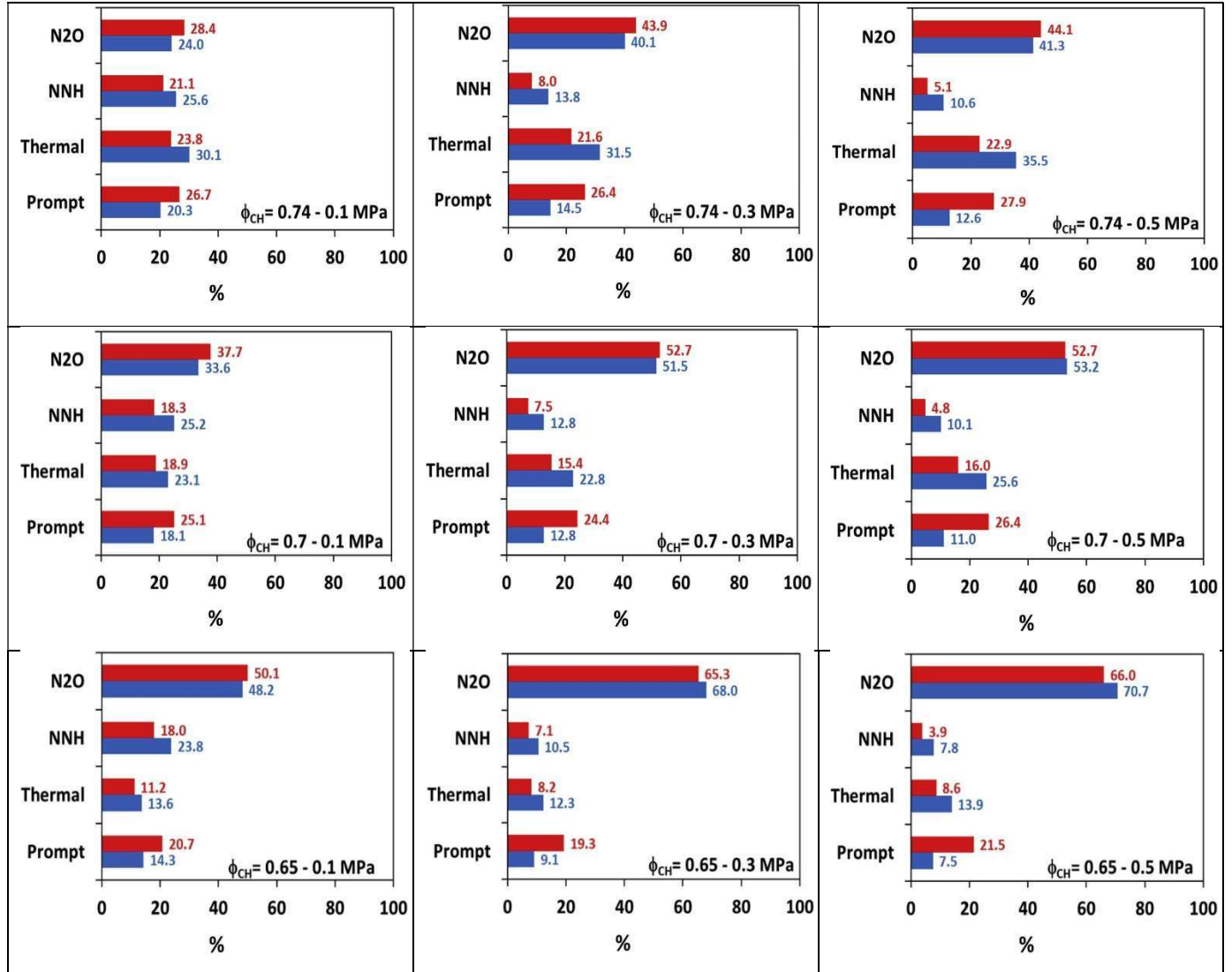


Figure 9: Operating pressure and equivalence ratio influence on the varying significance of NO formation routes for an H_2/CH_4 mixture with 20% hydrogen fraction, using “GDFkin@3.0_Nomecha2.0” (red) and “the Klippenstein mechanism” (blue). [131]

2.2.2 Higher risk of flashback in premixed flames

Flashback manifests when the flame retrogressively propagates upstream into the burner, occurring when the local flame velocity surpasses the flow velocity. This phenomenon is undesirable, as the flame reenters mixing passages and mixers not designed for such occurrences, potentially resulting in overheating and failure of combustor components [144]. Four distinct mechanisms contribute to flashback [145]: (i) flashback induced by combustion instabilities, (ii) core flow flashback, (iii) BLF, and (iv) CIVB.

Combustion instabilities, as previously elucidated, arise from the convergence of acoustic instabilities, unsteady heat release, and flow perturbations, resulting in oscillations in pressure and velocity within the flame. Such oscillations can engender flame movement and the formation of large vortices, precipitating flow reversal and thereby contributing to flashback [146]–[148]. The phenomenon of core flow flashback manifests when the turbulent flame velocity exceeds the flow velocity within the central region [149]. While increasing axial flow velocity can mitigate core flashback, certain flame stabilization methods commonly employed, such as those in swirl combustors, may inadvertently induce core flashback. In swirl combustors, for instance, the swirl action diminishes axial velocities, fostering vortices that elevate turbulent flame speed, potentially causing core flow flashback [150]. BLF predominates in jet/non-swirling flames. In a jet combustor, the core's free velocity typically exceeds the flame's turbulent velocity under normal conditions, while the flow velocity diminishes towards the combustor wall due to no-slip boundary conditions. Concurrently, the flame speed diminishes near the combustor wall due to factors such as heat loss or flame quenching. This reduction in flame speed can result in flashback, particularly when the velocity of the flame surpasses the local velocity of the flow near the wall [151], [152]. CIVB flashback is prevalent in swirler combustors, contingent upon the swirl number; if the swirl number exceeds a critical value, vortex breakdown occurs, potentially leading to flashback [145], [153], [154].

The introduction of hydrogen into a mixture has been observed to elevate flame speed, induce HDI, and diminish the quenching distance, thereby enhancing the susceptibility to flashback occurrence. Consequently, flashback tends to transpire at leaner conditions when compared to other fuels [155]–[159]. For laminar flow, the flashback mechanism is well-

understood, primarily relying on the critical velocity gradient concept [160]. This concept serves as an indicator of the propensity for BLF, where a higher velocity gradient correlates with an increased likelihood of flashback [145]. However, under turbulent conditions, the understanding of BLF is not fully comprehensive, necessitating further investigation into the impact of different parameters in turbulent settings. A study [160] comparing BLF in turbulent flow within a $\text{CH}_4/\text{H}_2/\text{air}$ mixture with critical velocity gradient indicates a deviation between calculated and observed flashback due to adverse pressure gradients and safety-critical flame positions. Hoferichter et al. [161] proposed a model to assess BLF propensity in GTs, demonstrating excellent concordance with experimental findings under ambient and preheated conditions. Subsequently, Bjornsson et al. [159] extended the model to predict flashbacks at higher preheat temperatures and backpressure. Despite these advancements, additional research is required to experimentally validate the model for diverse combustion conditions and assess the influence of quenching distance and turbulence statistics. Novoselov et al. [162] introduced a confined turbulent BLF model based on critically strained flames, demonstrating good agreement with experimental data for non-swirling burners employing hydrogen-air flames, with potential application to swirling combustors. Vance et al. [163] proposed a novel definition of the Karlovitz number, providing physical insights to mimic experimental data for flashbacks under different conditions. Although numerous studies have presented and enhanced models for predicting flashback in varied conditions, there remains a need for additional models that comprehensively consider all pertinent conditions across diverse flame configurations.

Numerous studies on swirler combustors have extensively investigated flashback mechanisms and the impact of various operating conditions on flashback propensity [164]–

[175]. Specifically, a reduction in swirl angle has been demonstrated to decrease flashback propensity, rendering flashback more sensitive to fuel composition [155], [173]. For low swirl values, BLF (BLF) tends to dominate, occurring either through the outer boundary layer or within the core flow, while higher swirl values lead to CIVB dominance, resulting in earlier flashbacks at elevated velocities, particularly when the fuel includes hydrogen [165], [166], [173]. Additional factors such as pressure, initial temperature, air-to-fuel ratio, and velocity exert notable effects on flashback propensity. Elevated pressure and AFT have been associated with increased flashback propensity, while heightened preheat temperatures (T_o) and velocity serve to mitigate it [164], [169], [172]. Despite the wealth of studies exploring the impact of diverse conditions on flashback in turbulent swirl combustors, the phenomenon remains intricate and not fully comprehended under varying operating conditions [145].

2.2.3 Hydrogen Induced Combustion Instabilities

2.2.3.1 Intrinsic Instabilities

Intrinsic instabilities pertain to disturbances inherent to the combustion process itself, independent of interactions with the surrounding environment. Two distinct types of intrinsic flame instabilities can be discerned: HDI, also known as DL instability, and TDI. HDI arises from the expansion of gas resulting from the heat liberated during chemical reactions. This expansion creates a motion that is likely to convect any disturbance of the flame more distant from its planar configuration. TDI, conversely, originate from the discrepancy in the diffusion rates, where heat moves away from the flame and mass moves toward the flame [176]. Numerous analytical perturbative investigations have delved into intrinsic flame instabilities, employing diverse degrees of simplifying assumptions.

Notably, studies on TDI effects have been conducted with a constant density assumption, and investigations into the combined influences of both TDI and HDI have been undertaken with the assumption that thermal expansion is finite. However, a comprehensive characterization of small wavelength stabilization for $Le < Le_0$ remains absent within this overarching framework. For further elucidation on intrinsic instability, refer to references [62] and [177].

Hydrogen flames manifest distinctive behaviors in the context of intrinsic flame instabilities when contrasted with HC fuels such as CH_4 . Figure 3 [61] provides a comparative analysis of flame propagation characteristics between CH_4 and hydrogen under varied conditions. Notably, intrinsic instabilities are discernible in both lean and stoichiometric flames of hydrogen, whereas the CH_4 flame exhibits a consistently smooth surface. Hydrogen lean flame manifests notable disturbances attributed to robust TDI, while the stoichiometric flame retains an approximately spherical configuration, marked by a comparatively diminished impact of HDI on the flame surface and consumption rates. Figure 10 illustrates the evolution of spherically expanding H_2 /air and C_3H_8 /air flames across both rich and lean mixtures under varying pressures, as per the experimental investigations conducted by Law [178]. The experiments were conducted within a meticulously designed spherical bomb, ensuring the maintenance of near-constant pressure conditions. At a pressure = 5 atm, both the rich C_3H_8 /air flame and the lean H_2 /air flame exhibit diffusive instability due to an effective Le below unity in the two instances. This instability becomes apparent shortly after ignition, particularly when the flame dimensions are sufficiently diminutive and commensurate with the flame thickness. In contrast, lean C_3H_8 /air and rich H_2 /air flames, at $p = 5$ atm, exhibit prolonged stability post-ignition

owing to a sufficiently large effective Le , indicating diffusive stability. However, at an elevated pressure of 20 atmospheres, both the lean C_3H_8 /air flame and the rich H_2 /air flame develop wrinkling early in the propagation process. This occurrence is attributed to the considerable reduction in flame thickness under high pressure, diminishing the stabilizing effects of diffusion and thereby precipitating HDI-induced wrinkling.

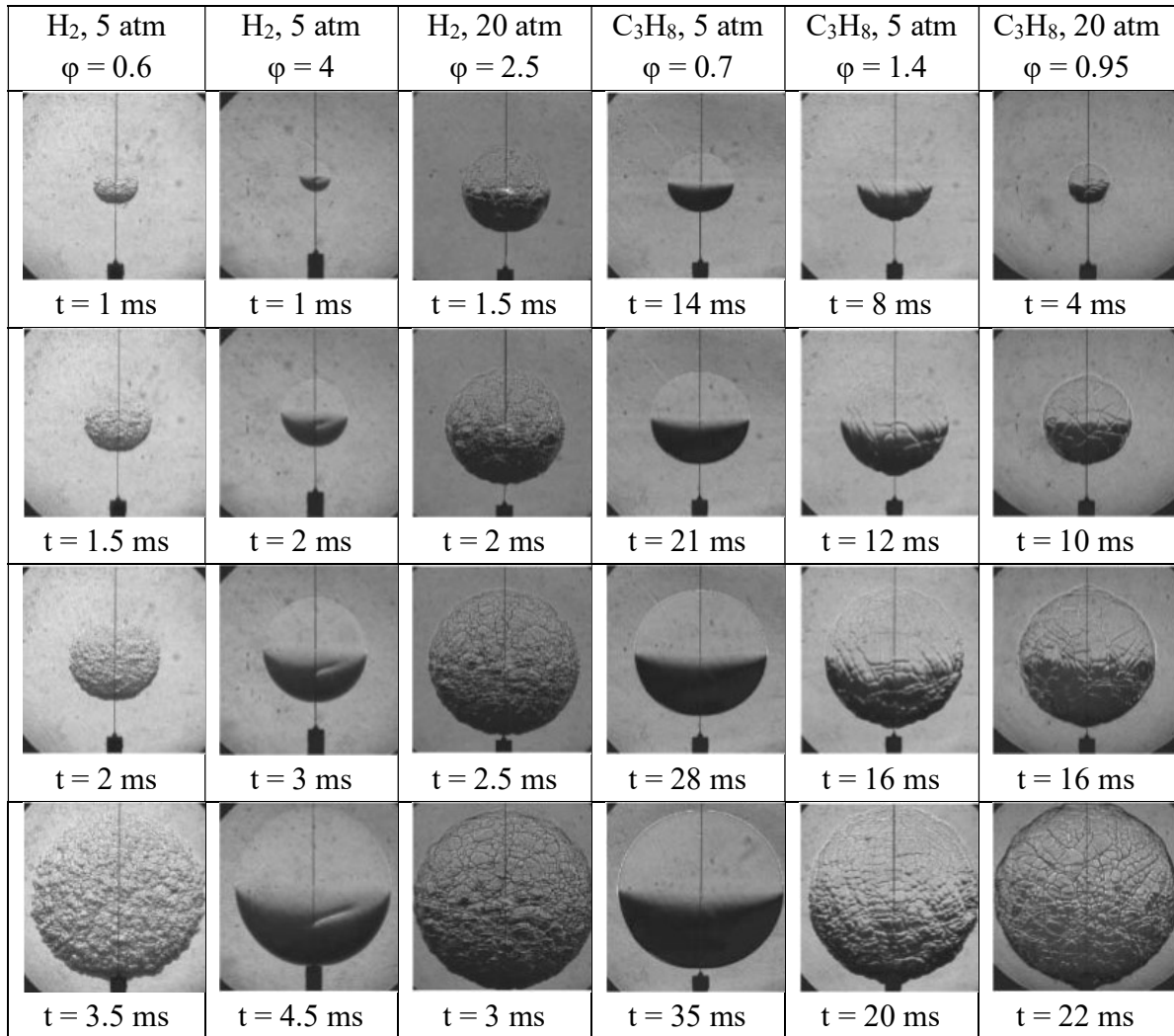


Figure 10: Images of the spherical expansion of C_3H_8 /air and H_2 /air flames across different equivalence ratios and pressures. [178]

Many investigations were conducted on HE-mixtures to assess the influence of pressure, initial temperature, equivalence ratio, and HF in the flame. Li et al. [179] systematically

examined the acceleration properties of CH₄/H₂/air flames under conditions of TDI and HDI, specifically at an elevated pressure of 250 kPa. The study involved varying the equivalence ratio and CH₄ addition. The findings, as illustrated in Figure 11, elucidate that an augmentation in CH₄ addition serves to stabilize the H₂/CH₄/Air flame at $\Phi = 1.0$ and $\Phi = 0.8$, thereby alleviating the destabilization effects of both instabilities. In contrast, for $\Phi = 1.4$, the stabilizing impact of TDI and the destabilizing influence of HDI diminish with increasing CH₄ enrichment, leading to a discernible change in flame front from a cellular to a smooth shape. Analogous observations were substantiated by Reyes et al. [180]. Additionally, AL-Khafaji et al. [181] conducted an exploration into the influences of initial pressure on H₂/CH₄/Air flames characterized by a 50% hydrogen fraction, as depicted in Figure 12. In their investigation of CO/H₂ mixtures, Li et al. [182] performed an exhaustive examination of the pressure, HF, and equivalence ratio influence on intrinsic flame instabilities. indicate that cellular irregularities in H₂/CO/air premixed flames become more pronounced due to the reduced impact of curvature and the heightened strength of baroclinic torque on the flame at higher initial pressure. Simultaneously, an increase in equivalence ratio mitigates cellular irregularities for hydrogen fractions of 50% and 70%. Conversely, for a hydrogen fraction of 30%, cellular irregularities intensify due to the influence of TDI. Moreover, an upsurge in hydrogen fraction correlates with an amplification in cellular irregularities. These same patterns are observed in hydrogen/ethanol mixtures [183].

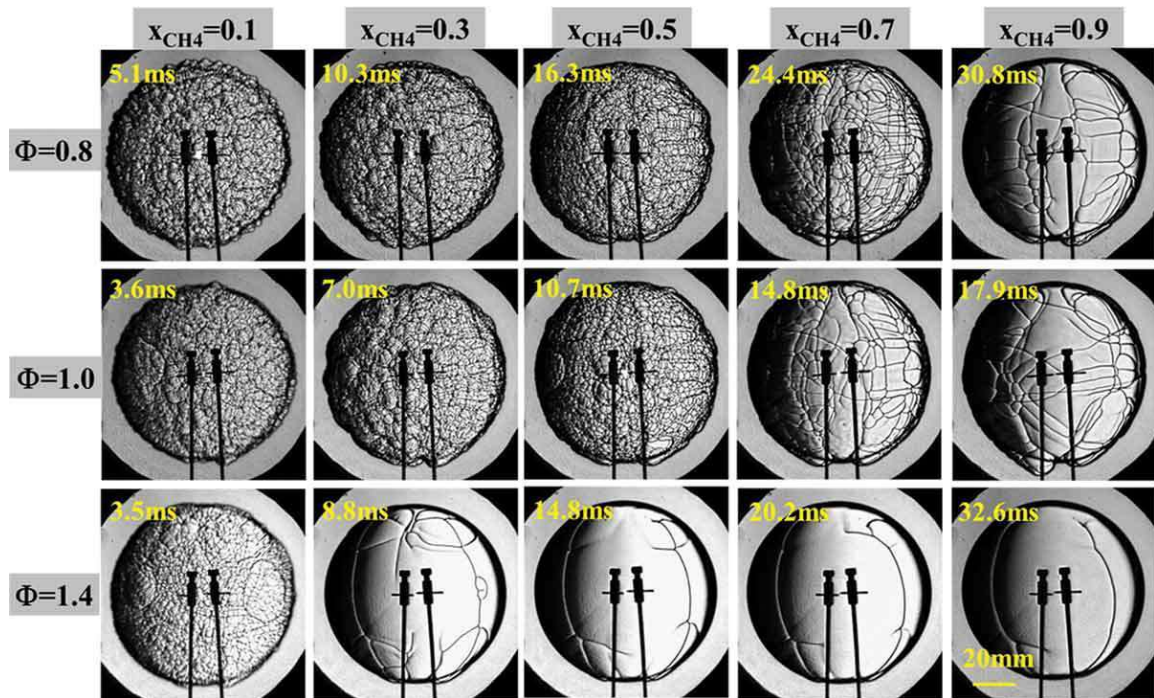


Figure 11: Images of the spherical expansion of CH₄/H₂ flames across different equivalence ratios and CH₄ fractions. [179]

	R= 15mm	R= 30mm	R= 45mm
0.1 MPa			
0.5 MPa			

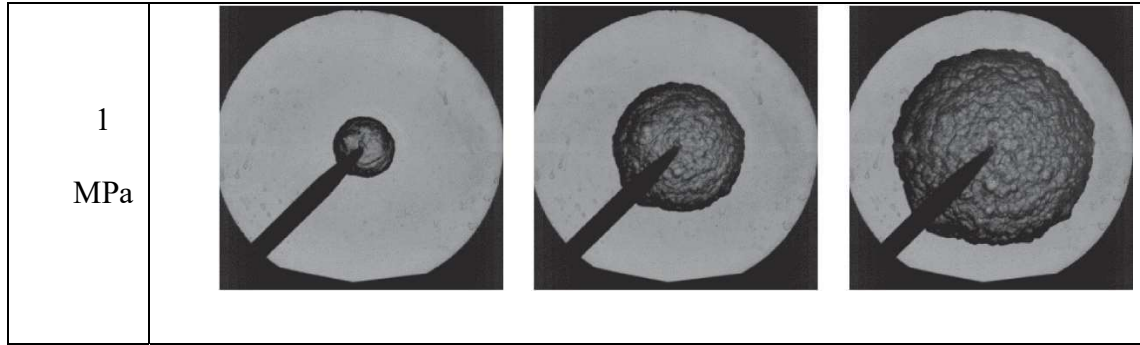


Figure 12: Images of the spherical expansion of CH₄/H₂/air flames across different pressures, $\phi = 0.9$, $T = 360\text{K}$ and 50 % hydrogen fraction. [181]

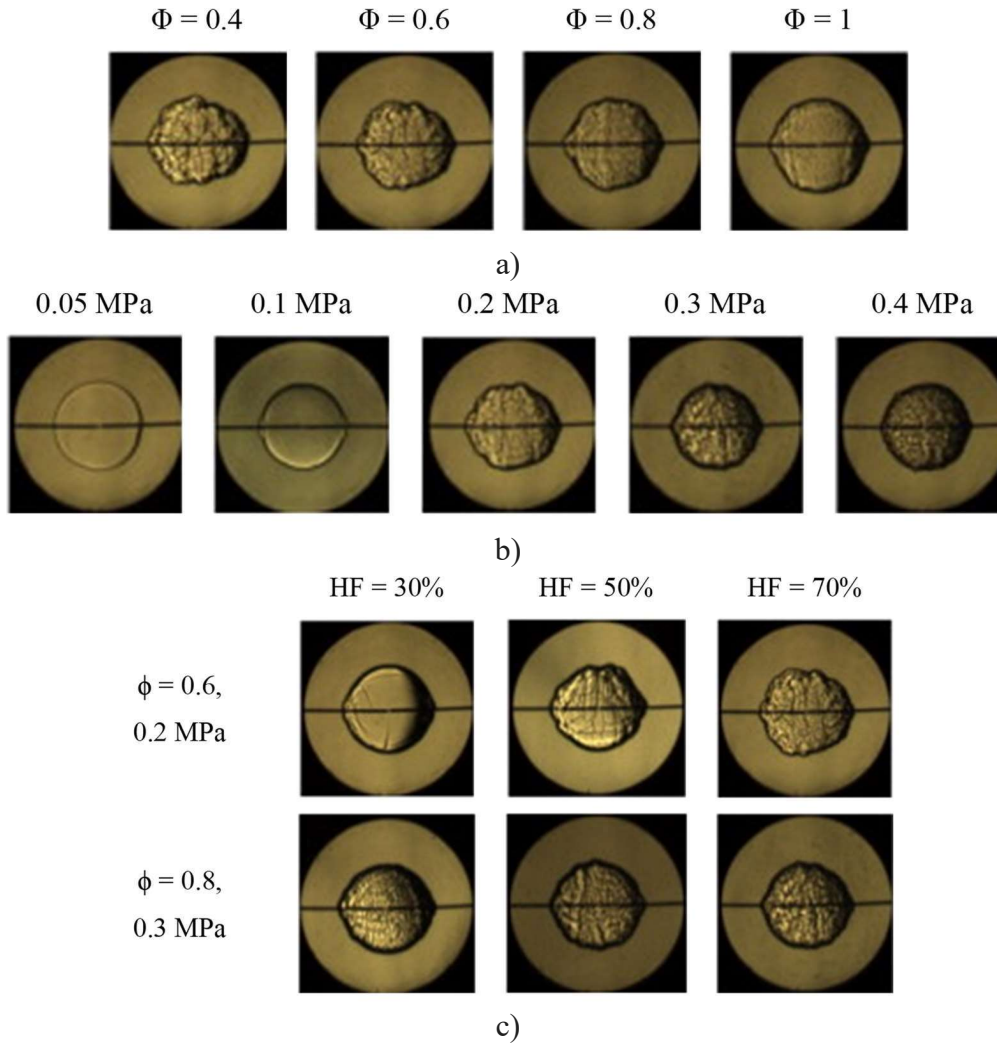


Figure 13: Images of the spherical expansion of CO/H₂ flames showing the effect of a) equivalence ratio (hydrogen fraction = 70%, $p = 0.2\text{ MPa}$), b) initial pressure (hydrogen fraction = 70%, $\phi = 0.8$) and c) hydrogen fractions. [182]

Numerous investigations have explored intrinsic combustion instabilities in premixed flames. Nevertheless, these instabilities, particularly their interaction with turbulence, remain inadequately comprehended, posing challenges in terms of predictability and control. The examination of intrinsic instabilities in non-premixed combustion remains notably limited compared to the extensive scrutiny applied to premixed flames. This discrepancy arises from challenges associated with discovering such perturbations in a simple setup suitable for analytical treatment and allowing direct comparisons with experimental data. This research gap underscores the need for further exploration and dedicated methodologies in the study of intrinsic instabilities in non-premixed combustion systems.

2.2.3.2 Dynamic (Thermos-acoustics) instabilities

Dynamic (thermoacoustic) instabilities are unwanted oscillations of the combustor's natural forms of acoustics which result from the combination of unstable heat release with oscillatory flow [184]–[186]. These oscillations can have high amplitudes, posing risks such as increased noise, mechanical vibrations, heightened rates of heat transfer, flame blow-off, flashback, and potential structural damage [144], [185], [187], [188]. The feedback mechanism governing self-sustaining combustion instabilities is depicted in Figure 14 [189]. A driving mechanism in this process causes disturbances in the flow/mixture, which causes fluctuations in heat release, which causes changes in acoustic pressure and velocity. These fluctuations then create more perturbations in the flow/mixture, closing the loop of feedback. In Acoustic oscillations arise as individual frequencies in enclosed flames at one of the combustor's natural acoustic regimes [186], [190]. Due to the resonance of the combustors and the efficiency of unsteady combustion

as a source for acoustic energy, acoustic waves emitted by variable heat release are reflected off the combustor surfaces, affecting the flow unsteadiness near the flame [191], [192]. Additional information on the conditions and driving factors underlying dynamic instabilities can be found in references [193] and [33].

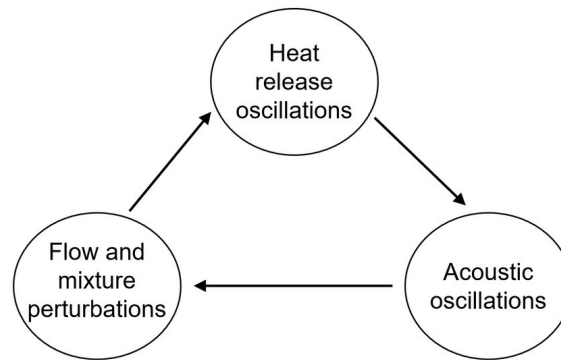


Figure 14: Feedback Mechanism of Combustion Dynamics [189]

Various studies have explored the effects of hydrogen enrichment on combustor dynamic stability. Janus et al. [28] added 25% hydrogen to NG in a premixed combustor, observing a shift in the unstable region towards lower air flow rates and equivalence ratios. Figura et al. [29] found similar shifts with up to 25% hydrogen in a variable-length combustor. Stability maps presented in Figure 15 illustrate this shift, showing the strongest instabilities at $\phi = 0.7$ for NG and at $\phi = 0.6$ for the 25% hydrogen blend with a lower amplitude. Furthermore, the second unstable region at $\phi = 0.65$ for NG was shifted to $\phi = 0.55$ with a significantly diminished amplitude when 25% hydrogen was added. Taamallah et al. [21], [194] studied the effects of hydrogen addition (0%, 10%, and 20% by volume) on the combustion instabilities of CH₄ flames at atmospheric pressure, with a constant Re and varying equivalence ratio. Figure 16 shows their results, which indicate that HE-flames became unstable at lower equivalence ratios than pure CH₄ flames. The instability region shifted to lower equivalence ratios as hydrogen concentration increased, consistent with

other studies [30], [31], [195]. Karlis et al. [32] and Zhang and Ratner [31], [196] also experimented with CH₄-hydrogen blends (up to 40% by volume) and found that hydrogen addition increased the instability tendency of the flames, passing through stable, intermittent, and limit cycle regimes. They identified extinction strain rate thresholds and equivalence ratio effects on the instability behavior.

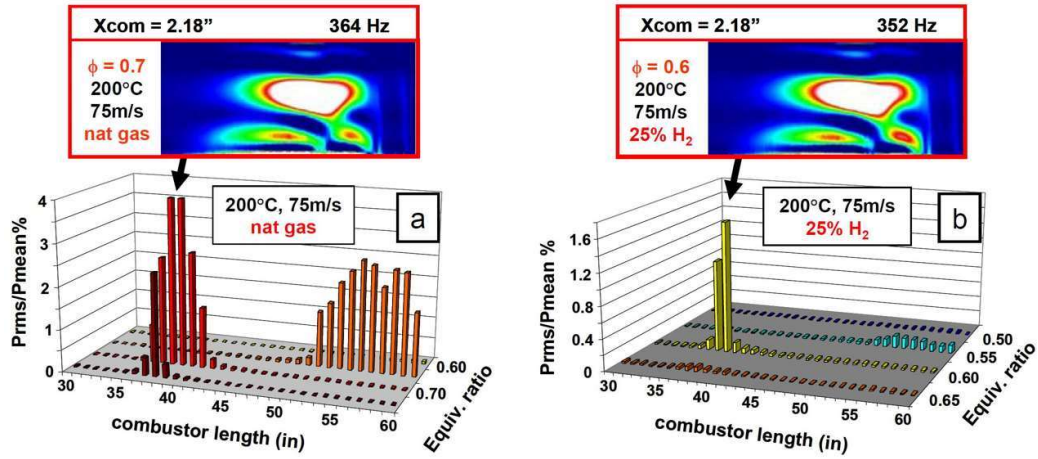


Figure 15: Stability charts and accompanying CH* chemiluminescence flame visuals for (a) pure natural gas and (b) a blend of natural gas with 25% hydrogen by volume, $T_{in} = 200$ °C and $V = 75$ m/s. [29]

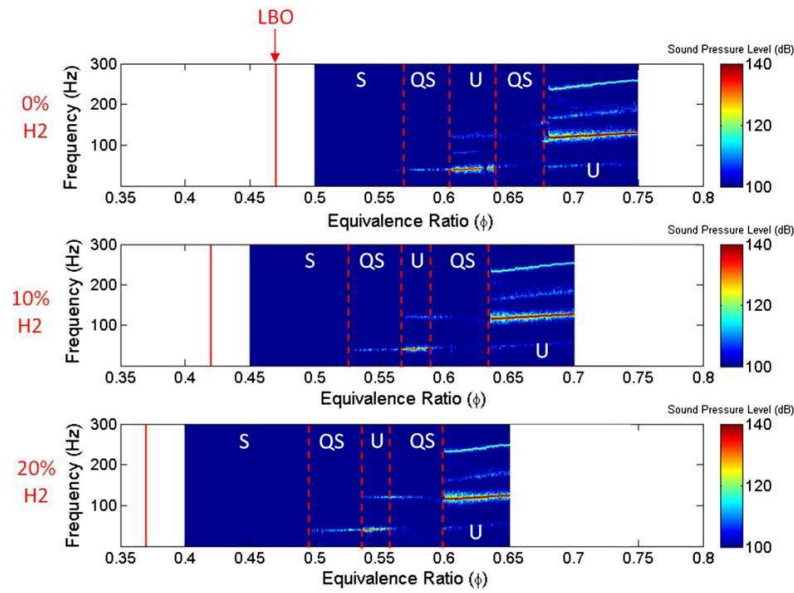


Figure 16: Dynamic stability maps depicting combustion behavior for CH₄-hydrogen fuel blends, with markers indicating stability conditions: (S) stable, (U) unstable, and (QS) quasi-stable combustion. The solid red line represents the lean blowout (LBO) limit, while quasi-stability is characterized by pressure fluctuations with relatively low amplitude, as per the authors' definition. [21]

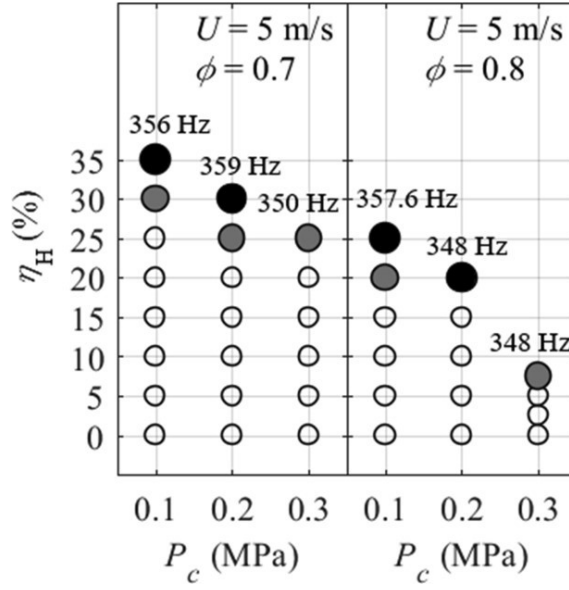


Figure 17: Dynamic instability maps illustrating the relationship between hydrogen concentration and combustor pressure. [31]

Runyon et al. [197] compared the combustion instabilities of pure CH_4 and HE- CH_4 flames at different pressures (1.1 bar to 3.3 bar) and an equivalence ratio of 0.55. They kept the non-dimensional mass flow constant to isolate the effects of turbulence and thermochemistry. They found that both flames oscillated at the combustor's resonant frequency, with higher pressure and higher HRRs increasing the oscillation amplitudes. The HE-flame had lower amplitudes and a thinner and more stable reaction zone than the pure CH_4 flame. Zhang and Ratner [31] also studied the instabilities in thermoacoustics of H_2/CH_4 flames at different pressures (atmospheric, 2 bar, and 3 bar) and hydrogen concentrations (up to 40% by volume) with varying equivalence ratios and Res. They used OH, PLIF images to show that hydrogen addition and pressure increase enhanced the flame front wrinkling. Figure 17 shows how pressure affected the dynamic stability of HE-mixtures at equivalence ratios of 0.7 and 0.8, with a fixed inlet velocity of 5 m/s. They observed that higher pressure and higher equivalence ratio lowered the hydrogen concentration needed to induce combustion instabilities, due to the higher turbulent

burning velocity. Emadi et al. [198] also reported that higher pressure increased the flame front wrinkling in CH₄-hydrogen blends compared to pure CH₄.

According to literature, a notable connection exists between periodic flashback events and thermoacoustic instabilities in CH₄-hydrogen fuel mixtures. Tuncer et al. [156] conducted experiments on fully premixed burners operating under atmospheric pressure conditions, using CH₄-hydrogen blends with up to 50% hydrogen content. The inclusion of hydrogen led to an increase in root mean square (RMS) pressure amplitudes and a noticeable shift in the dominant frequency towards lower values, particularly in the range of 20% to 25% hydrogen concentration. This frequency shift corresponded to the occurrence of flashback, as depicted in Figure 18. The spectra analysis of pressure, heat release, and flashback revealed no flashback in the case of pure CH₄, while a 40 Hz flashback signal was observed in the 50% hydrogen flame. At higher hydrogen concentrations, the periodic flashback signal synchronized with pressure and heat release oscillations, which took place at the frequency of pressure oscillations. The interpretation of these findings suggests that the flame oscillates within the premixer, generating heat release oscillations at the flashback frequency, and subsequently coupling with one of the combustor's acoustic modes. Furthermore, García-Armingol and Ballester [199] investigated a volumetric blend consisting of 50% CH₄ and 50% hydrogen. Their research demonstrated a coupling between flashback and combustor acoustics, with significantly higher RMS pressure fluctuations observed in the 50% hydrogen blend compared to pure CH₄. Phase-resolved OH* chemiluminescence images during instability cycles confirmed the correlation between combustion instabilities and oscillating flashback events. These studies not only highlight the increased risk of flashback caused by thermoacoustic instabilities when

hydrogen is added to NG but also underscore the potential coupling between periodic flashback events and combustion instabilities.

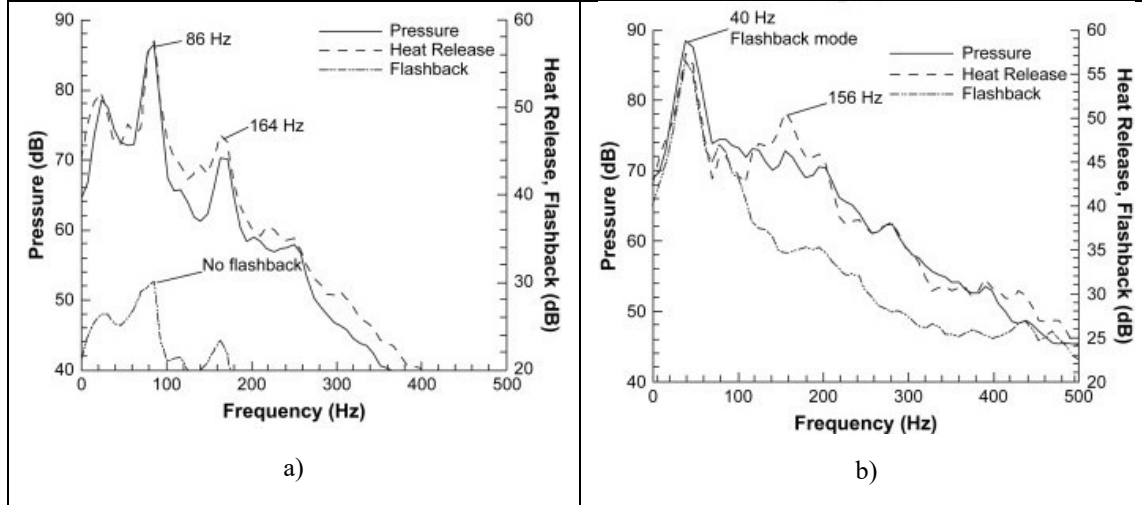


Figure 18: Flashback triggered by combustion instabilities resulting from hydrogen enrichment: Analysis of pressure, heat release, and flashback spectra at a fuel-air equivalence ratio of 0.7, a) pure CH₄ and b) 50% hydrogen enriched CH₄. [156]

Previous studies show that hydrogen addition changes the dynamic instability regions of the combustor, moving them to lower equivalence ratios. This is related to the higher turbulent flame speed of hydrogen, which affects the flame position and the thermoacoustic behavior of the combustor. As a result, a combustor that was stable before may become unstable, or vice versa, depending on the equivalence ratio. Moreover, hydrogen addition can cause transitions from stable to unstable combustion, with intermittent regimes of random high-amplitude oscillations and stable states. Furthermore, hydrogen addition can excite different natural frequencies of the combustor, including higher frequency instabilities.

2.3 Recommended Implementation of Hydrogen Enrichment for Improved Performance and Emission Control

2.3.1 Hydrogen Pilot for Mitigating Flashback Risk

The addition of hydrogen to the primary fuel mixture, as discussed in section 2.2.2, has been found to increase flashback propensity. However, studies have explored effective strategies to mitigate flashback in hydrogen fuel flames. Notably, hydrogen injection downstream of the combustor has been examined as a viable approach.

Paschereit and his group [200]–[203] studied the effect of adding an axial injection to a swirler hydrogen combustor to increase its flashback resistance. An axial non-swirling jet of fuel on the central axis of the swirler affects the vortex breakdown position and shifting it downstream which increases the flashback resistance. Increasing the amount of axial jet and reducing the swirl angle enhances the flashback resistance, however the second one increases the NO_x emissions while the first doesn't. Due to the low volumetric heating value of hydrogen (3.5 lower comparing with NG), higher volumetric flow rate of hydrogen is required for same power. This leads to a higher fuel momentum at the central axis. So, increasing the equivalence ratio will increase the fuel momentum more, shifting the flame front downstream and increasing the flashback resistance. Brunetti et al. [204] also studied the axial injection of hydrogen fuel from movable lances downstream of a swirling combustor to mitigate flashback propensity in atmospheric pressure. Sattelmayer and his group [169]–[171] studied the effect of axial and edge undiluted hydrogen injection on the flashback limits in swirl combustor. Both injection methods improve the flashback limits. However axial injection leads to high emissions, it gives a better improvement in flashback limits than edge injection. Axial injection leads to shifting the recirculation stabilization

zone for swirl burner downstream which gives a noticeable increase in CIVB resistance and makes the BLF dominate. BLF can be reduced by boundary layer dilution. Lean direct injection (LDI) is another approach to reduce flashback propensity in hydrogen combustion [205]–[207]. LDI idea is to inject fuel through a number of small holes (hundreds or thousands) into the combustion zone in presence of excess air to get a rapid mixing [208]. Many studies [209]–[212] tried to achieve LDI approach by developing and testing micromixer burners for low emissions and safe combustion with hydrogen fuel. The studied configurations include coflow mixing [210], jet in crossflow and swirl-based mixing in small cups with radial and axial inflow [211]. Micromixer combustor with about 1600 miniature injectors, as shown in Figure 19, was tested with a small auxiliary power unit APUGTCP36-300 and worked successfully [212].

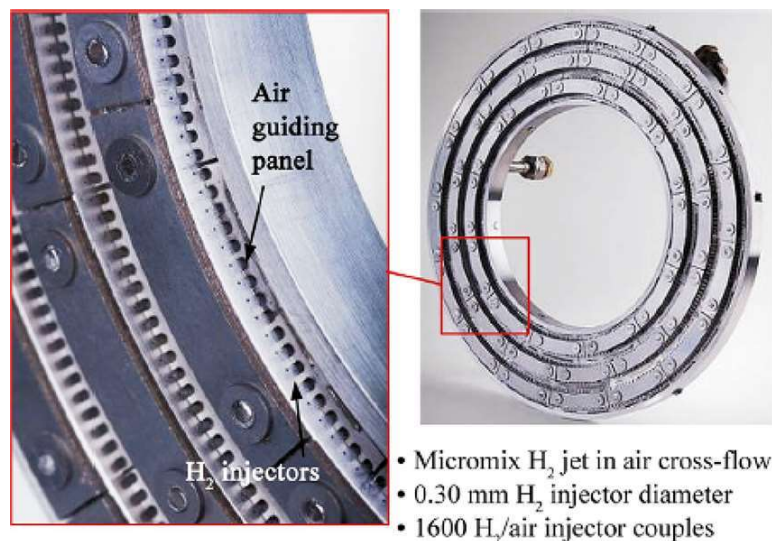


Figure 19: Micromixer combustor with about 1600 miniature injectors [212]

2.3.2 Hydrogen Pilot for Mitigating Dynamic Instabilities

Addressing dynamic instabilities in combustion involves regulating the underlying mechanisms through techniques aimed at disentangling phase coupling among heat release, pressure, and velocity perturbations. These control methods fall into two categories: active

and passive. Active methods in mitigating thermoacoustics in a combustor involve the real-time control and manipulation of combustion parameters to actively suppress or modify the dynamic instabilities that lead to thermoacoustic oscillations. These methods typically employ feedback systems and actuators to continuously monitor combustion conditions and adjust relevant parameters [191]. Passive control strategies seek to mitigate the susceptibility of combustion to acoustic instability by modifying combustor design or dissipating acoustic energy using dampers or perforated plates [213]. Despite their applicability, passive controls are considered less preferable for several reasons. Firstly, they exhibit constraints in their operational range under varying conditions. Secondly, their effectiveness diminishes notably at lower acoustic levels. Furthermore, the implementation of changes to the system design through passive controls is characterized by a time-consuming and costly process. These limitations underscore the preference for active control strategies, characterized by real-time monitoring and adjustable feedback mechanisms, offering greater adaptability and responsiveness in addressing the multifaceted and dynamic challenges posed by thermoacoustics in combustion systems.

Pilot fuel injection represents a prevalent technique within the domain of active control for mitigating thermoacoustic instabilities in combustors. The underlying principle involves the introduction of pure fuel into the flame, thereby generating a heterogeneous mixture. This deliberate heterogeneity serves to disentangle the interdependencies among heat release, pressure, and velocity perturbations [129], [214], [215]. Extensive investigations have been conducted to scrutinize the impact of stratified combustion on dynamic stabilities [216]–[222]. Albrecht et al. [219] have reported significant suppression of combustion instabilities through the utilization of pilot flames, emphasizing that the

introduction of a premixed pilot flame not only mitigates instabilities but also results in reduced NO_x emissions. Furthermore, Tachibana et al. [220] delved into the effects of pilot fuel injector parameters, including angle, position, and quantity, on the attenuation of pressure oscillations in CH₄ flames. Their findings indicate that an injector angle of 30 degrees at the combustor inlet is conducive to reducing pressure oscillations, and an increase in the percentage of secondary fuel from 2% to 10% correlates with a commensurate enhancement in pressure oscillation reduction.

The examination of hydrogen's efficacy as a pilot fuel in suppressing instabilities has been subject to scrutiny in several studies [222]–[225]. Barbosa et al. [222] conducted an investigation into the impact of swirler hydrogen injection in mitigating thermoacoustic instabilities within a lean propane/air flame. Their findings revealed that the swirler injection of hydrogen successfully attenuated pressure oscillation amplitudes by a factor of 2. In a comparative study, Schuller et al. [223] assessed the effects of hydrogen enrichment in both fully premixed and pilot injection modes within a CH₄/air mixture. Their results demonstrated that the two modes exhibited opposing influences, with pilot hydrogen injection inducing an overlap between heat release fluctuations at the flame base and downstream, consequently reducing global fluctuations in the flame and mitigating thermoacoustic instabilities. Moreover, Oztarlik et al. [224] corroborated these findings and additionally asserted that hydrogen pilot injection could more effectively diminish thermoacoustic instabilities compared to CH₄ pilot injection.

2.3.3 Small Hydrogen Fractions for Lower NO_x Emissions

The introduction of hydrogen into fuel blends presents a range of challenges, primarily centered on its effects on flame temperature and consequent alterations in NO_x emissions,

as discussed in Section 2.2.1. Effectively managing hydrogen content within defined limits emerges as a crucial consideration, offering a strategic tool to either maintain or potentially reduce NO_x emissions compared to combustion scenarios involving alternative fuels. A thorough examination of the literature reveals numerous investigations systematically exploring the intricate relationship between hydrogen percentage and NO_x emissions, yielding valuable insights into this complex interplay. For example, Schefer et al. [30] conducted a study on premixed lean mixtures in a swirler combustor, gradually introducing hydrogen up to 45% of the fuel mixture. In this experimental context, the results intriguingly indicated that adding hydrogen had no discernible impact on NO_x emissions. Notably, this was accompanied by a noticeable reduction in CO emissions, suggesting a potential avenue for mitigating emissions. Moreover, Kim et al. [27] elucidated the nuanced influence of swirl angle and hydrogen addition (up to 9%) on a lean premixed swirl flame. Their exploration revealed a nuanced scenario where introducing hydrogen at low swirl angles diminished recirculation effects, promoting increased combustibility, accelerated flow speed, and reduced residence time of hot gases. This, in turn, contributed to a reduction in NO emissions. However, a counterintuitive trend emerged, indicating an increase in NO emissions at larger swirl angles with escalating hydrogen fractions. Further insights were gleaned from the comprehensive investigation by Coppens et al. [121], who explored the impact of hydrogen addition (up to 35%) in CH₄/air premixed mixtures. Their findings nuanced the narrative by revealing that NO_x emissions exhibited a negligible change on the lean side within the explored hydrogen addition range. However, a discernible decrease in NO_x emissions was recorded on the rich side, attributable to the diminished presence of radicals in rich combustion conditions. Zhu et al. [133] expanded

the horizon of inquiry to ammonia fuel mixtures, shedding light on the possibility of achieving low NO_x emissions at high equivalence ratios, provided the hydrogen fractions remained below 10%. In a related vein, Wicksall and Agrawal [120] conducted a meticulous investigation into the impact of hydrogen addition (up to 40%) to CH₄ and propane fuels under swirl premixed conditions. Their findings, as depicted in Figure 20, indicate that the introduction of hydrogen does not exert a discernible impact on nitrogen oxide (NO_x) emissions. Instead, it is discerned that the AFT emerges as the predominant determinant. The presented results suggest the feasibility of maintaining NO_x emissions at notably low levels, and in certain instances, achieving a reduction, with the incorporation of a minor proportion of hydrogen into the combustion process.

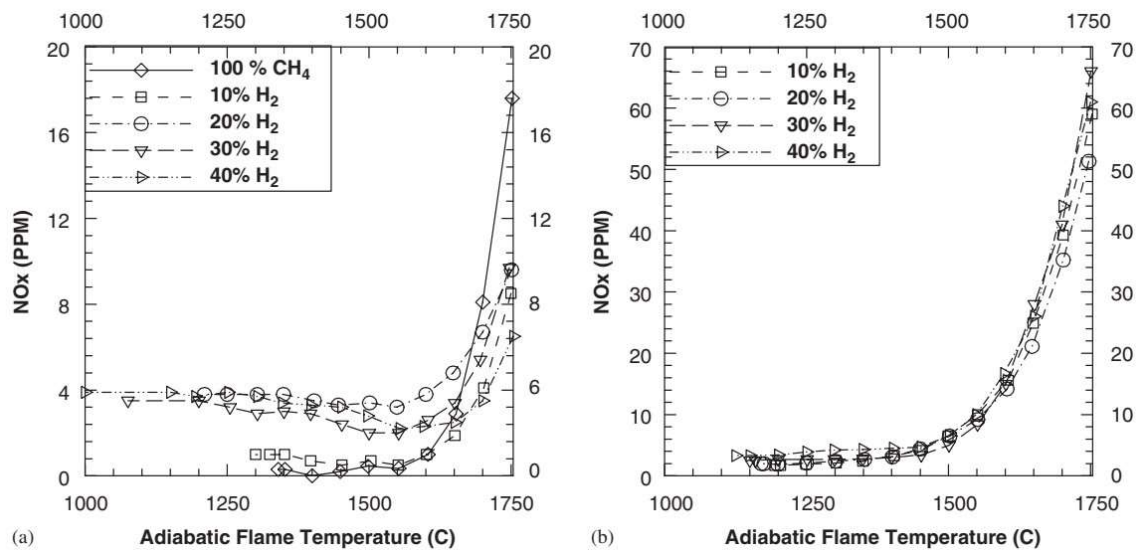


Figure 20: NO_x emissions versus adiabatic flame temperature (AFT) (a) CH₄/H₂ and (b) C₃H₈/H₂ mixtures. [120]

2.3.4 Lean Combustion for Mitigating NO_x Emissions

The intricate relationship between the formation of nitrogen oxides (NO_x) and flame temperature is a central theme, as extensively discussed in Section 11. The deliberate reduction of flame temperature stands out as a particularly effective method for addressing

NO_x emissions, with lean premixed combustion [129], [137], [226] emerging as a key approach in this regard. This comprehensive discussion explores various studies that have delved into the complex dynamics of NO_x emissions and the modulation of flame temperature, specifically in the context of introducing hydrogen under lean combustion conditions. Guo et al. [119] delved into the impact of hydrogen addition to a lean premixed CH₄ mixture. Despite noting an increase in NO emissions at a consistent equivalence ratio, they intriguingly suggested that ultra-lean combustion conditions could offer both stable combustion and a substantial reduction in NO and CO₂ emissions. Meziane and Bentebbiche's research [130] adds further depth to our understanding, revealing that the exit temperature of the combustor increases with hydrogen addition at a constant mass flow rate. Conversely, at a constant velocity, the exit temperature becomes more uniform, accompanied by a reduction in both NO and CO emissions as hydrogen addition is increased. Nonetheless, it is crucial to note that reducing the average temperature of the exit combustor may have implications for its output power. The study demonstrated that even with a modest 10% addition of hydrogen, a reduction in both NO and CO emissions by 14% and 60%, respectively, can be achieved. Jin and Kim's investigation [134] into hydrogen addition to CH₄/C₃H₈ fuels under lean premixed combustion conditions provides another layer to the discussion. Their findings, encapsulated in Figure 21, suggest that hydrogen addition does not significantly impact NO emissions under lean conditions. Sun et al. findings [140] broaden our understanding by showcasing that reducing the equivalence ratio from 1.2 to 0.6 can significantly decrease NO emissions for CH₄ combustion. Shifting the focus to NH₃/H₂ fuel combustion, Roberts and colleagues [133], [135] emphasize that NO emissions can be maintained at remarkably low levels under

extremely lean combustion conditions. This consistency is noteworthy, especially considering their experiments spanned a range of pressures (1 to 5 bar), affirming the robustness of the observed NO_x reduction effects. Figure 22 further illustrates the nuanced impact of equivalence ratio on NO emissions for NH₃/H₂/N₂ fuel combustion (HF = 45%) [136], portraying a peak at $\phi = 0.8$ and a subsequent decrease in leaner directions due to temperature moderation and in richer directions due to oxygen deficiency. Furthermore, insights from other studies [122], [227] highlight the efficacy of dilution by CO₂ or N₂ in decreasing flame temperature and NO_x emissions across various equivalence ratios. This diverse body of research collectively underscores the multifaceted nature of leaner combustion as an effective strategy not only for reducing flame temperature but also for mitigating NO_x emissions in diverse combustion scenarios.

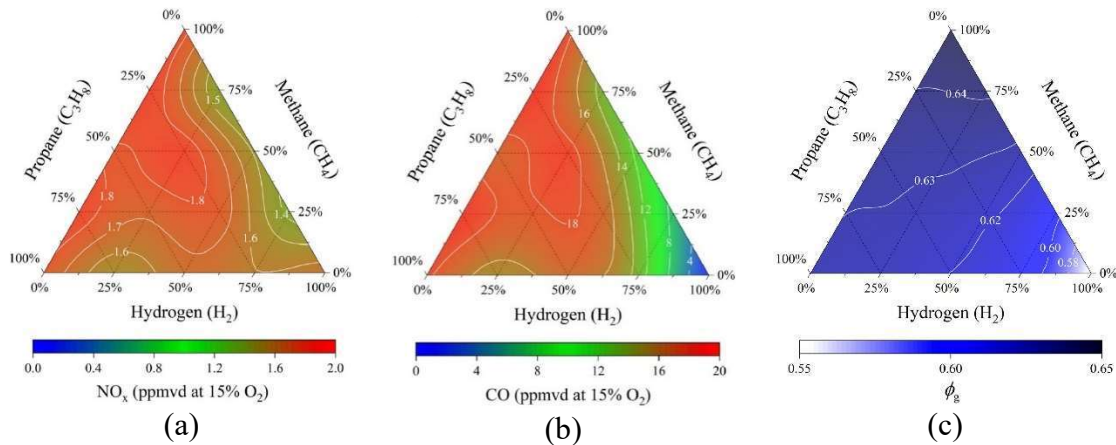


Figure 21: Iso-contours emissions for CH₄/C₃H₈/H₂ flames, a) NO_x, b) CO and c) equivalence ratio. [134]

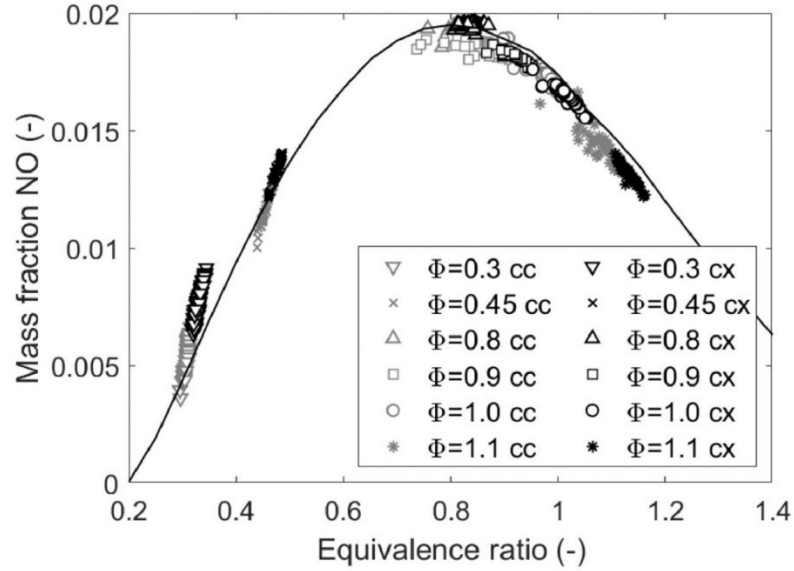


Figure 22: NO mass fraction versus equivalence ratio for $\text{NH}_3/\text{H}_2/\text{N}_2$ flame. [136]

2.3.5 Hydrogen Pilot for Enhancing LBO limit.

To achieve the stabilization of turbulent flames, a commonly employed method is the utilization of a pilot flame. This involves splitting the main fuel entering the combustor into main and pilot nozzles, thereby increasing the equivalence ratio in the stabilization region. This approach aims to establish a locally stabilized flame with elevated heat and radical concentrations, facilitating the anchoring of the flame and enabling blowout to occur at leaner equivalence ratios [219], [228], [229]. Numerous studies [214], [228]–[242] have delved into the investigation of the pilot flame's impact on enhancing the LBO limit. Kibrya and Karim [232] investigated extending the LBO limit of a CH_4 jet diffusion flame by introducing smaller pilot jet flames (CH_4 , hydrogen, and propane) in a co-flowing air stream. Results showed that addition of side jet diffusion flames significantly extends the central jet flame's LBO limit, surpassing the auxiliary fuel expenditure by about an order of magnitude. This improvement is consistent across all three auxiliary fuels when considering their thermal contributions. The effect of non-premixed pilot flame interaction on the enhancement of blowout velocity is experimentally investigated in another

study[243]. It analyzes how flame interaction changes with different factors, such as fuel flow rate, nozzle separation distance, number of nozzles, and array shape (diamond, cross, matrix, and circle shapes). The findings reveal that multiple small-diameter jets have higher blowout velocities than a single large-diameter jet with the same area. Furthermore, the flames in matrix and circle shapes can keep burning even without a center nozzle in choking conditions, because of the recirculation inside the fuel jet arrays. Pignatelli et al. [234] investigated the impact of pilot flame operation on the combustion of pure CH₄ and CH₄ enriched with hydrogen fuels in a burner model used for GT under atmospheric conditions. Two pilot burner configurations, non-premixed and partially premixed, were examined. Their findings showed that pilot flames improve the lean blow-off limit for all Res and fuel blends, with no significant dependence on the type or amount of pilot flame. Emara et al. [238] investigated various injection techniques (fuel-only, premixed air and fuel, and air-only) and their impact on combustion stability at different total equivalence ratios. They found that, under constant total equivalence ratios, injecting air exclusively through the pilot lance outperformed the alternatives involving pilot fuel and premixed air and fuel. Successful combustion stabilization and reduced NO_x emissions were achieved by redirecting less than 10% of the primary airflow through the pilot. Optimal results were consistently observed when sitting the pilot lance at the apex of the burner cone. However, all axial positions of pilot injections contribute to stabilizing the combustor. In their study, Muruganandam et al. [231] conducted a comparison between two pilot injector nozzles, specifically an atomizing nozzle and a pressure jet nozzle. The findings indicated that both nozzles contributed to a reduction in the Lean Blowout (LBO) limit, with the pressure nozzle proving more effective in stabilizing the combustor. This particular pilot nozzle

demonstrated a 6% decrease in the blowout equivalence ratio at a 15% pilot fraction. In a related investigation, Liu et al. [244] highlighted the effectiveness of matching the pilot spray with swirling air streams as a method to enhance stable combustion capability in fuel-staged multi-injection combustors. Additionally, another study [236] emphasized the efficacy of a pulsed flame injection in improving flame stability and reducing NO_x emissions, attributing these benefits to the lower flame temperature. Lazik et al. [245] reported on ignition and LBO testing of a lean burn injector system using a pilot pressure atomizer under atmospheric conditions. Their results revealed a trade-off between LBO air–fuel ratio (AFR) and ignition performance concerning swirl intensity. However, when substituting the pressure atomizer with a pilot air blast configuration, the outcomes demonstrated a promising potential for achieving high LBO with a reasonable ignition AFR. Zhao et al. [246] conducted an investigation into the impact of variations in fuel decreasing rates and pressure drops of the injector on Lean Blowout (LBO) performance within a multi-swirl staged combustor featuring an airblast injector. Their findings indicated a shifting of LBO limits toward leaner conditions with heightened injector pressure drops. As the rate of fuel reduction increases, there is a corresponding elevation in the exhaust temperature preceding flame extinction, concomitant with a reduction in the LBO Fuel-to-Air-Ratio (FAR). It is noteworthy that, across diverse fuel decreasing rates and pressure drops, flames exhibit akin dynamic characteristics in proximity to the LBO state. The impact of the venturi angle on the formation and propagation of the kernel flame during the ignition process has been demonstrated. Specifically, ignition performance is superior at a venturi angle of 60° compared to that at a venturi angle of 40° [247].

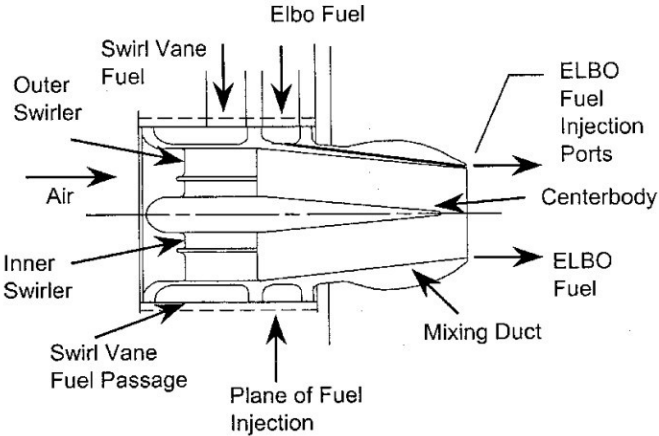
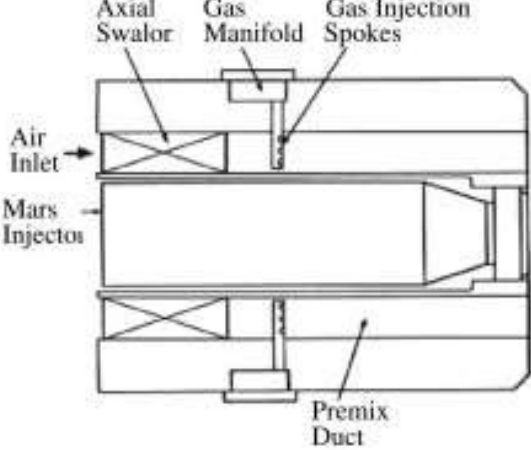
2.3.6 Lean Combustion for Improving Turbine Turn-Down Ratio

In the field of GT technology, it's crucial for turbines to operate steadily across a broad range of conditions. This isn't just a good feature to have—it's a fundamental necessity. This stability significantly boosts the overall dependability of GTs, which are essential in industries, power plants, and aircraft propulsion systems alike. Enhancing the turndown capability of GTs is often achieved through the incorporation of pilot fuel to stabilize the flame under extremely lean conditions [248]. Table 4 enumerates several burners employed in extant GT systems, wherein the inclusion of a pilot inlet constitutes a principal design feature. GE's DLN2.6 combustor, implemented in F-Class industrial GTs in 2015, represents a state-of-the-art technology known for its remarkable emission performance, achieving values in the single-digit range [248]–[250]. The fundamental combustion architecture involves a multi-can configuration comprising 18 identical transition pieces, combustor liners, and combustor head-ends. Recent enhancements include the integration of a novel center fuel nozzle and pre-mixer into the head-end assembly, equipped with controls designed to stabilize the premixed flame zone across a broad spectrum of conditions and fuel characteristics. This innovation has resulted in significant improvements in operability, emissions reduction, and load turndown capabilities for both the 9FA and 9FB combined-cycle platforms. Furthermore, the system ensures load turndown with emissions compliance, guaranteeing operation below 40% GT load under ISO conditions. The 4th Generation Dry Low Emission Burner designed and manufactured by Siemens Industrial Turbomachinery AB has undergone extensive testing under atmospheric conditions. In efforts to enhance operability and mitigate flame dynamics behavior, the burner incorporates multiple fuel and air circuits, including Rich-Pilot-Lean

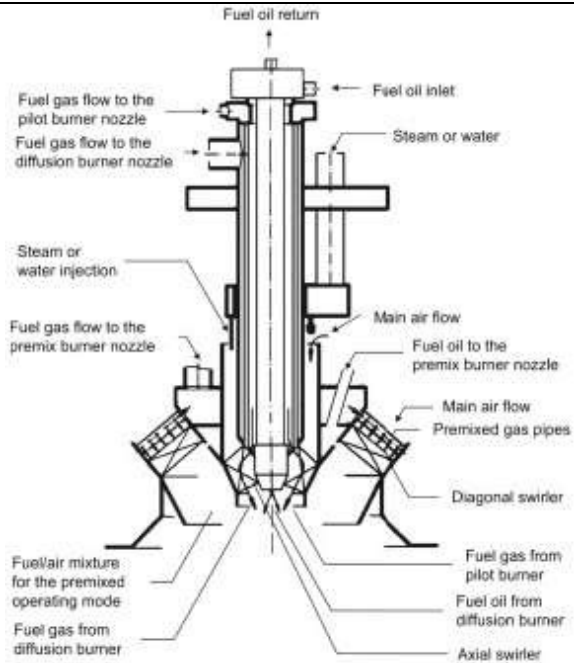
(RPL), Pilot, and Main. Fuel flexibility extends to 90% vol. H₂ with NG and over 50% vol. N₂ with stable operation in both cases [251]. Klingmann and Collin [252] conducted experimental studies on a downscaled prototype of this burner used for the SGT-750. The multi-stage configuration demonstrates lower emission capability and a wider window for stable operation through optimal fuel staging. Stabilization of the RPL and main flame is facilitated by the recirculation of combustion products and the vortex breakdown process. The interaction between the RPL and Pilot stages significantly influences flame shape, heat release location, and emissions. Additionally, an increase in Pilot fuel split leads to decreased CO emissions, providing advantages for expanding the Lean Blowout (LBO) margin. A low swirl injector (LSI) burner is another concept that had been used for Solar's Taurus 70 (T70) GT, boasting a power capacity of 7.5 MW [253]. Rigorous testing of this burner has been conducted under both high-pressure and atmospheric conditions. The outcomes of these experiments revealed a noteworthy reduction in the Lean Blowout (LBO) flame temperature with a substantial increase in pilot fuel flow, particularly at elevated levels of 30% and 50%. This observed improvement in stability holds promising implications for refining the control strategy of the T70, especially during critical operational phases such as light-off and transient conditions, where transient emissions peaks may be permissible. In the evaluation of two fuel injector configurations for the Rolls-Royce Deutschland RRD combustor using a high-pressure fully annular rig, contrasting trends were identified. Low swirl configurations demonstrated the highest lean blowout air-fuel ratios (AFRs), albeit with compromised ignition performance. Conversely, high swirl configurations exhibited the opposite trend. specific pilot air blast

configurations held a promised potential to achieve high lean blowout with a reasonable ignition AFR [245].

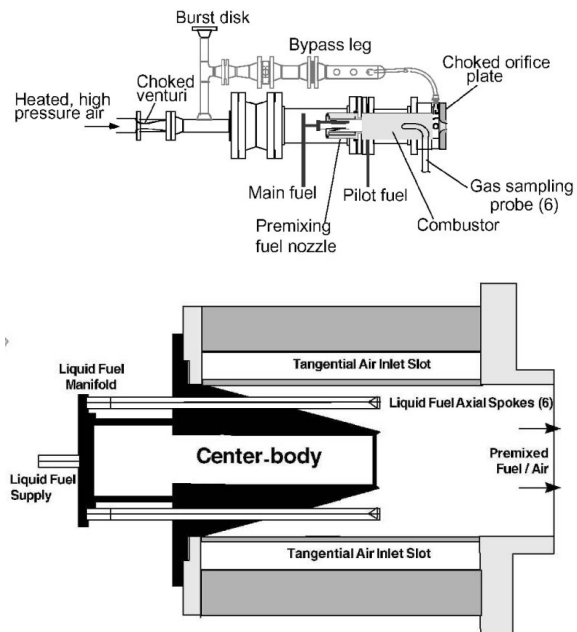
Table 4: Several burners employed in extant GT systems, wherein the inclusion of a pilot inlet constitutes a principal design feature.

Company	Burner
GE LM6000 aero-derivative DLE combustion system [254]	
Solar turbines SoLoNOx combustion system [255]	

Siemens Vx4.3A
land-based
combustion system
[256]–[258]



Pratt & Whitney
FT8 combustion
system [259]



CHAPTER 3

Methodology

3.1 Experimental Setup and Test Conditions

3.1.1 Physical Combustor and Instruments

This experiment investigates combining the concepts of stratification and hydrogen-addition to improve the stability of a lean premixed swirl-stabilized CH₄/air flame. Stratification is achieved by introducing enrichment H₂ in non-premixed mode in form of eight peripheral jets at the base of the CH₄/air flame. Hydrogen is added in non-premixed mode based on some reasons; First, simplicity in implementation as there is no need to replace the entire setup to add hydrogen in the combustor but hydrogen is added as external circuit to be installed easily. Second, adding hydrogen in this manner will reduce the flashback risk as if it introduced in fully premixed mode, flame speed will be escalated, and this rising the possibility for flashback. Third, this configuration is already used in actual GT combustor which is dual annular counter-rotating swirl combustor (DACRS) [260]. Figure 23 and Figure 24 show the test rig used for this investigation. CH₄ and Air are introduced into a mixing tube, which has length of one-meter and a 2-inch diameter, where they are completely premixed, due to the large L/D for the mixing tube (~20). To improve mixing, the pipe used for CH₄ introducing is closed at one end, and CH₄ is fed in the mixing tube by 12 staggered radial apertures located on three plains that are axially aligned with the air inlets. The main burner, which introduces the fully premixed CH₄/air mixture into the combustion zone, consists of a 55° swirler followed by a converging-

diverging nozzle has a throat diameter of 2-cm as well as a solid conical center body. Both the convergence, which accelerates the swirling flow, and the solid conical center body, which mitigates vortex breakdown, are used to decrease flashback propensity [261]. The gradual convergence (30°) decreases the loss in swirling momentum, while the 45° divergence on the downstream side avoids the unforeseen expanding in the combustor. The swirl number of CH_4/air primary mixture is ~ 0.98 , based on the formula provided in Ref. [94]. Enrichment or Enhanced-Lean-Blowout (ELBO) hydrogen (secondary fuel) is supplied to an annular plenum around the main burner. Eight equally spaced symmetrical inclined grooves with rectangular cross-sections ($3 \times 0.2618 \text{ mm}^2$) connect the plenum to the burner's faceplate. These grooves introduce hydrogen fuel jets into the combustion zone with an angle of inclination to the centerline having value of 30° . Downstream of the combustor, the optically accessible combustor is comprised of a quartz glass, with length equals 300 mm and diameter equals 80 mm, for visualization and imaging purposes.

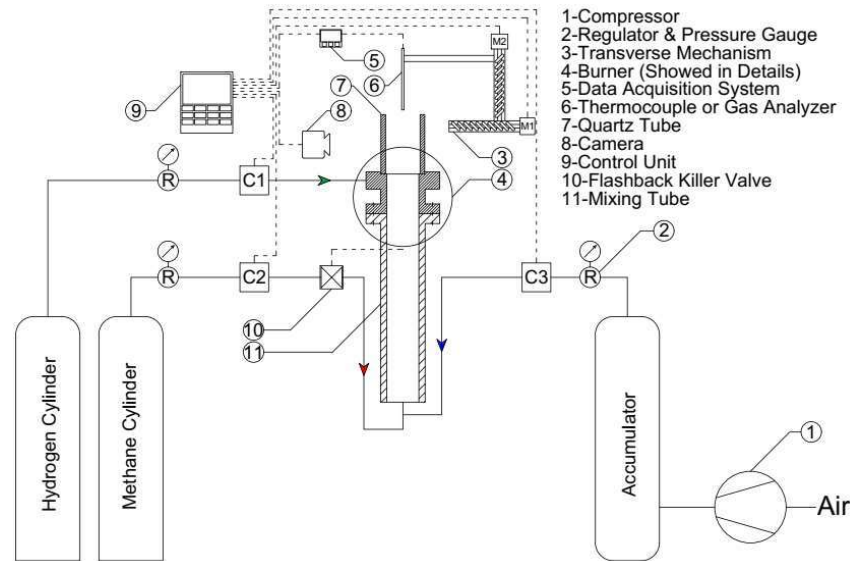


Figure 23: Schematic drawing of the experimental setup.

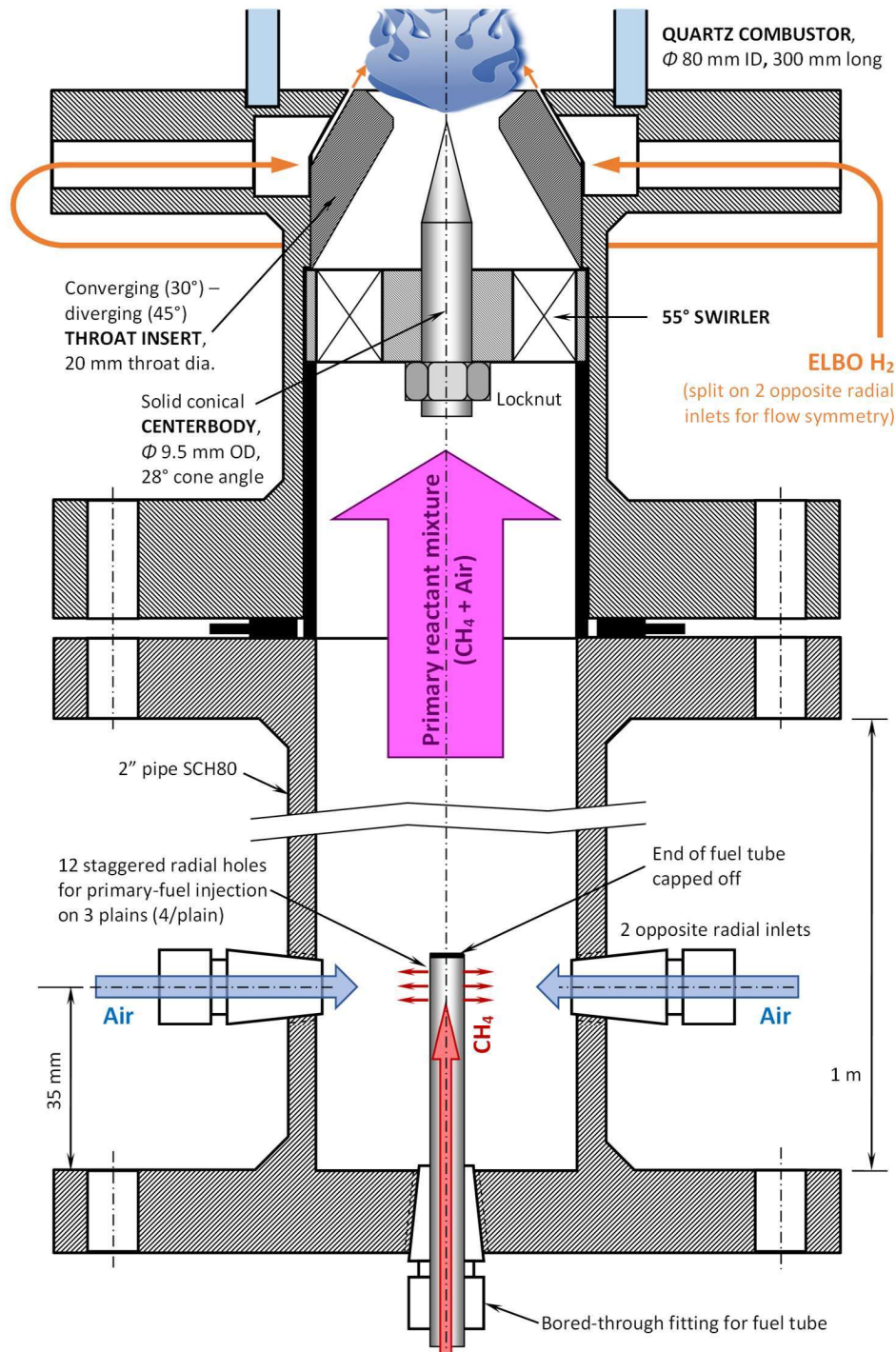


Figure 24: Schematic drawing of the combustor.

CH₄ and hydrogen are supplied from pressurized cylinders, while atmospheric air is provided from a remote compressor. A regulator and a pressure gauge are installed on each supply line to decrease the pressure for the flow controllers. Thermal mass flow controllers

for Aalborg Inc. company, having uncertainties equal $\pm 0.5\%$ of the full scale, are used to control the flow rates for the three mentioned gases. A shut-off valve used for emergency is fitted on CH₄ route to shut off fuel in the flashback scenario based on a thermocouple signal from the mixing tube. For temperature measurements, an R-type thermocouple (PtRh-13%/Pt) having a junction diameter of value 1-mm is used. The thermocouple is connected to a LabVIEW data acquisition system that is configured to sample and average 10000 temperature readings after the thermocouple has approached steady state. The EES code incorporates Blevins and Pitts model [262] to make temperature corrections for radiation losses. This model balances the radiation loss from the thermocouple bead with the convective heat transferred from the bead to the surrounding air. The equation representing this balance is as follows,

$$h(T_g - T_b) = \varepsilon_b \sigma (T_b^4 - T_\infty^4) \quad (5)$$

where T_g refers to the actual temperature of the flame, T_b represents the thermocouple temperature, and T_∞ is the surrounding temperature (300 K). The thermocouple bead emissivity, denoted as ε_b , is assumed to be 0.9 [263]. The Stefan–Boltzmann constant is represented by σ . The convective coefficient of heat transfer between the thermocouple bead and the surrounding gases is denoted as h . To calculate h , the thermocouple bead is assumed to be a sphere subjected to external flow. The Nu is determined using Whitaker's correlation for external flow over a spherical shape [264]. The correlation equation is as follows:

$$Nu = 2 + (0.4Re^{0.5} + 0.06Re^{\frac{2}{3}})Pr^{0.4} \quad (6)$$

The Nu and Re are expressed by the following equations,

$$Nu = \frac{h D_b}{k_g} \quad (7)$$

$$Nu = \frac{\rho_g U_g D_b}{\mu_g} \quad (8)$$

Where D_b is the diameter of hot junction for the thermocouple, ρ_g , μ_g and k_g are the density, viscosity and thermal conductivity of the surrounding gases U_b is the local speed near the thermocouple hot junction. To calculate U_b near the thermocouple bead, a simulation is performed using ANSYS-Fluent. This simulation utilizes the same burner dimensions, swirling angle, and inlet velocity to accurately determine the velocity at the specific points where temperature measurements are taken.

In the context of error analysis, turbulence intensity data is derived from the ANSYS computational model. This turbulence intensity data is subsequently employed to quantify the fluctuations in velocity within the system. It is worth noting that these velocity fluctuations exert an influence on the convection heat loss calculation, thereby contributing to discrepancies in temperature readings. These discrepancies are considered as errors and are incorporated into the overall error, augmenting the thermocouple error component, which is acknowledged as 0.25% of the total thermocouple reading.

For flue gas analysis, a gas analyzer of type Testo 350 is used. Table 5 shows the uncertainties for each sensor as well as reaction time. A transverse mechanism, with a sensitivity of 0.00025 inches/step for each motor, is used to hold the thermocouple to make the axial and radial measurements precisely. A high-resolution camera, which is set at 1/60 s shutter speed, f/5.6 f-stop and 1600 ISO sensitivity, is used for flame imaging to capture

visible-light images of the flame. All flow controllers, data acquisition systems and motors for the transverse mechanism are connected to a PC for monitoring and controlling.

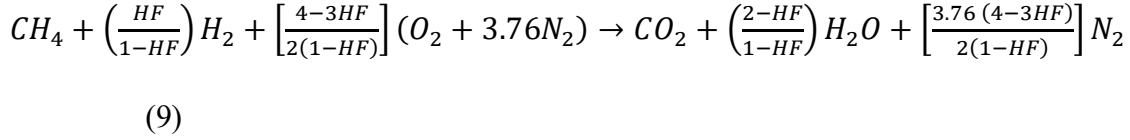
Table 5: Testo 350 gas analyzer specifications.

Sensor	Measuring range	Accuracy	Resolution	Reaction time (t_{90})
NO	0 to 4000 ppm	± 5 ppm	1 ppm	< 30 s
CO	0 to 500 ppm	± 0.5 ppm	1 ppm	< 40 s
HC	100 to 40000 ppm	< 400 ppm (100 to 4000 ppm)	10 ppm	< 40 s
O ₂	0 to +25 Vol.%	$\pm 0.8\%$ of FSV	0.01 Vol.%	< 20 s

3.1.2 Operating Conditions and Governing Equations

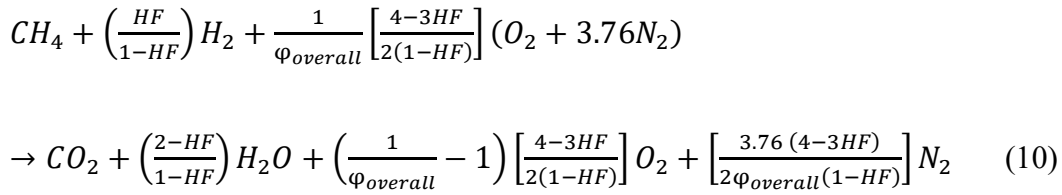
A number of experiments have performed at ambient pressure to show the effects of hydrogen introduction on static LBO limits, temperature profiles, emissions characteristics, and flame shapes for different equivalence ratios values of CH₄/air flames. Swirl is used for main flame (CH₄/air) stabilization, while hydrogen is injected as non-swirling inclined jets into the combustion zone. The range of experimentally studied overall equivalence ratios (ϕ_{overall}) investigated is from 0.487 up to 0.73 while the ratio of HF investigated is from 0% up to 21%. HF is defined on the volumetric fraction of H₂ in the total fuel (CH₄+H₂) entering the combustor. For all studied cases, the velocity of primary swirling flame at the throat is kept at constant value of 6 m/s to preserve the same cold-flow experiments and turbulence intensities for all isothermal flow fields as well as neutralize its influence on flame stability as it is more dominating parameter on flame stability than Re [265], [266]. To calculate flow rates for all gases in each flame, calculations are done based on constant velocity, HF and ϕ_{overall} .

The stoichiometric combustion for HE- CH₄/air flame can be described as,



For actual combustion, the actual air mass flow rate can be expressed as $\dot{m}_{air} = \frac{\dot{m}_{air_{stoic}}}{\phi_{overall}}$.

Then, the actual combustion for HE- CH₄/air flame can be described as,



For the primary mixture flow, the mass flow rates can be showed at the throat as follows,

$$\dot{m}_{prim} = \dot{m}_{CH_4} + \dot{m}_{air} = \frac{pM_{prim}}{R_u T} A_p v_a \quad (11)$$

where M_{prim} is the apparent molecular weight of the primary flow obtained from

$$M_{prim} = 16 y_{CH_4} + 28.97 y_{air} \quad (12)$$

where y is the mole fraction in the primary CH₄/air mixture. The primary flame equivalence ratio ϕ_{prim} is defined as,

$$\phi_{prim} = \frac{(Fuel/Air)_{actual}}{(Fuel/Air)_{stoi}} = 17.16 \left(\frac{\dot{m}_{CH_4}}{\dot{m}_{air}}\right) \quad (13)$$

where A_p is throat area, V_a is the axial component of primary swirling flow, pressure is the ambient pressure, and all gases are at 300 K with no preheating.

By solving equations 11 – 13, mass flow rates for the primary flame components are calculated according to,

$$\dot{m}_{CH_4} = 16 \left(\frac{pA_p v_a}{R_u T} \right) \left(1 + \frac{9.48}{\phi_{prim}} \right)^{-1} \quad (14-a)$$

$$\dot{m}_{air} = 274.6 \left(\frac{pA_p v_a}{R_u T} \right) (9.48 + \phi_{prim})^{-1} \quad (14-b)$$

ϕ_{prim} is related to $\phi_{overall}$ based on the enrichment HF as follows,

$$\frac{\phi_{prim}}{\phi_{overall}} = \frac{2 (1-HF)}{2 (1-HF) + 0.5 HF} \quad (15)$$

The hydrogen mass flow rate and its jet velocity are calculated based on,

$$\dot{m}_{H_2} = \frac{\dot{m}_{CH_4}}{8} \left(\frac{HF}{1-HF} \right) \quad (16)$$

$$v_{H_2} = \frac{\dot{m}_{H_2}}{\rho_{H_2} A_E} \quad (17)$$

where ρ_{H_2} is hydrogen density and A_E is the area of ELBO-fuel jets. Combustor HRR (HRR) is calculated based on the following equation,

$$HRR = \dot{m}_{CH_4} \times CV_{CH_4} + \dot{m}_{H_2} \times CV_{H_2} \quad (18)$$

where CV_{CH_4} and CV_{H_2} are heating calorific values for both CH_4 and H_2 , respectively.

Combustor stability has also been analyzed based on the combustor PD (MW/m³/bar) and primary-flame Re which are defined as,

$$PD = \frac{\dot{m}_{CH_4} \times CV_{CH_4} + \dot{m}_{H_2} \times CV_{H_2}}{\text{volume of quartz confinement} \times p} \quad (19)$$

$$Re = \frac{vD\rho_{prim}}{\mu_{prim}} \quad (20)$$

$$\rho_{prim} = \frac{p(\dot{m}_{CH_4} + \dot{m}_{air})}{R_u T \left(\frac{\dot{m}_{CH_4}}{16} + \frac{\dot{m}_{air}}{28.97} \right)} \quad (21)$$

$$\mu_{prim} = \frac{y_{CH_4} \mu_{CH_4} \sqrt{16} + y_{air} \mu_{air} \sqrt{28.97}}{y_{CH_4} \sqrt{16} + y_{air} \sqrt{28.97}} \quad (22) [267]$$

AFT is calculated based on thermodynamic analysis of Equation (10). Complete combustion is assumed for simplicity, as dissociation has no impact on the key structures and conclusions presented here [268]. Moreover, the lean examined conditions and cold corresponding flame temperatures reduce species dissociation. Exit emissions were measured and presented here as area-weighted average values using the following formula,

$$\text{Average concentration} = \frac{\sum_i^n \text{Conc}_i A_i}{A_t} \quad (23)$$

where the combustor exit area (A_t) has been discretized into concentric annular areas (A_i), and the emissions concentrations (Conc_i) have been measured along a radial profile.

3.2 Computational Model Setup

Computational simulations were carried out on the combustor to augment the existing dataset and scrutinize the influence of HF and equivalence ratio on a span of parameters. The primary objective was to elucidate their effects on emissions of CO, NO_x, UHC, O₂, and CO₂, as well as examine the velocity and temperature distributions, concentrations of OH, H, and O radicals, progress variable, product formation rates, flame thickness, flame speed, critical strain rate, and concentrations of CH₄, H₂O, H₂, CO, NO, O₂, NO, and CO₂ throughout the investigated domain. The studied equivalence ratios ranged from 0.563 to

0.893, while the HF was incrementally elevated from 0% to 25%, facilitating a comprehensive exploration of the combined effects of these parameters.

3.2.1 Conservation Equations

The current model employed the RANS methodology to solve mass, momentum, energy, and scalar transport conservation equations within the 3-D domain of the combustor numerically. The commercial version of ANSYS-Fluent 22.2 software was utilized for performing all simulations. In order to predict the flow structure, heat transfer, and emission behavior of the stratified HE- CH₄ flames in the swirler combustor, the 3D elliptic equations were simultaneously solved. The fundamental concept of conservation served as the foundation for the governing equations for the conservation of mass, momentum, energy, and species transport [269]–[271],

$$\frac{\partial}{\partial x_j} (\bar{\rho} \bar{u}_j \Phi + \bar{\rho} \overline{u_j \phi}) = \frac{\partial}{\partial x_j} \left(\Gamma_\phi \frac{\partial \Phi}{\partial x_j} \right) + \rho \bar{S}_\phi \quad (24)$$

where u_j indicates the velocity component in the j direction and Φ and ϕ stand for the dependent variable's Reynolds-averaged and fluctuating components, respectively. Additionally, in a particular system, S_ϕ denotes the source and Γ_ϕ denotes the diffusion coefficient.

3.2.2 Radiation Model

The DO radiation model is utilized to simulate heat transfer by radiation through the combustor, in such a way that one radiative iteration occurs for every 10 energy iterations. This model has been proposed for simulating the combustion process since it is valid over a broad variety of optical thicknesses [265], [272], [273]. The governing equation for the

DO model is based on the radiative transfer equation, which describes the transport of radiant energy through a participating medium. In its basic form, the formula in the direction $\vec{S}$ can be shown as follows:

$$\nabla \cdot (I(\vec{r}, \vec{S})\vec{S}) + (a + \sigma_s)I(\vec{r}, \vec{S}) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{S}') \Phi(\vec{S}, \vec{S}') d\Omega' \quad (25)$$

Where $\vec{r}, \vec{S}, \vec{S}'$ are position, direction, scattering direction vectors, respectively. a denotes to absorption coefficient, n denotes for refractive index, σ_s denotes for scattering coefficient, σ denotes for Stefan-Boltzmann constant, I denotes for radiation intensity, T denotes for local temperature in Kelvin, Φ denotes for phase function and Ω' denotes for solid angle. The radiation field is represented as discrete angular directions, and the spatial domain is divided into a grid. The intensity of radiation is calculated at individual points within the domain for each direction, accounting for absorption, emission, and scattering within the medium.

3.2.3 Turbulent Model

The RANS formulas are fundamental in CFD for simulating turbulent flows. These equations are used to model the mean flow field, where the effects of turbulence are represented through additional turbulence model which is SST k- ω model. The governing equations for the RANS models for describing the flow of fluid substances are as follows [274], [275] :

Continuity equation;

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho \bar{u}_i) = 0 \quad (26)$$

Momentum equation;

$$\frac{\partial}{\partial t}(\rho \bar{u}_i) + \frac{\partial}{\partial x_j}(\rho \bar{u}_i \bar{u}_j) = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left(\mu \frac{\partial \bar{u}_i}{\partial x_j} \right) - \frac{\partial}{\partial x_i}(\rho \overline{u'_i u'_j}) \quad (27)$$

where ρ is fluid density and μ is dynamic viscosity, t is the time, p is pressure. The $\overline{u'_i u'_j}$ term is known as the Reynolds stresses which are, according to a Boussinesq's approximation [276], a linear relationship between it and mean strain rate are expressed as,

$$\tau_{ij} = \overline{\rho u'_i u'_j} = \frac{2}{3} \rho k \delta_{ij} - \mu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \quad (28)$$

Where μ_t is turbulent viscosity and δ_{ij} is Kronecker delta. “ k ” is the turbulence kinetic energy, and it is expressed as,

$$k = \frac{1}{2} \overline{u'_i u'_i} = \frac{1}{2} (\overline{u_1'^2} + \overline{u_2'^2} + \overline{u_3'^2}) \quad (29)$$

The RANS equations serve as the foundation for SST k - ω turbulent models, which, in order to represent the effects of turbulence, introduce extra transport equations for the turbulent kinetic energy and its dissipation rate.

The SST k - ω system is an extension for k - ω model, combining features of both k - ϵ and k - ω models. It uses k - ω model near the wall where the flow is strongly influenced by wall effects and k - ϵ model in the regions away from boundary layer. By doing so, it aims to address the limitations of both models, providing improved accuracy in regions with large variations in pressure and separation. Governing equations for SST k - ω model, which include the formulas for the turbulent kinetic energy (k) and turbulent dissipation specific rate (ω) are as follows:

Turbulent kinetic energy equation:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_i} \left(\Gamma_k \frac{\partial k}{\partial x_i} \right) + \tilde{G}_k - Y_k \quad (30)$$

Turbulent specific dissipation rate equation:

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_i} \left(\Gamma_\omega \frac{\partial \omega}{\partial x_i} \right) + G_\omega - Y_\omega + D_\omega \quad (31)$$

where $\tilde{G}_k, G_\omega, \Gamma_k, \Gamma_\omega, Y_k, Y_\omega, D_\omega$ are the production of turbulence kinetic energy as a result of average velocity gradients, ω generation, k and ω effective diffusivity, k and ω dissipation, the term of cross-diffusion, respectively. For further information about calculation of these variables and the model constants, it will find in these sources [277], [278]. The SST model is particularly useful for simulating flows with strong streamline curvature and separation, making it a popular choice in practical engineering simulations.

3.2.4 Reaction Kinetics Model

The combustion process was simulated using the model of thin flamelet, which is available as a partially premixed option within the FLUENT software framework, accompanied by a secondary flow option. This model allows for adjustments to be made, transforming it into a premixed flame model for the primary flame. This transformation was achieved by setting the inlet mixture fraction for the main flows to a consistent value representing the CH₄-to-air ratio, thereby indicating that the primary inlet mixture comprised a combustible blend. Additionally, the mixture fraction variance was maintained at 0, a consequence of the constant equivalence ratio. Concerning the secondary flow, it was configured to utilize 100% hydrogen fuel.

In this study, the model used adopts a flame front topology approach, which assumes that the flame is composed of an extremely thin flame front positioned between unburnt and

burnt mixtures. This flame front is represented by a variable known as the reaction progress variable, which ranges between 0 (indicating the unburnt mixture) and 1 (representing the burnt mixture). The impact of turbulence on the flame brush is considered to be purely kinematic, primarily involving wrinkling phenomena. To account for these effects, the Zimont turbulence flame speed model was employed to describe the mean reaction rate term. Chemical reactions, species concentrations, and associated integrations were computed using a chemical equilibrium-assumed shape PDF (b-PDF) based on the composition of the inlet mixture. The number of species used is 20. The solution methodology involves solving the Favre-averaged filtered transport equations for the reaction progress variable "c" and the mixture fraction "f," along with the governing equations for continuity, momentum, and enthalpy. The mixture fraction can be mathematically expressed as follows:

$$f = \frac{sY_{fu} - Y_{ox} + Y_{ox,0}}{sY_{fu,1} - Y_{ox,0}} \quad (32)$$

The symbol "s" is used to represent the ratio of oxygen to fuel, while "Y" denotes the mass fraction of species. The subscripts 'ox' and 'fu' are associated with the oxidizer and fuel, respectively, with '0' and '1' indicating the inlet streams of the oxidizer and fuel.

The mean reaction progress variable is employed to define the flame brush, which takes on values between 0, indicating the unburnt mixture, and 1, representing the burnt mixture. This progress variable is defined in terms of the mass fraction of species and can be expressed as follows:

$$C = \left(\frac{\sum_{i=1}^n Y_i}{\sum_{i=1}^n Y_{i,ad}} \right) \quad (33)$$

The symbol Y_i represents the mass fraction of species 'i' in the products, with subscript 'ad' indicating completed combusted species. Various thermochemical parameters, including fractions of species, temperature and density, are intricately linked to the PDF of the mixture fraction (f) and the reaction progress variable (c), denoted as:

$$\bar{\phi} = \bar{C} \int_0^1 \phi_b(f)p(f)df + (1 - \bar{C}) \int_0^1 \phi_u(f)p(f)df \quad (34)$$

Subscripts 'b' and 'u' in the formulation above stand for the burnt and unburnt blends, respectively. A three-dimensional look-up table is built to account for enthalpy. Introducing the heat-release factor " γ ," a non-dimensional quantity that can be used to quantify heat release during combustion. It is defined as follows:

$$\gamma = \frac{T_{ad} - T_0}{T_{ad}} = 1 - \frac{T_0}{T_{ad}} \quad (35)$$

where T_0 represents the unburned temperature of the gas mixture and T_{ad} represents the AFT. The following correlation is used to calculate the flame thickness, which is a measure of the length of the preheat layer and the inner-layer section of the front of the laminar flame:

$$\delta = \frac{\lambda_u}{\rho_u c_p S_L} \quad (36)$$

Where ρ_u , c_p and λ_u refer to the density, specific heat capacity and thermal conductivity of the mix of unburned reacting gases, respectively. While S_L refers to LFS.

3.2.5 Boundary Conditions

Ninety degrees of the computational domain were employed to create a 3D mesh for simulation purposes. This decision was based on the identification of symmetry within the domain, as visualized in Figure 25. This sector encompasses a complete hydrogen slit along with the other two halves on either side of the domain.

For the primary flame, which consists of CH_4 and air, both the tangential and axial velocities were maintained at a constant value of $3\sqrt{2}$. Variation in the operating conditions was achieved solely by altering the mean mixture fraction (fuel mass fraction), calculated from different equivalence ratios. As for the hydrogen jets, the mean mixture fraction was kept constant, while adjustments to the hydrogen fraction (HF) were made by altering the normal velocity of the hydrogen jets. Higher HF values necessitated higher hydrogen jet velocities. The mixture fraction variance remained at 0 for both flows. The inlet temperature was held constant at 298 K for both flows.

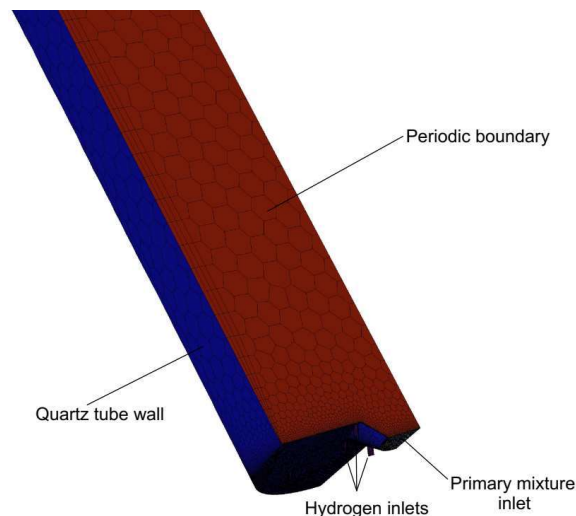


Figure 25 : 3D mesh used in numerical simulations with boundary conditions.

At the outlet of the combustor, a pressure-outlet boundary condition was applied. Given that the combustor confinement was constructed from quartz glass, a mixed thermal

boundary condition was assigned to the combustor wall to account for both convective and radiative modes of heat transfer to the surroundings. This condition specified values for the convective heat-transfer coefficient and free-stream temperature at 20 W/m²/K and 298 K, respectively. The 6-mm-thick quartz wall was modeled as semi-transparent, and radiative heat transfer through it was simulated using a four-wavelength non-gray band model. A periodic boundary condition was imposed at the symmetry faces adjacent to the wall

A pressure-outlet boundary condition was implemented at the combustor's exit. A mixed thermal boundary condition was applied to the combustor outer surface to take into consideration both convection and radiation heat losses to the surrounding environment as the combustor confinement was made of quartz glass. The heat-transfer coefficient for convection heat transfer and lab air temperature were to be set at 20 W/m²/K and 298 K, respectively. A non-gray band model with four wave lengths used to simulate the quartz tube glass which has a thickness of 6 mm. At the symmetrical faces, a periodic boundary condition was applied.

3.2.6 Mesh Independency and Model Validation

A mesh-independence assessment was carried out by examining the simulation outcomes for velocity and temperature along the central axis of the flame using nine different mesh configurations. The study began with a mesh containing approximately 100,000 cells and increased in increments of 50,000 cells, as illustrated in Figure 26. In this three-dimensional mesh, the cells closer to the burner were finer, while cell size gradually became coarser as one moved towards the outlet and the walls, with inflation applied at the wall boundary. Under the same conditions, it was observed that the disparity in centerline temperatures among all the mesh configurations was nearly insignificant. However, the

100,000-cell mesh exhibited a different velocity profile compared to the other mesh options. As a result, the mesh comprising 150,000 cells was selected for the computational analysis in this study.

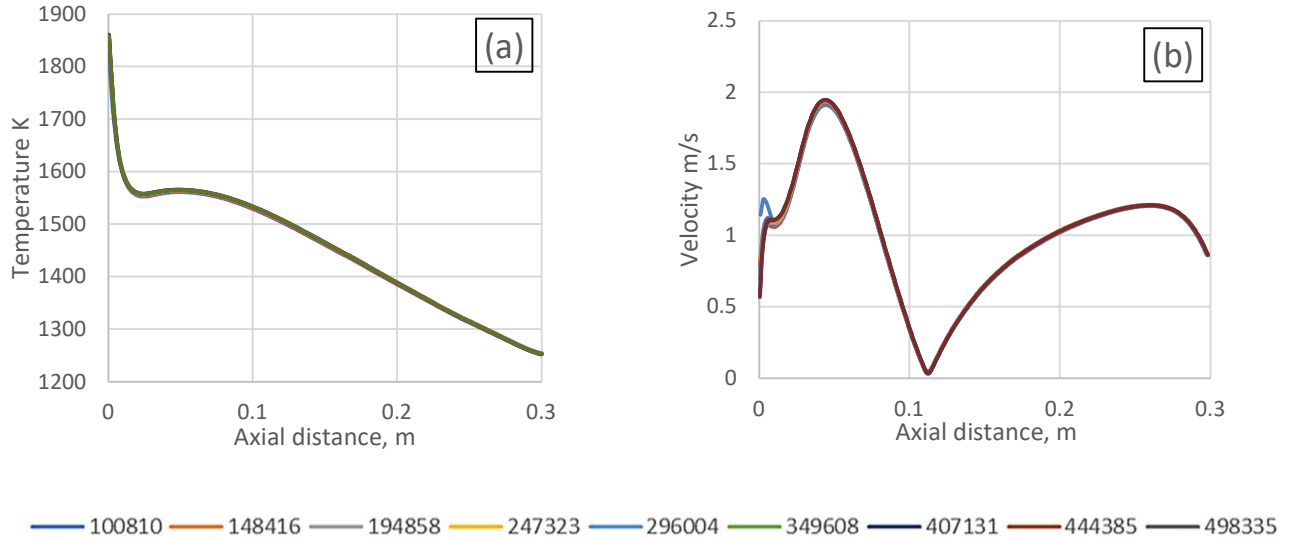


Figure 26: Mesh independence test for nine meshes using a) center line temperature and b) center line velocity, The chosen one is the 148416 mesh.

The numerical model's accuracy was assessed by comparing its results with measured temperature data at three different equivalence ratios, specifically 0.73, 0.644, and 0.563, all with a fixed hydrogen fraction (HF) of 5%. The comparison between the experimental and numerical axial temperature profiles along the combustor axis is presented in figure 4. Although the limited operational range of the thermocouple prevented the direct measurement of temperature at the flame core, these temperature values were computed numerically, as indicated in Figure 27. The results illustrate that for lower equivalence ratios (0.644 and 0.563), the temperature predictions of the numerical model closely align with the experimental data. However, for higher equivalence ratios, the numerical model slightly underestimates the flame temperature. Nevertheless, it's important to note that the overall error in temperature prediction for all cases does not exceed 16.33%. This indicates

that, in general, the numerical model provides a reasonably accurate representation of the actual temperatures, with some minor deviations observed at higher equivalence ratios.

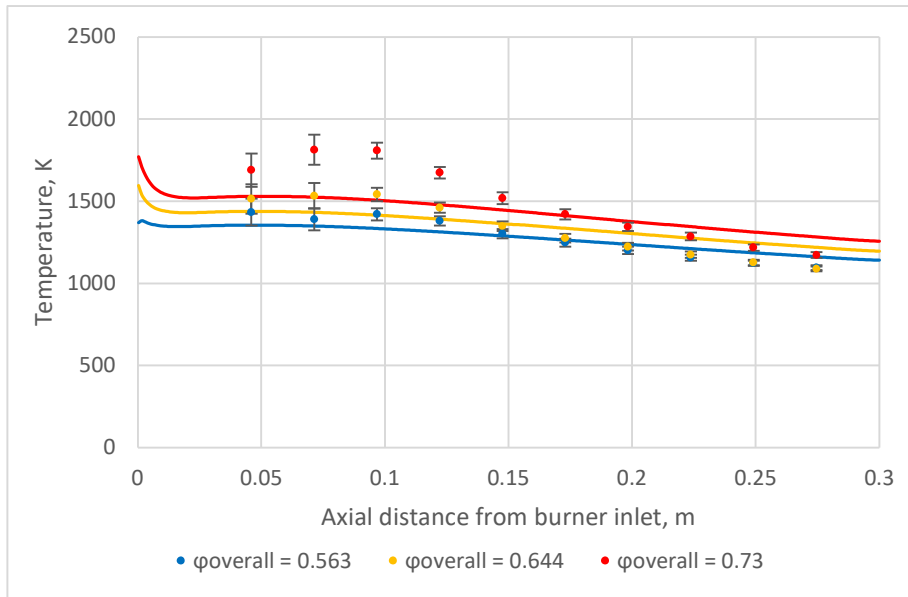


Figure 27: Experimental versus numerical center line temperatures for model validation at three equivalence ratios and constant hydrogen fraction of value 5%

CHAPTER 4

Experimental Results and Discussion

4.1 Combustor Stability Maps with Hydrogen Enrichment

This experiment investigates combining concepts of stratification and hydrogen-enrichment to enhance the lean stability of a premixed swirl-stabilized CH₄/air flame. Stratification is achieved by introducing enrichment H₂ in non-premixed mode in form of eight peripheral jets at the base of the CH₄/air flame. Combustor stability map (LBO limit) is drawn at constant bulk velocity (6 m/s) for the main CH₄/air flame over a range of HF from 0 up to 21% and $\varphi_{overall}$ from 0.4 up to 0.8. To draw the stability map, we followed the following procedure.

- Ignite the combustor on hydrogen only with no CH₄. This is because hydrogen combusts in non-premixed mode which is very stable with no fear from blowout or flashback.
- After that we increase the mass flow rate for CH₄ gradually with gradual decrease in hydrogen flow rate until we reach the desired blowout condition with 0% HF.
- Increasing HF gradually with adjusting CH₄ and air flow rates to reach the blowout condition at different values of HF.
- Collect blowout conditions with different HF values and draw a map for equivalence ratio versus HF with contours of AFT, PD and Re.

The blowout condition is considered here to be when a tall weak conical primary flame is reached, as seen in Figure 28, that is free of any eddies or vortices. Since such tall weak

flame would not exist in an actual gas-turbine combustor, this condition was considered blowout here. Figure 29 shows LBO equivalence ratio with different hydrogen fractions while Figure 30 and Figure 31 show the stability maps for the combustor plotted against contours of constant AFT and PD, respectively. For 0% HF, results show a good agreement with literature [85] (lean blowout equivalence ratio was reported as 0.49).



Figure 28: Blowout condition at 0% HF.

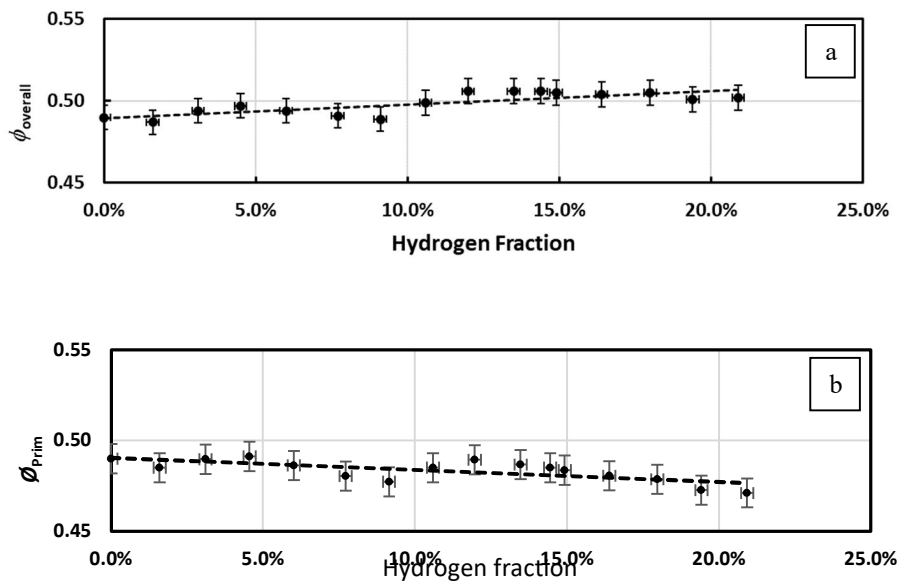


Figure 29: Lean Blowout equivalence ratio a) overall equivalence ratio, b) primary equivalence ratio with different hydrogen fractions.

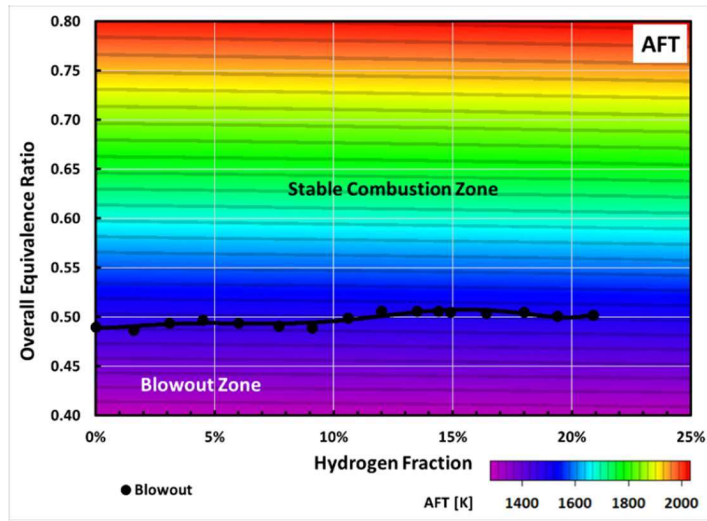


Figure 30: Lean Blowout limit with different hydrogen fractions against the contours of constant adiabatic flame temperature.

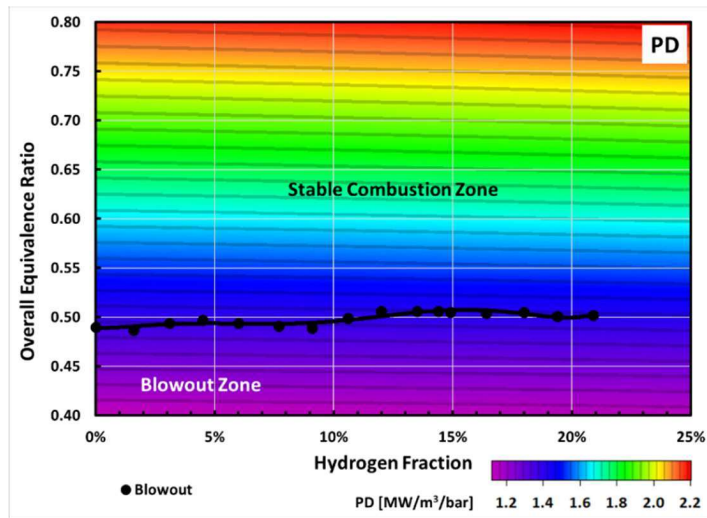


Figure 31: Lean Blowout limit with different hydrogen fractions against the contours of constant power density.

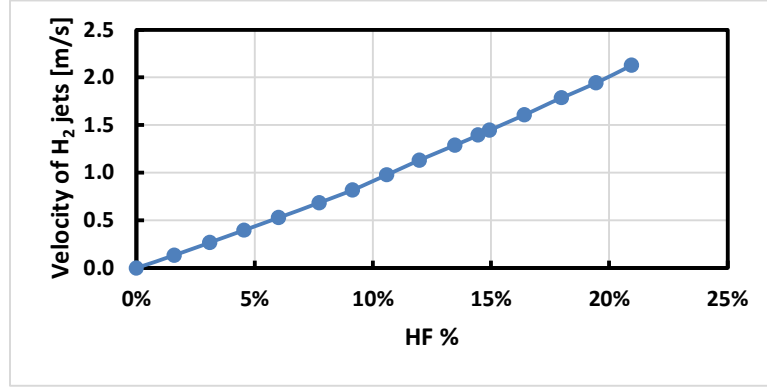


Figure 32: Velocity of hydrogen jets at different hydrogen fractions at blowout condition.

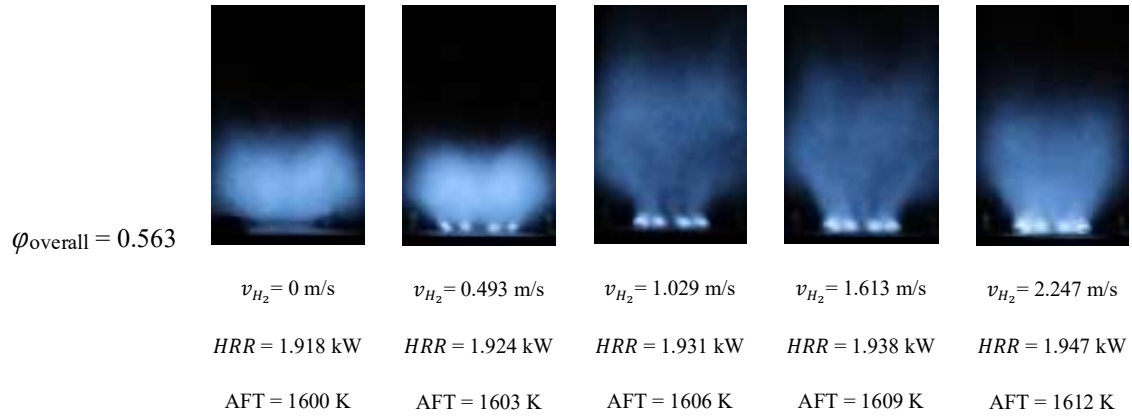
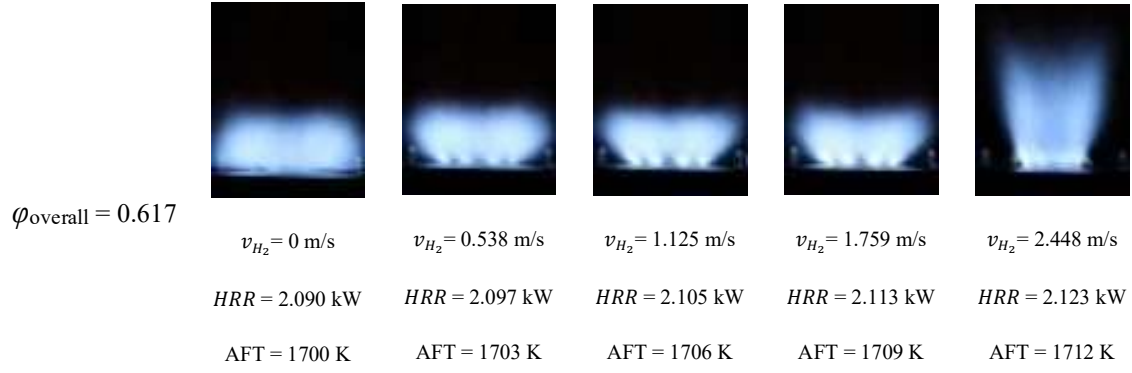
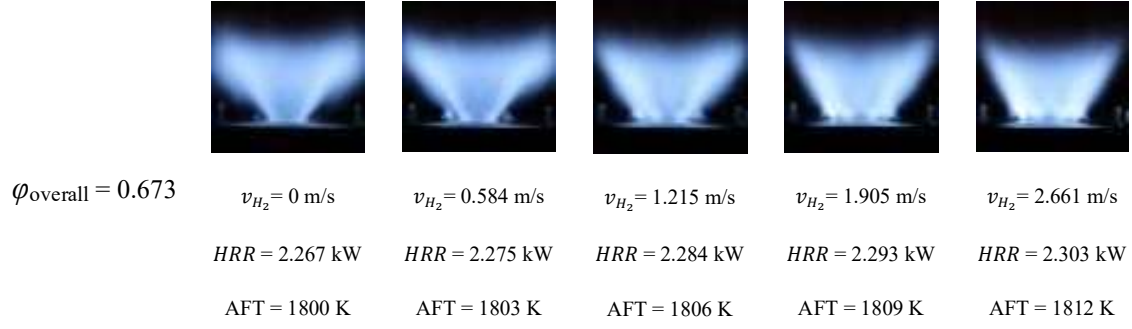
Increasing hydrogen fraction has two effects on the flame. The first one, hydrogen addition helps to increase flame temperature around the flame base, increase OH concentration, increase reaction rates and makes flames anchored around the non-premixed flame jets. This effect, plus the effect of swirl from the main combustor, should make the primary CH₄ flame more stable at leaner mixtures or higher velocities [85], [279]–[281]. On the contrary, increasing HF is associated with higher velocities of the hydrogen jets (Figure 32), which has a negative effect on LBO limit. Increasing velocities of these non-swirling hydrogen jets weakens the swirl intensity of the primary CH₄ flame and leads to shifting its recirculation stabilization zone downstream, which increases its tendency for blowout. This effect should be very effective to mitigate flashback propensity [169]–[171], however, it worsens LBO limit. Because of these two contradicting effects, hydrogen addition neither enhances LBO limit nor worsens it in a noticeable way (since it is fluctuating around $\phi_{\text{overall}} = 0.5$ in this study). This is contrary to what happens in fully premixed HE-flames, in which hydrogen enrichment leads to enhancement in LBO limit to leaner equivalence ratios [85], [280], [281]. It can thus be concluded that introducing enrichment hydrogen from the non-premixed fuel circuit of the DACRS burner is not an effective technique to benefit from

hydrogen for enhancing the burner LBO limit. Hydrogen should be premixed with the primary swirling reactants instead.

From a Damköhler-number (Da) perspective, HE-flames blow out at constant Da [94], [106], [282]. For a fully premixed mixture and constant flow rate (constant Re), flow time scale is constant, however adding hydrogen enhances flame kinetics, which results in a shorter chemical time scale. This leads to the ability for operating at lower equivalence ratios of slower flame kinetics (opposite effect to hydrogen addition), until reaching same Da number at which blowout occurs. Hence, LBO limits of fully premixed flames are typically enhanced by hydrogen enrichment. On the contrary, hydrogen addition in a stratified fashion (like the present study) leads to shorter flow time scale because of higher velocities of hydrogen jets. Also, it shortens chemical time scale because of faster reactions kinetics for hydrogen combustion. These two effects cancel each other, which leads to operating at constant Da number.

4.2 Effect of Hydrogen Enrichment on Flame Shape

HF	0 %	5 %	10 %	15 %	20 %
					
$\phi_{\text{overall}} = 0.73$	$v_{H_2} = 0 \text{ m/s}$	$v_{H_2} = 0.631 \text{ m/s}$	$v_{H_2} = 1.310 \text{ m/s}$	$v_{H_2} = 2.058 \text{ m/s}$	$v_{H_2} = 2.867 \text{ m/s}$
	$HRR = 2.446 \text{ kW}$	$HRR = 2.454 \text{ kW}$	$HRR = 2.464 \text{ kW}$	$HRR = 2.474 \text{ kW}$	$HRR = 2.485 \text{ kW}$
	AFT = 1900 K	AFT = 1902 K	AFT = 1905 K	AFT = 1908 K	AFT = 1911 K



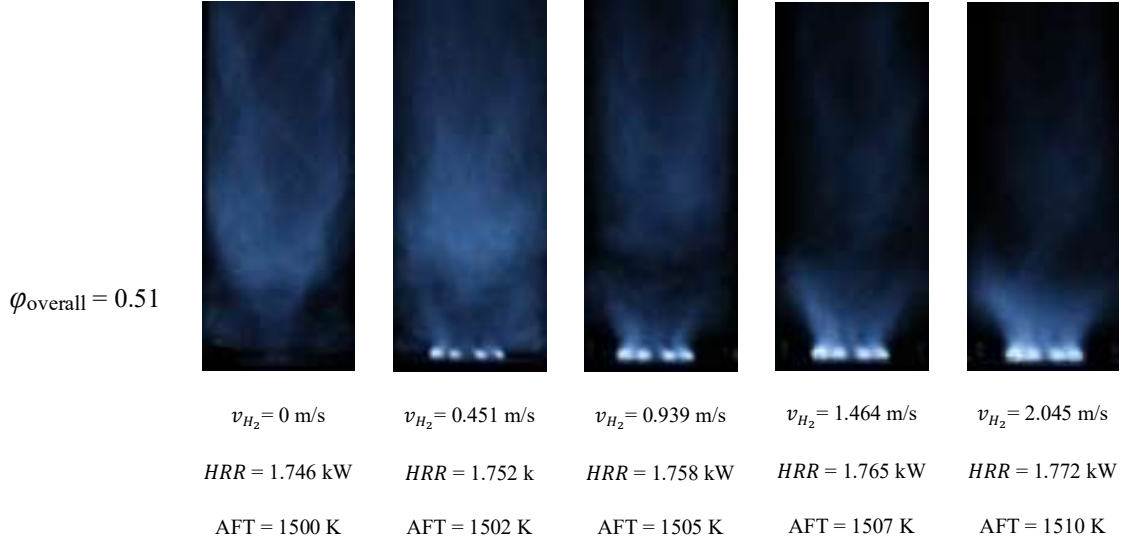


Figure 33: Effect of overall equivalence ratios (ϕ_{overall}) and hydrogen fractions on the flame structures.

Flame images are taken to study the effect of equivalence ratio, HF and hydrogen jets' velocities on the macrostructure of flame. At constant inlet velocity for the main mixture with value of 6 m/s, the flame images are taken by considering the nearest point to LBO limit with 0% HF, which is $\phi_{\text{overall}} = 0.51$ and AFT = 1500K, as a reference point then increasing the AFT by 50K for each later point until flame reached near flashback (noisy sound is heard) and AFT reached 1900K. After the equivalence ratios are set up for 0% HF, images are taken at same equivalence ratio with increasing HF percentage by 5% until we reach 20% HF. Figure 33 shows the flame images with respect to equivalence ratios, HF, velocities of hydrogen jets and HRRs (HRR). The flame images show some points,

- Velocity of hydrogen jets is increased with increasing both hydrogen fraction and equivalence ratio as for higher hydrogen fractions, more hydrogen is injected and at higher equivalence ratios, more fuel including hydrogen is burned. Hydrogen jet velocity reached 2.045 m/s at 20% HF and $\phi_{\text{overall}} = 0.51$ and reached 2.867, which is its maximum value, at 20% HF and $\phi_{\text{overall}} = 0.73$. Also, increasing hydrogen

fractions leads to an increase in the HRR for the combustor. The reason for this is part of the main fuel which is CH₄ with low heating value is replaced by hydrogen with higher heating values (nearly 2.4 times CH₄ heating value) which leads to increase in AFT as well.

- At 0% HF, CH₄/air flame has elongated conical shape, nearly filling the whole quartz confinement, with weak appearance of the effect of swirling stabilization near LBO limit ($\phi_{\text{overall}} = 0.51$). At this lower ϕ_{overall} , flame speed, AFT and reaction kinetics are low which makes flames images paler. By increasing equivalence ratio, flame speed as well as reaction kinetics increase. Thus, Flame becomes shorter, more compact, brighter and swirling effects become more dominant. Flame stabilization method changes with increasing equivalence ratios. At first, flame is stabilized by the ORZ until ϕ_{overall} reaches 0.617. After this, flame stabilizes by the IRZ. The change in stabilization mode can be noticed from the shape of flame which is changed from the elongated swirl conical shape to the shorter cup-shaped intense flame near the burner headend, then a V-shape which is stabilized by IRZ at higher equivalence ratios. The same observations are noticed by Imteyaz et al. [94] when they studied HE-oxy-methane premixed flames in a swirl combustor.
- By increasing hydrogen content near LBO limit (constant $\phi_{\text{overall}} = 0.51$), hydrogen jets appear at the base of flame. By increasing HF, hydrogen is injected in more quantities and velocities which results in higher reaction kinetics and flame speeds. Thus, hydrogen jets become brighter and help to stabilize the flame around it. On the other hand, a gradual increase in hydrogen velocities is noticed to separate the flame into two parts, part anchored around hydrogen jets and the other part is shifted

downstream. The higher the velocities of hydrogen jets, the more shifting occurs to the separated part of the flame. Due to lower temperatures and weakness of swirling effect downstream, this separated flame is hardly stabilized, leading to its extinction.

- Between $\phi_{\text{overall}} = 0.536$ and 0.589 , flame shapes appeared under the effects of two opposing forces. The first one is the swirling action aided by the effect of increasing the HF which both helps in stabilization of the flame near the combustor base making it shorter and more compact. The second one is the effect of increasing momentum of the non-swirling hydrogen jets with increasing hydrogen fraction, resulting in scattering the flame and increasing its length. At 0% HF, flame appears to be stabilized by the swirling effect. By adding 5% HF, flame reaction kinetics increase which can be noticed from the brighter flame leading to more stabilized and shorter flame. By adding 10% HF, hydrogen jets speeds reach nearly 1 m/s. The high momentum of hydrogen disperses the flame, making it longer and paler. After adding 15% HF, the effect of high reaction kinetics of hydrogen overcomes its momentum effects making the flame anchored around the hydrogen jets. Thus, the flame becomes more compact, shorter and brighter. This effect is increased by adding 20% HF.
- At $\phi_{\text{overall}} = 0.617$, flame is preserved its shape as we increase the HF from 0% up to 15% with increasing in its brightness. The reason after keeping the flame length constant is the balance between the effect of increasing reaction kinetics due to high HF and the effect of high momentum of hydrogen jets. At 20%, The effect of high momentum overcomes the effect of high reaction kinetics which makes the flame

dispersed and taller. However, as the effect of momentum appeared at higher HF, the flame appeared brighter than the dispersed one at lower equivalence ratios. Between $\phi_{\text{overall}} = 0.664$ and 0.701, flame is preserved its shape as we increase the HF with increasing in its brightness over all HFs. This means that the positive effect of increasing reaction kinetics due to high HF equalizes the negative effect of high momentum of hydrogen jets.

- Near flashback ($\phi_{\text{overall}} = 0.73$), the flame becomes anchored around the IRZ at 0% HF. By increasing hydrogen fraction, flame has different shapes. Generally, the flame becomes brighter because of increasing reaction kinetics due to high HF. At 5% HF, hydrogen addition increases kinetics as well as flame speed. Flame appears to be shorter with a higher tendency for flashback. By increasing HF to 10%, the effect of high momentum of hydrogen jets resists the effect of increasing reaction kinetics, resulting in increasing the flame length and shifting it downstream. This effect is increased with increasing the HF. At 20% HF, flame has same length of that for 0% HF but with brighter shape and more curved towards the hydrogen jets around which it stabilizes. The effect of high hydrogen momentum jets is very effective to mitigate the flashback and make the flame stabilize at higher equivalence ratios [169]–[171].

4.3 Effect of Hydrogen Enrichment on Temperature Profiles

Temperature profiles are taken to show the effect of HF and equivalence ratios and on the progress and strength of reactions in the combustor as well as enriching the literature with experimental data that can be used for validation and improvement of numerical models. Temperature readings are taken as close as possible to the flame combustion core because

of the limitations on the highest temperatures that the thermocouple can measure, in addition to the disturbance that may occur from the thermocouple probe on the flame flow field. Figure 34 shows the axial temperature profiles at the center of quartz tube at different values of HF from 0 up to 20%. To show the effect of HF, equivalence ratio effect is stalemated by taking the temperature readings at constant equivalence ratio = 0.644. It should be noted that the AFT is almost constant as it is strongly affected by equivalence ratio rather than HF. Similarly, and under the same operating conditions, radial temperature profiles are taken at two heights, which are 71.4 mm and 122.2 mm from the burner inlet, and they are presented in Figure 35. Also, and under the same operating conditions, flame images for these flames are presented in Figure 36. As discussed previously, flame shape has almost the same length and shape with increasing in its brightness by increasing the HF. The reason behind this is the neutralization of the positive effect of increasing reaction kinetics due to higher HF and the negative effect of high momentum of hydrogen jets. However, it was expected that as hydrogen has better combustion characteristics and improves the reaction kinetics of the combustion, its addition will lead to higher flame temperatures. Results show that hydrogen addition doesn't affect the temperature profiles with almost no variations in temperatures by adding more hydrogen in axial and radial temperatures. The reason is the small amounts of hydrogen flow rates compared to main mixture flow rate. This can be a good indicator for NO_x emissions as they don't increase with increasing HF up to 20%. In the literature, similar studies [94], [111], [121] show that hydrogen addition with small values has negligible effect on flame temperature and NO_x emissions.

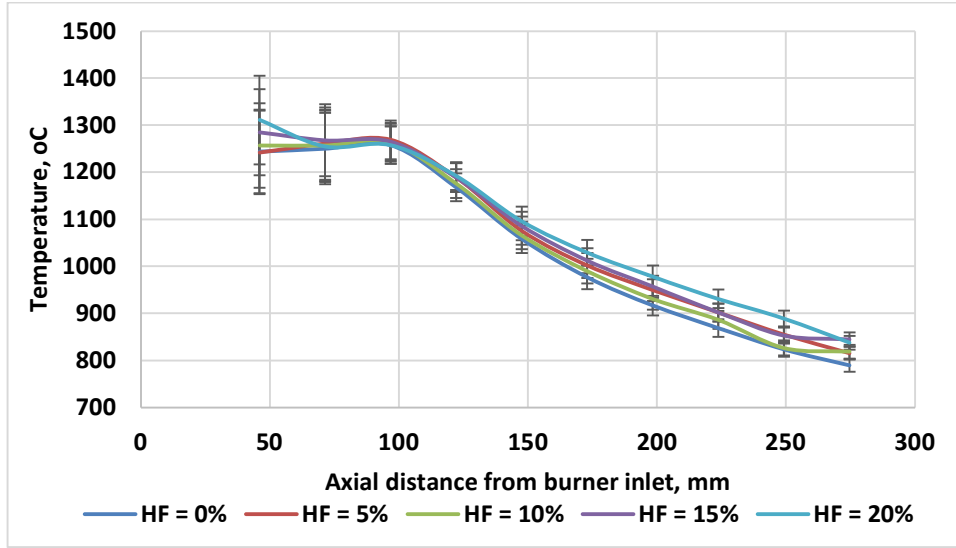
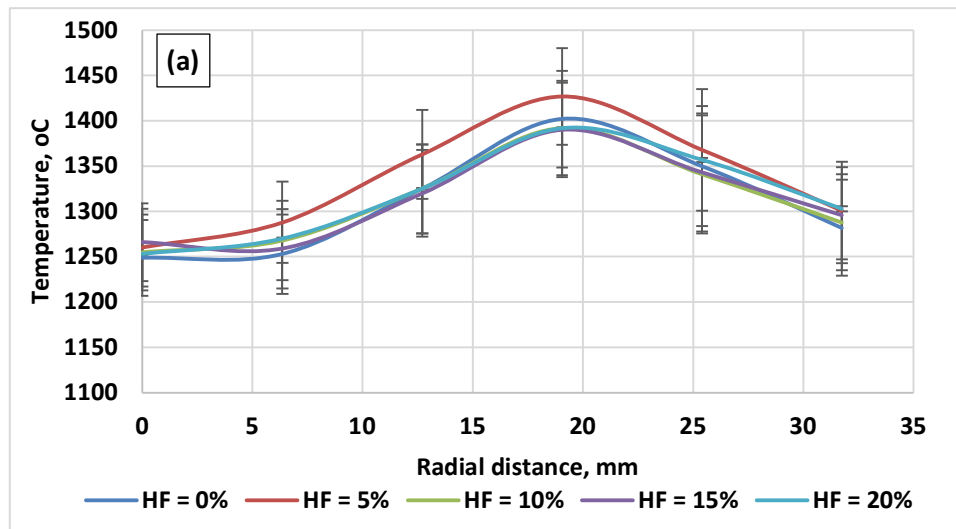


Figure 34: Effect of hydrogen fractions on the axial temperatures at constant overall equivalence ratio ($\phi_{\text{overall}} = 0.644$).



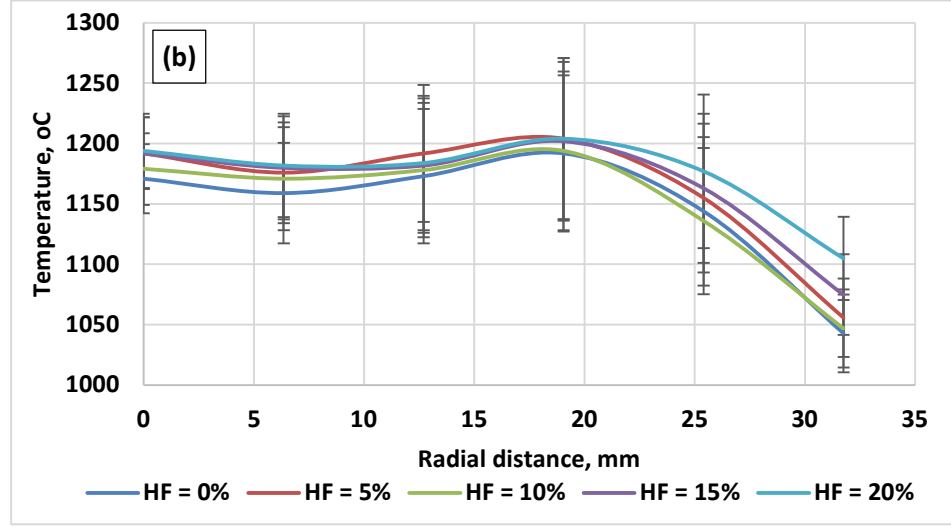


Figure 35: Effect of hydrogen fractions on radial temperatures at two axial locations (a) 71.4 mm, (b) 122.2 mm at constant overall equivalence ratio ($\phi_{\text{overall}} = 0.644$).

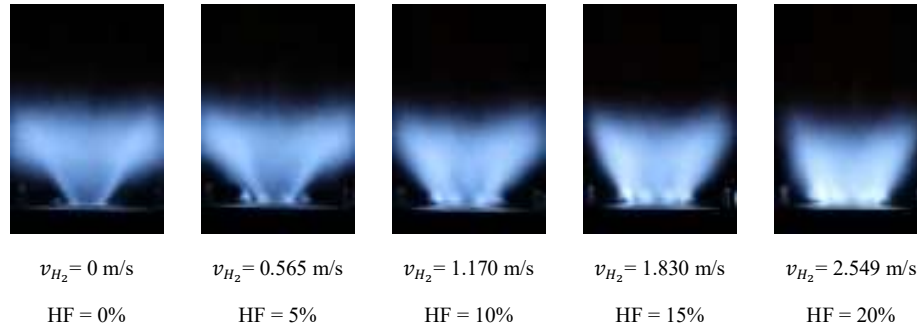


Figure 36: Effect of hydrogen fractions on the flame structure at constant overall equivalence ratio ($\phi_{\text{overall}} = 0.644$).

For the axial direction, flame temperatures decrease as we go downstream. This is because of heat losses to the walls and ambient surroundings as the flow progresses downstream. The radial temperature profiles exhibit an M-shape with a small profile factor. Temperature is slightly lower at the centerline due to the cooling effect that comes from the main swirling mixture as well as the cooler recirculated combustion products. Then, the temperature increases as we move further in radial direction because of crossing the flame sheet and reaction zone. After this, temperature decreases again due to the cooling effect of the quartz tube wall. As we move away from the base of the combustor, the highest radial temperature is shifted towards the center. This is because of two effects, the first one

is the weaker swirl intensity further downstream, and the second one is the greater effect of wall cooling which makes temperatures at the wall lower.

Figure 37 and Figure 38 show the axial and radial temperature profiles at two axial positions which are 71.4 mm and 122.2 mm from the burner inlet, respectively. These graphs show the effect of changing equivalence ratios on the temperature distribution inside the combustor. Three flames are studied at constant HF (5%) with equivalence ratios of 0.536, 0.644 and 0.73, and AFT equals 1603, 1752 and 1902 K for each, respectively. Figure 39 shows the images for the three flames studied. As discussed before, AFT is strongly affected by the equivalence ratios which obviously appeared in increasing the AFT with increasing equivalence ratio values. Increasing equivalence ratio enhances the reaction kinetics of the flame which, with the aid of hydrogen addition effect, make the flame more compact and brighter with higher tendency to flashback. Results show that increasing equivalence ratio leads to an increase in the temperature of the whole flame in axial and radial directions. For radial temperatures profiles, profiles have the same M-shape discussed before.

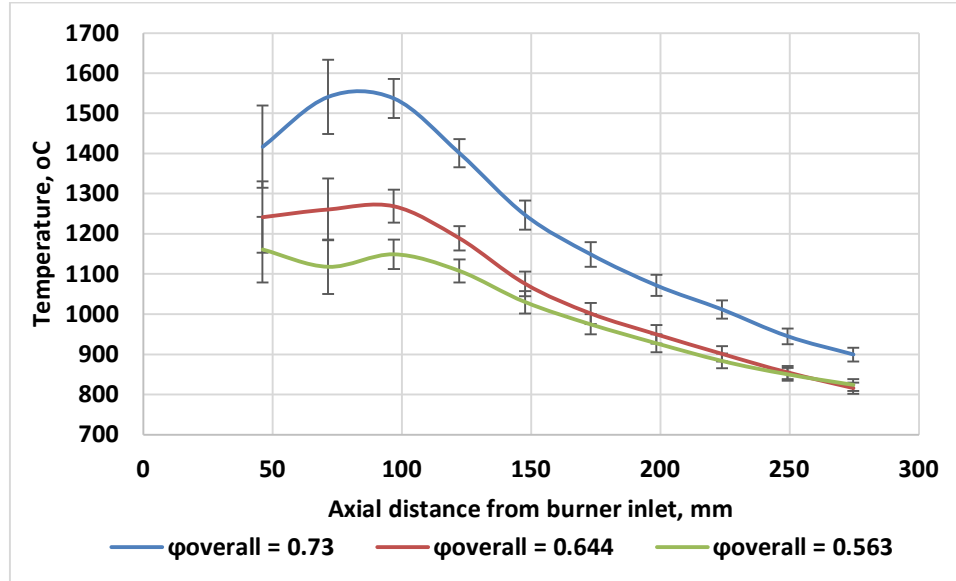
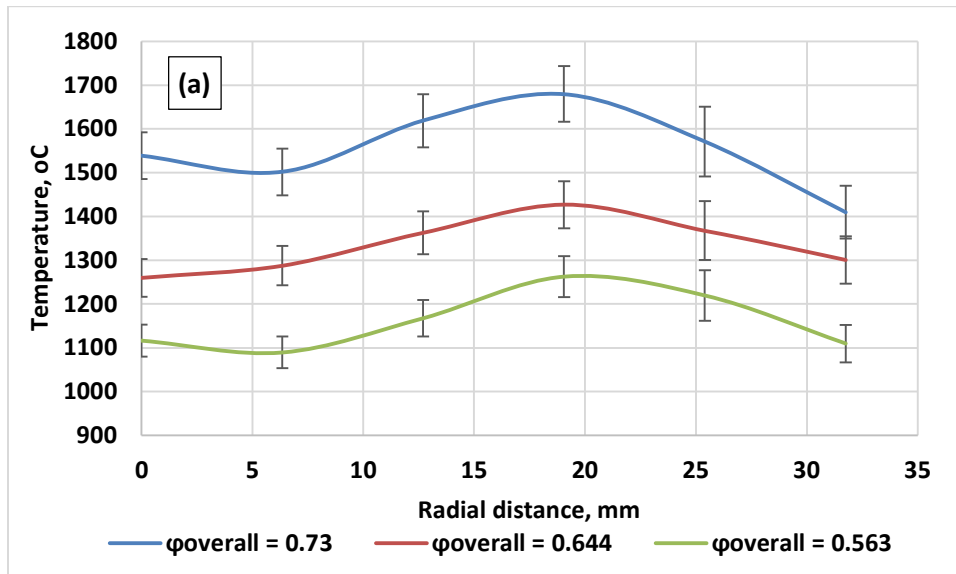


Figure 37: Effect of overall equivalence ratio (ϕ_{overall}) on axial temperature at constant hydrogen fraction=5%.



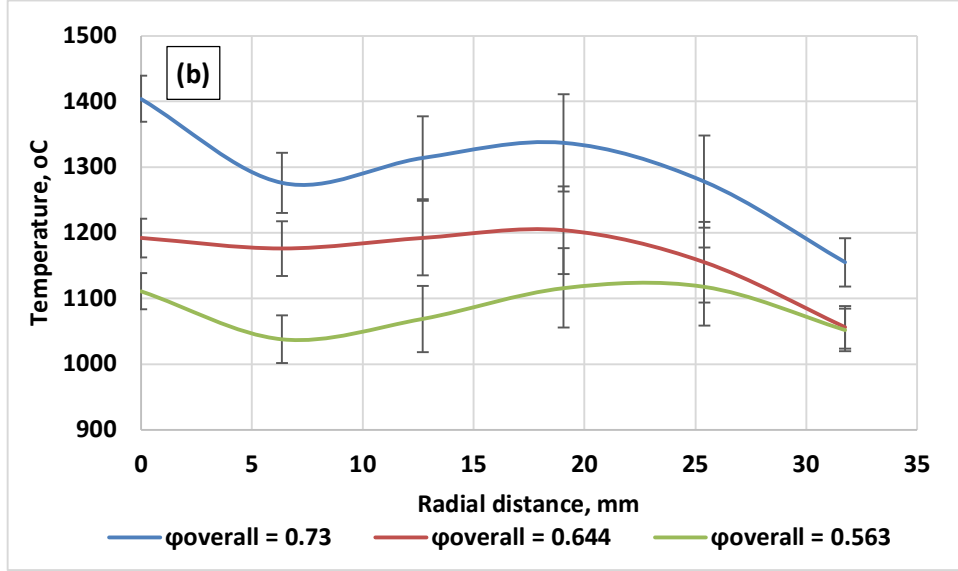


Figure 38: Effect of overall equivalence ratio (ϕ_{overall}) on radial temperature at two axial locations (a)71.4 mm, (b)122.2 mm at constant hydrogen fraction=5%

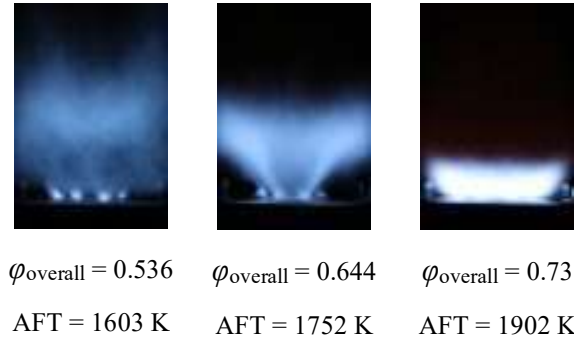


Figure 39: Effect of overall equivalence ratio (ϕ_{overall}) on the flame structure at constant hydrogen fraction=5%.

4.4 Emissions Analysis with Hydrogen Enrichment

The effect of hydrogen fractions on flame emissions are studied. These results are taken at constant equivalence ratio of value 0.644 and for hydrogen fractions up to 20%. The area-weighted average NO_x, CO and HC emissions at burner exit are calculated and shown in Table 6. Generally, results show that lean operating conditions are favorable for low emissions. Results show that NO_x and CO emissions have maximum values of 2 and 4 ppm at burner exit, respectively. NO_x emissions are shown to be reduced by adding 5% hydrogen fraction recording 0 ppm. The reason for this low value is that operating at very

lean conditions resulted in reducing flame temperatures ($AFT = 1750$) which decreases thermal NO. On the other hand, adding hydrogen decreases N and HCN radicals which results in NO formed by prompt mechanism [127], [283], [284]. CO emission values are considered very low because of very lean operating conditions which decrease the dissociation of CO_2 in products. CO emissions are reduced by 1 ppm when the HF increased to 10 % with negligible effect at higher HF values. On the contrary of literature, HF increase leads to a noticeable increase in unburned HC emissions. Because of the undesired effect of the momentum of hydrogen jets on the CH_4 flame, a part of it is shifted downstream, leading to an increase in HC emissions. This shows at HF = 5% with a minor increase at 10%. After 10% HF, HC emissions are almost constant.

The effect of equivalence ratio on flame emissions is also studied. The results are taken at constant HF of 5%. The emissions are measured in axial and radial direction (at distance equals 228.6 mm from quartz tube exit) and shown in Figure 40. Also, the area-weighted average NO_x, CO and HC emissions at burner exit are calculated and shown in Table 7. Generally, equivalence ratio has a dominating effect on flame emissions, as changing it leads to a considerable change in the flame temperatures. At burner exit, NO_x emissions are 0 up to $\phi_{overall} = 0.644$ and then it increases to 4, 14 and 17 ppm as we increase $\phi_{overall}$ to 0.73, 0.759 and 0.79 respectively. The rapid increase in NO_x emissions is because of increasing the flame temperature which motivates thermal NO_x formation. For axial distribution, no NO_x emissions are recorded for all points of $\phi_{overall} = 0.563$ and 0.644. When $\phi_{overall}$ increased to 0.73, NO_x increases to 4 ppm and increases gradually as we go down inside the combustor until it reaches a value of 6 ppm because of the effect of residence time, i.e., more time to generate more NO_x at the elevated temperature. For axial

distribution at 228.6 mm depth inside the quartz tube, the NO_x emissions are almost constant and decrease by 1 ppm near the quartz tube wall due to the cooling effect of the outer surface. At very low equivalence ratios near blowout ($\phi_{\text{overall}} = 0.563$), CO emissions are very high and fluctuating with high frequencies and values due to the instability in the flame. This can be appeared clearly on the high value of CO at burner exit at $\phi_{\text{overall}} = 0.563$ and in axial and radial distribution for CO emissions. By increasing the equivalence ratios and flame becomes more stable, CO emissions decrease as well as their fluctuations in axial and radial directions. For $\phi_{\text{overall}} = 0.644$ and 0.73, CO emissions are almost having the same values and distribution along the combustor with values nearly equal to 3 ppm. By increasing the equivalence ratios more up to 0.79, CO emissions decreased to 0 ppm. For HC emissions, equivalence ratio also has the dominant effect on their values. At lower equivalence ratios near blowout, the flame is unstable which reflect on the higher values and fluctuations for HC emissions. By increasing the equivalence ratios, flame become more stabilized and HC emissions decreased.

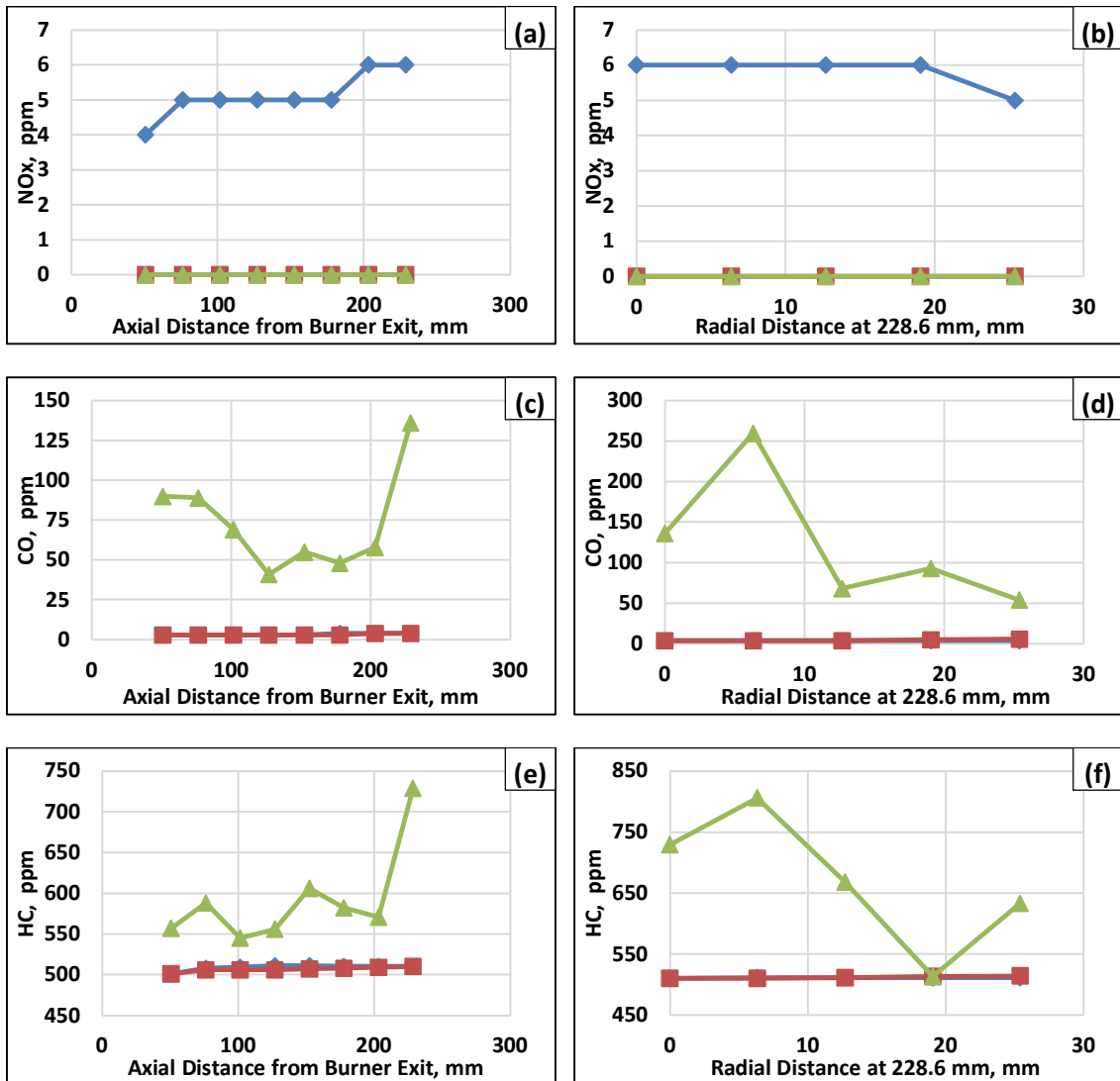
Table 6: Effect of HF at constant $\phi_{\text{overall}} = 0.644$ on average NO_x, CO and HC (unburned HCs) emissions at burner exit.

HF %	Emissions			
	O ₂	CO	NO _x	HC
	%	ppm	ppm	ppm
0	8.3	4	2	465
5	8.4	4	0	504
10	8.3	3	0	513
15	8.3	3	0	515
20	8.3	3	0	510

Table 7: Effect of ϕ_{overall} at constant HF = 5% on average NO_x, CO and HC (unburned HCs) emissions at burner exit.

ϕ_{overall}		emissions
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	AFT	O ₂	CO	NO _x	HC
		%	ppm	ppm	ppm
0.563	1600	9.96	90	0	557
0.644	1750	8.35	3	0	501
0.730	1900	6.41	3	4	501
0.759	1950	5.66	0	14	406
0.79	2000	4.97	0	17	435



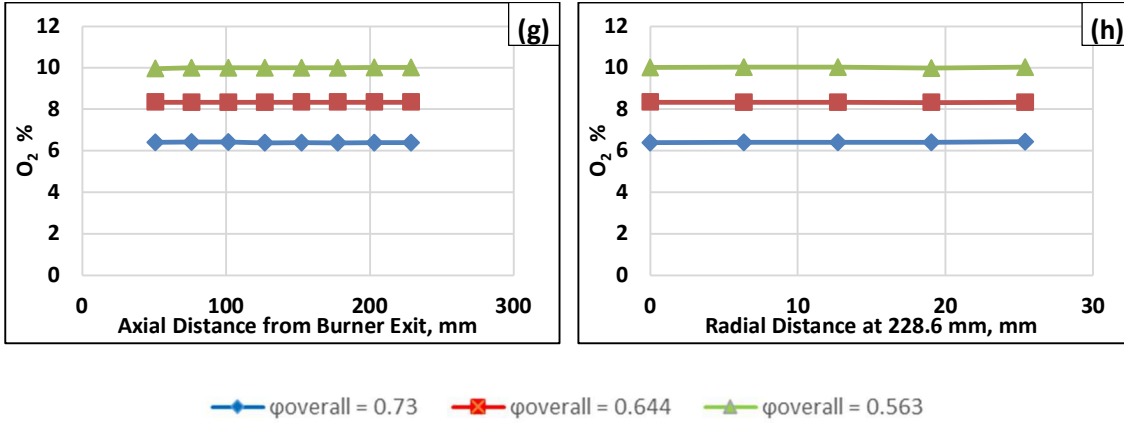


Figure 40: Effect of overall equivalence ratio (ϕ_{overall}) at constant HF=5% on NOx emissions [(a) axially, (b) radially], CO emissions [(c) axially, (d) radially], HC emissions [(e) axially, (f) radially], and oxygen percentage in combustion products [(g) axially, (h) radially].

CHAPTER 5

Numerical Results and Discussion

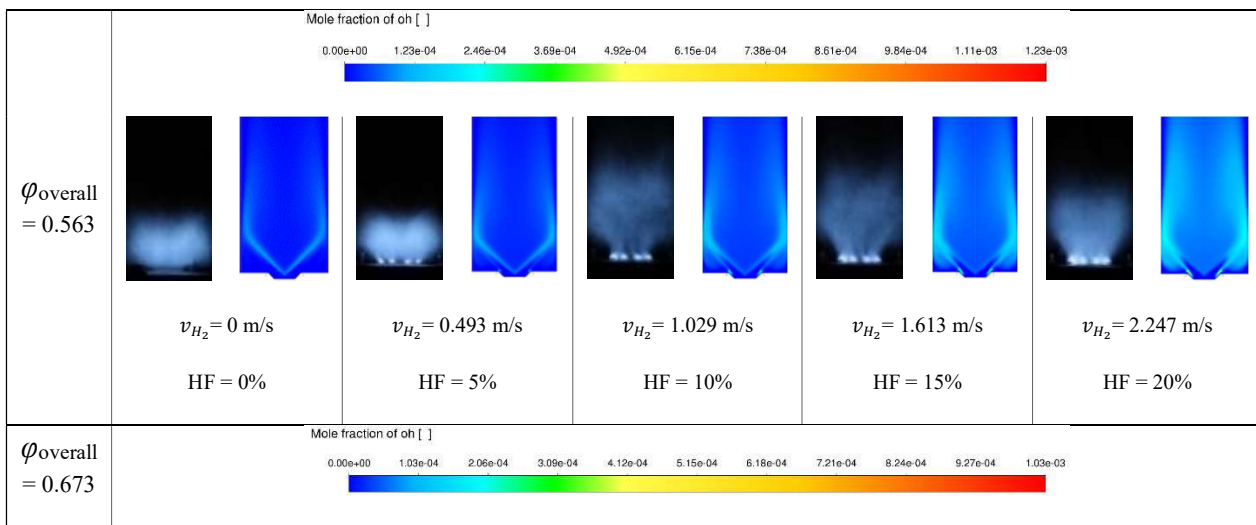
5.1 Experimental/Numerical Flame Structure

Figure 41 shows the comparison between the experimental and numerical flame image for $\phi = 0.563$ and 0.673 across HFs from 0 to 20%. The numerical flame shape is depicted by OH contour plots. The following points are revealed,

- The speed of the hydrogen jets increases with higher fractions of hydrogen and equivalence ratios, owing to the augmented injection of hydrogen and increased combustion of the fuel, including hydrogen, at elevated equivalence ratios. The emergence of hydrogen jets at the flame base heightens the reaction kinetics, resulting in a brighter appearance and enhanced stabilization of the surrounding flame. This effect is evident in both numerical simulations and experimental images. Experimental flame images clearly reveal a shaded region adjacent to the burner wall and below the flame base, indicating the quenching effect attributable to the wall's cooling mechanism. This localized quenching phenomenon hinders any reactions within the narrow region adjacent to the burner wall.
- At a low equivalence ratio ($\phi_{\text{overall}} = 0.563$), the flame adopts shapes influenced by two competing forces. The first force involves a swirling motion facilitated by the increasing HRR (HF), contributing to the stabilization of the flame near the base of the combustor, resulting in a more concise and compact appearance. The second force corresponds to the escalating momentum of the non-swirling

hydrogen jets due to the growing hydrogen fraction, causing the flame to disperse and spread out, thereby elongating and taking on a confined shape. When no hydrogen fraction (HF) is present, the swirling effect serves to stabilize the flame. With the addition of a 5% HF, there is an observable increase in the reaction kinetics of the flame, manifesting as a brighter flame, leading to enhanced stability and a shortened flame. Upon introducing a 10% HF, the speed of the hydrogen jets reaches almost 1 m/s. The high momentum of the hydrogen leads to flame dispersion, resulting in a longer and less intense flame. Upon further addition of a 15% HF, the heightened reaction kinetics of the hydrogen surpass its momentum effects, causing the flame to anchor itself around the hydrogen jets. Consequently, the flame becomes more condensed, shorter, and brighter. This effect is further intensified by the introduction of a 20% HF.

- Under high equivalence ratio conditions ($\phi_{\text{overall}} = 0.673$), the flames exhibit more intense and condensed characteristics, maintaining their shape with greater vigor. The increased brightness and prominence of swirling effects suggest enhanced reactivity of the fuel mixture and higher reaction kinetics.



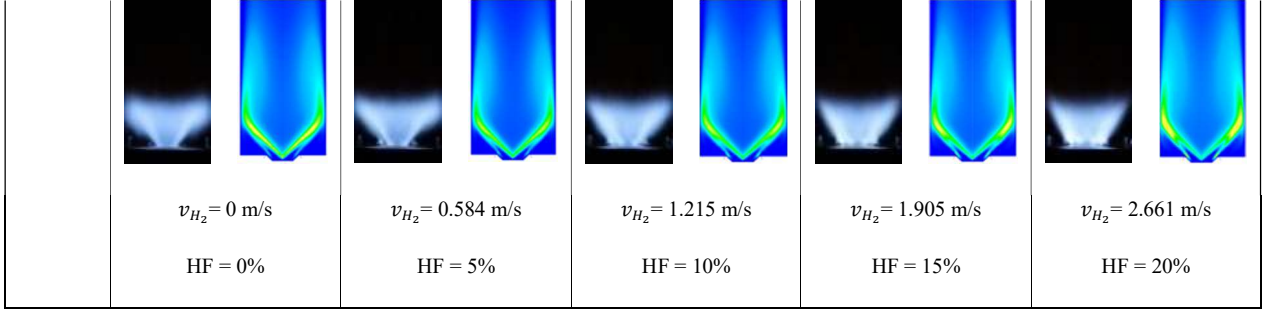


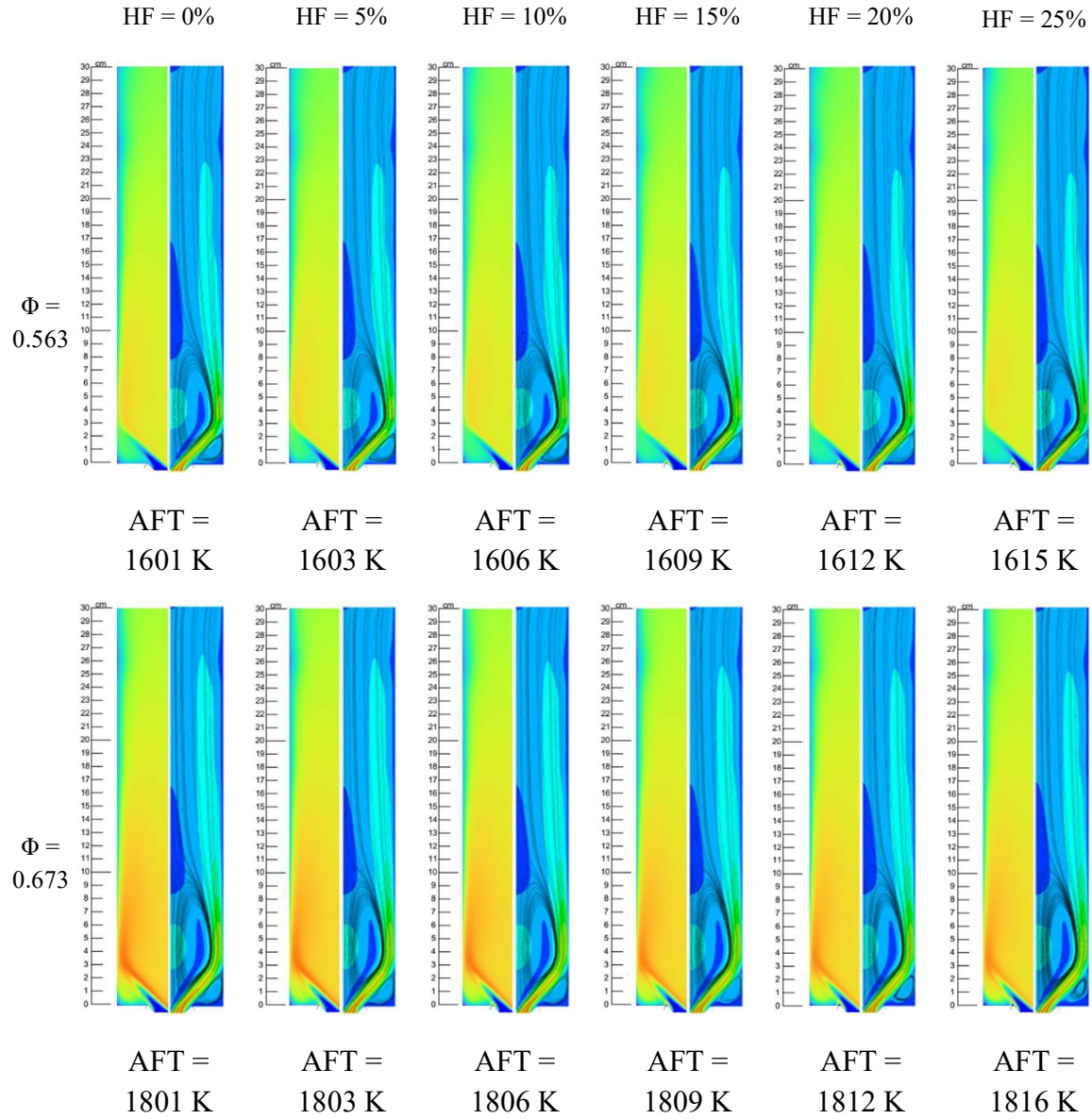
Figure 41: Experimental versus numerical flame (OH concentrations) images for $\phi_{\text{overall}} = 0.563$ and 0.673 across hydrogen fractions from 0 to 20% along hydrogen velocity jets.

5.2 Temperature/Velocity Contours.

Figure 42 presents temperature fields, velocity contour fields, and AFT for the combustor, illustrating the influence of both equivalence ratio and hydrogen fraction (HF). Additionally, Figure 43 displays centerline temperatures for the combustor.

The findings indicate that temperature is mainly influenced by the equivalence ratio, with minimal impact from increasing hydrogen fractions. A higher equivalence ratio results in an increased fuel-to-air ratio, leading to heightened reaction rates and temperatures. On the other hand, an increase in hydrogen fraction contributes to a localized temperature rise around the hydrogen jets, but a lower overall flame temperature. This is because a higher hydrogen fraction reduces the primary equivalence ratio for the CH_4 -air mixture, to keep the overall equivalence ratio constant. This reduction lowers the overall flame temperature. This effect is more pronounced with a higher overall equivalence ratio, as more CH_4 fuel is replaced by hydrogen fuel, and the primary equivalence ratio decreases more (as shown in Figure 44), which leads to a larger decrease in flame temperature. These observations suggest that the configuration employed in this study represents an effective approach for introducing hydrogen without causing a simultaneous elevation in flame temperature. Such

a strategy holds promise for mitigating flame emissions, particularly reducing NO_x emissions associated with higher flame temperatures.



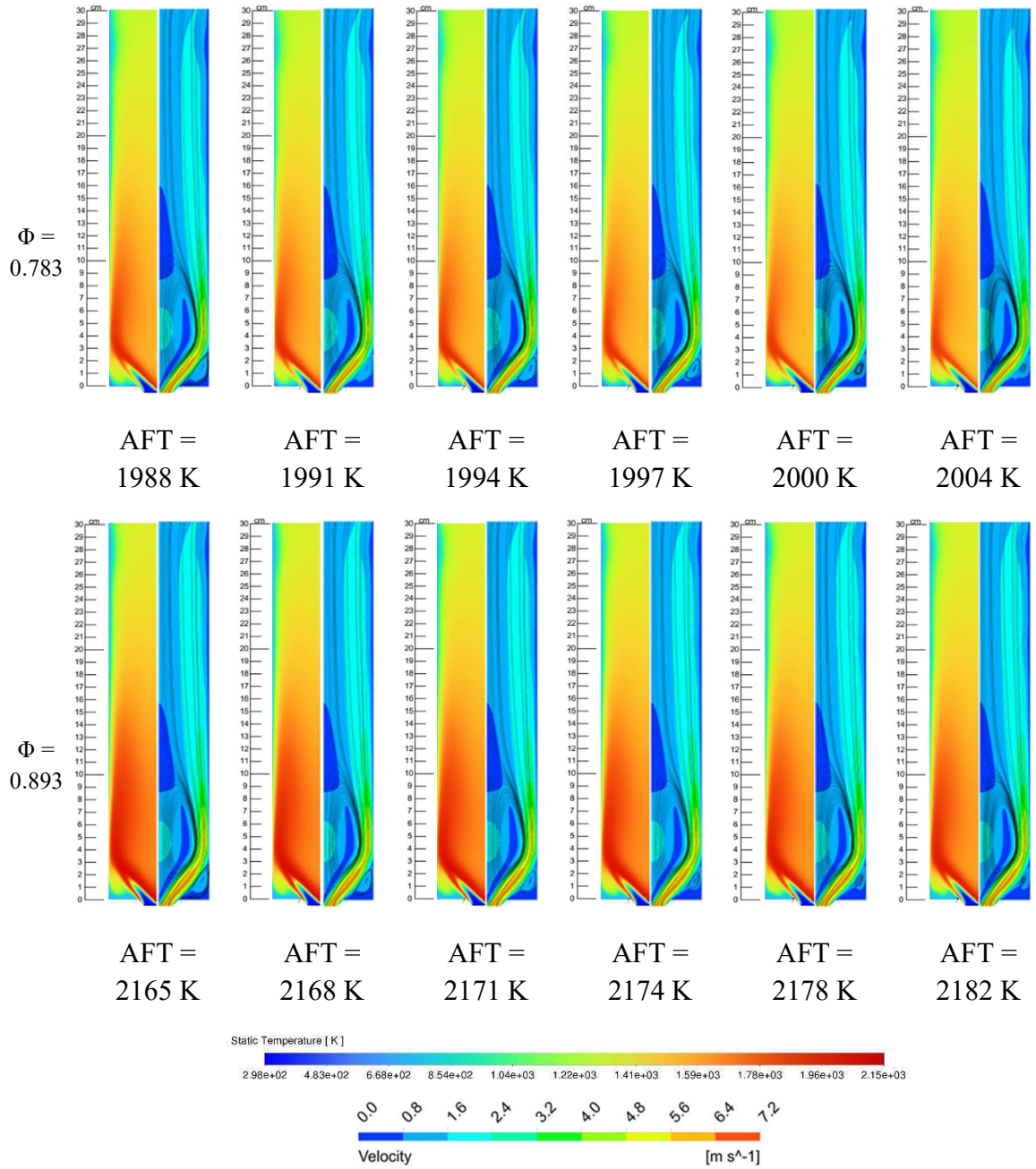


Figure 42: The effect of overall equivalence ratio and hydrogen fraction on Temperature field (left) / velocity contours field and streamlines (right).

The velocity field within a combustor plays a pivotal role in shaping the combustion dynamics, enhancing mixing efficiency, and influencing the overall performance of the combustion system. In order to isolate the impact of the inlet velocity on the combustion characteristics of the combustor, a consistent inlet velocity of 6 m/s is maintained across

all investigated cases. Given that the combustor is a swirler combustor, the induced swirling motion manifests distinct zones of recirculation, as depicted in the velocity field. The IRZ is near the central axis, where gases recirculate before entering the combustion zone. The ORZ is farther away and involves the recirculation of combustion products. An augmentation in the equivalence ratio corresponds to heightened reaction rates and temperatures within the combustor. This temperature elevation contributes to an expansion in the volume of combusted gases and an increase in velocity within the combustor. Furthermore, an escalation in the equivalence ratio results in the enlargement of the IRZ. Conversely, variations in hydrogen fractions within the combustor did not yield discernible changes in the velocity field.

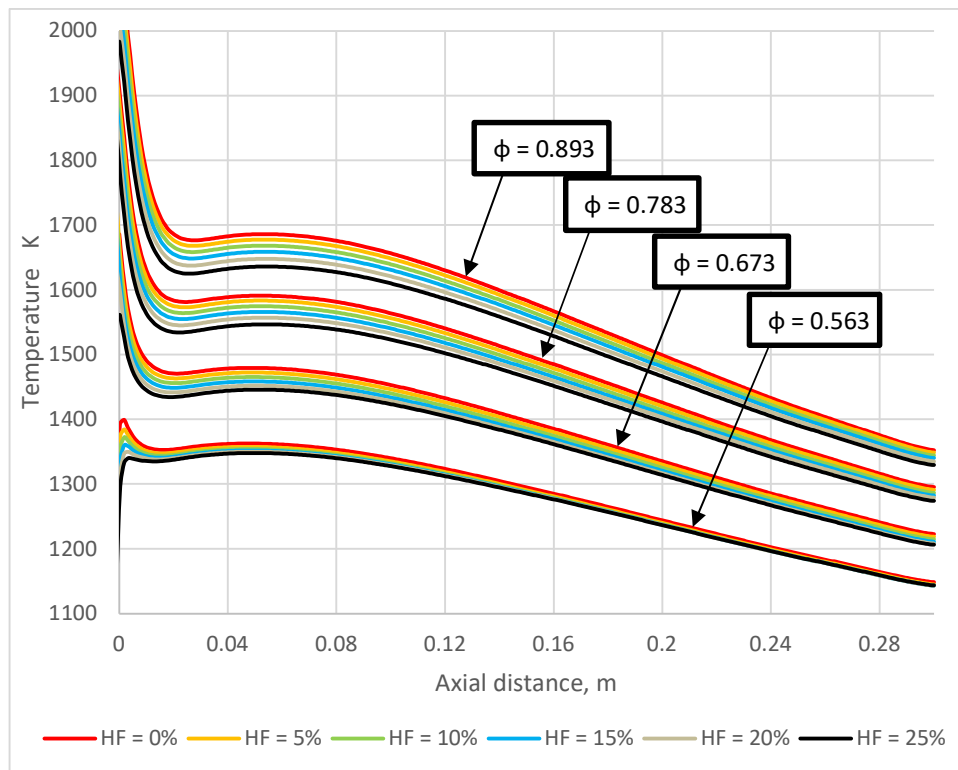


Figure 43: The effect of overall equivalence ratio and hydrogen fraction on axial temperatures at the center line.

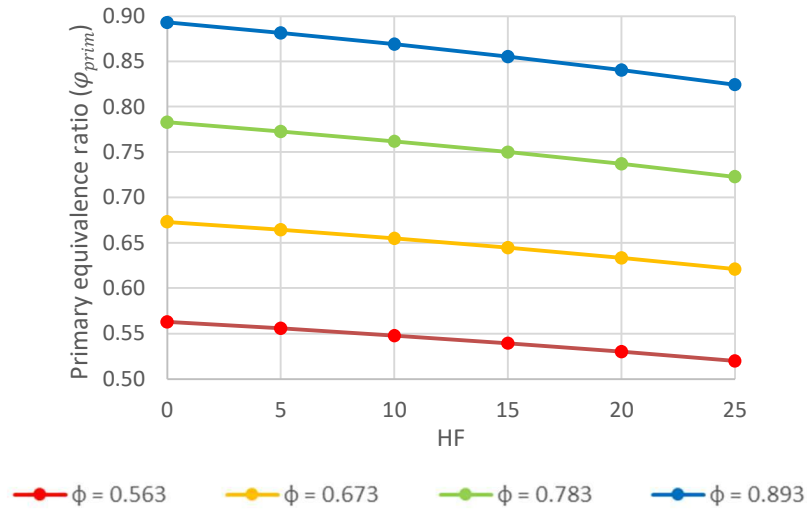
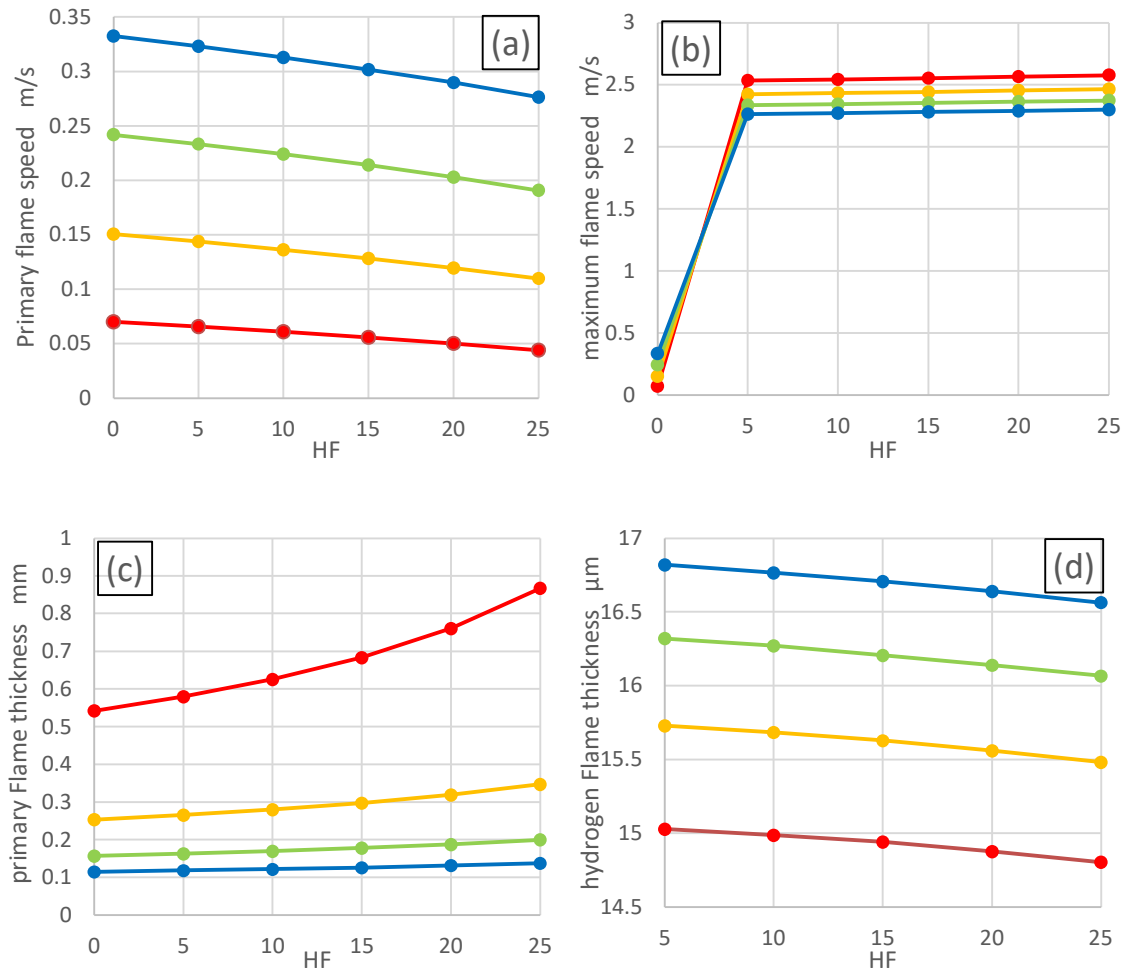


Figure 44: Primary equivalence ratio variation with hydrogen fractions.

5.3 Flame Speed, Thickness and Strain Rate



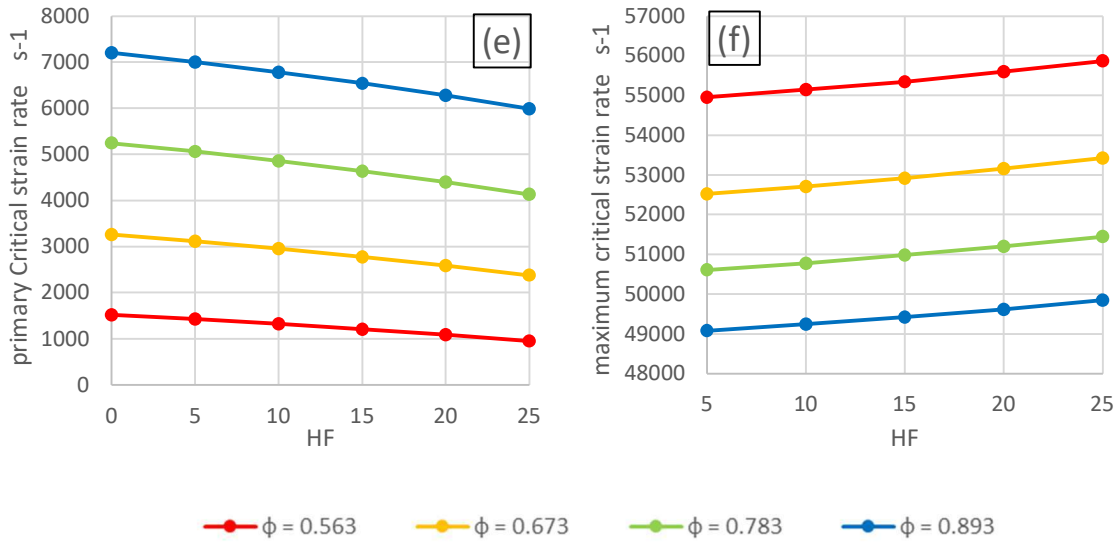


Figure 45: The effect of overall equivalence ratio and hydrogen fraction on Flame speeds, Flame thickness and Critical strain rate.

This investigation additionally highlights the impact of hydrogen enrichment and equivalence ratio on flame speeds, flame thicknesses, and critical strain rates concerning the stratified H_2/CH_4 flame. Owing to the presence of stratification and the heterogeneous nature within the flame, two distinct flame fronts are identified within the flame. Consequently, two corresponding values are determined for each of the aforementioned parameters. The first set of values pertains to the primary mixture, which is the main flame in the combustor. The second set of values represents the maximum values observed across the entire domain, specifically at the hydrogen flame front.

The non-uniform flame speed across the entire domain is a direct consequence of the stratification present within the combustor. As illustrated in Figure 45a, the flame speed for the primary mixture varies with both the equivalence ratio and the hydrogen fraction (HF). It is evident that an increase in the equivalence ratio results in a corresponding increase in the flame speed. This can be attributed to the higher availability of fuel for the combustion process at elevated equivalence ratios. The surplus fuel facilitates a more

robust and accelerated combustion, thereby boosting the flame speed. Furthermore, the surplus fuel at higher equivalence ratios contributes to an increased release of heat during combustion. This additional heat elevates the temperature within the reaction zone, fostering swifter chemical reactions and consequently raising the flame speed. Conversely, the introduction of HF to the primary flame leads to a reduction in the primary flame speed. This reduction occurs because the increased hydrogen fractions, while maintaining a constant overall equivalence ratio, effectively consume a portion of the primary fuel. This fuel consumption leads to a reduction in the primary equivalence ratio (as depicted in Figure 44) and subsequently results in a decrease in the primary flame speed.

Figure 45b illustrates the maximum flame velocity observed near the hydrogen jet. This notably high flame speed is attributed to the distinctive nature of hydrogen fuel, known for its exceptionally high flame speed. At a 0% hydrogen fraction (HF), the flame speed aligns with that of the primary flame. However, the introduction of hydrogen leads to a substantial increase in the maximum flame speed, reaching a value close to 2.5 m/s, which is consistent with hydrogen flame speeds reported in the literature [82], [83]. It's noteworthy that the maximum flame speed is most pronounced at the leanest equivalence ratio and diminishes as the equivalence ratio increases. This behavior can be attributed to the availability of oxygen under lean conditions, which facilitates improved mixing of the hydrogen non-premixed jets with oxygen, consequently leading to higher flame speeds. Conversely, at higher equivalence ratios, the excess fuel may not have adequate oxygen for complete combustion. This limitation can result in incomplete combustion, subsequently reducing the hydrogen flame speed.

As illustrated in Figure 45c, the primary flame thickness, calculated based on the primary flame speed, follows an inverse relationship with the flame speed. In essence, a higher flame speed implies a more rapid occurrence of combustion reactions. This accelerated progression through the unburned mixture leads to a thinner flame front, consequently reducing the flame thickness, and vice versa. Consequently, an increase in the equivalence ratio corresponds to an increase in the flame speed, resulting in a reduction in the primary flame thickness. However, under lean conditions, the impact of hydrogen addition becomes more pronounced, leading to a substantial increase in the flame thickness. This phenomenon can be attributed to the fact that under these lean conditions, the flame struggles to stabilize between the IRZ and ORZ, as depicted in Figure 46. Consequently, the introduction of hydrogen with high momentum and velocity leads to dispersion of the flame, as shown in Figure 41. This dispersion leads to a cooler flame with a larger flame thickness. At higher equivalence ratios, the impact of hydrogen addition diminishes, resulting in a comparatively smaller increase in the flame thickness despite higher hydrogen fractions. Figure 45d presents the calculated hydrogen flame thickness based on the maximum flame speed observed within the investigated domain. Evidently, the significantly high flame speeds of hydrogen fuel contribute to a notably smaller flame thickness in comparison to that of the primary mixture.

Furthermore, critical strain rates have been computed for both the primary mixture and the hydrogen jet (maximum value), as illustrated in Figure 45e and Figure 45f, respectively. The notion of a critical strain rate is intimately tied to understanding the limitations of flame propagation in turbulent combustion. It represents the rate at which the flame is subjected to stretching, reaching a point where it can no longer sustain the necessary

chemical reactions for continuous propagation, ultimately leading to flame extinction. The critical strain rate in combustion plays a pivotal role in ascertaining the boundaries of flame stability and the initiation of flame extinction under varying flow conditions. Comprehending this parameter is of paramount importance in the design and optimization of combustion systems, particularly in the development of engines and GTs. Engineers, by taking the critical strain rate into account, can ensure that the combustion process remains stable and efficient, averting issues such as flame quenching, flashback, or combustion instability. Maintaining the flame within the confines of the critical strain rate is indispensable for achieving dependable and consistent combustion performance in practical applications. Generally, a higher critical strain rate indicates greater resistance of the flame to distortion and quenching under turbulent conditions. This attribute can be advantageous in upholding stable combustion, especially in environments where turbulence prevails, such as certain types of engines or industrial combustion systems.

The dependence of the critical strain rate on both the equivalence ratio and flame speeds is demonstrated in Figure 45e and Figure 45f. Notably, a low equivalence ratio is associated with a corresponding decrease in the critical strain rate. When operating under lean conditions, the surplus air can prompt a reduction in the flame temperature, rendering the flame more susceptible to the disruptive effects of turbulence. This heightened susceptibility increases the likelihood of flame distortion or even extinguishment, making it notably more challenging to sustain stable combustion compared to conditions with higher equivalence ratios. Furthermore, an increase in the flame speed contributes to a corresponding elevation in the critical strain rate. This relationship arises from the accelerated advancement of the flame front associated with a faster flame speed. As the

flame front progresses more rapidly, it is more prone to heightened levels of stretch and distortion induced by the turbulent flow in its vicinity.

5.4 Flame Progress Variable / Product Formation Rate

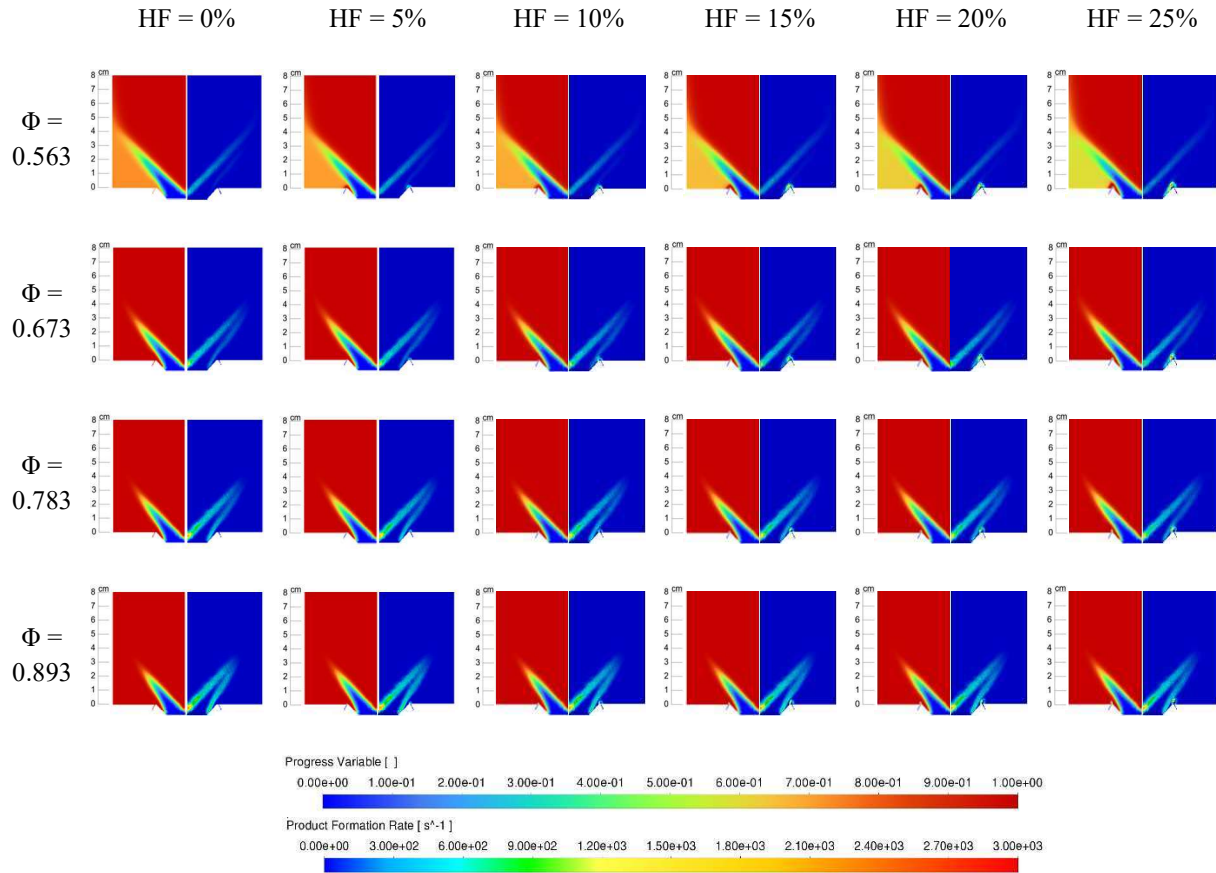


Figure 46: The effect of overall equivalence ratio and hydrogen fraction on Progress variable (left) / product formation rate (right).

The progress variable holds significant relevance as a metric for the characterization of flame thickness and the assessment of the extent of completion of the combustion reaction, thereby serving as an indicator of the kinetics of the reaction. It aids in visualizing the transformation from an initial mixture of unburnt reactants to a fully consumed product state. Additionally, the product formation rate (PFR) pertains to the velocity at which diverse chemical compounds are generated during the progression of the combustion

process. It effectively operates as a marker for identifying the stabilized location of the flame within the combustion system. The rate at which products evolve in a specific region offers valuable insights into the efficacy of the combustion process and the intricate distribution of chemical reactions transpiring within the flame. In a stabilized flame, the product formation rate tends to exhibit heightened levels in the areas where the combustion process is actively underway. This phenomenon corresponds to the regions characterized by an augmented concentration of reactants, effective intermixing of fuel and oxidizer, and optimal conditions conducive to sustained combustion. Figure 46 delineates the impact of the equivalence ratio and hydrogen fractions on the progress variable and PFR, providing a visual representation of their interdependence within the combustion dynamics.

Regarding the progress variable, observations at the leanest equivalence ratio ($\Phi = 0.563$) reveal an incomplete flame at the ORZ owing to the combination of low flame temperature and sluggish reaction kinetics. Introduction of hydrogen under this lean condition facilitates the completion of the flame, particularly around the region of the non-premixed hydrogen jet. Nonetheless, a decrease in the progress variable in the ORZ can be attributed to the diminished primary equivalence ratio resulting from the addition of hydrogen at a constant overall equivalence ratio, leading to a leaner primary flame and decelerated reaction kinetics. At higher equivalence ratios, the discernible impact of heightened hydrogen enrichment on the progress variable appears to be minimal, as indicated by the limited disparities in the findings. However, an increase in the equivalence ratio results in a slight reduction in flame length, indicating the anticipated acceleration of reactions.

As observed, the region of chemical reactions is situated between the inner and outer shear layers, where the flame finds stabilization on both layers. At low equivalence ratio, the

product formation rate (PFR) demonstrates a notable increase on the inner thin layer, suggesting that the IRZ stabilizes the flame with a negligible effect of the ORZ at lower equivalence ratio. Moreover, by increasing the hydrogen fraction (HF) in the flame, the PFR exhibits an enhancement around the non-premixed hydrogen jets, which act as stabilizing aid factors for the flame, enabling the production of more radicals. At higher equivalence ratio, the PFR displays an increment in the thinner inner and outer shear layers, indicating more intense and compact flames that are stabilized by both the IRZ and the ORZ, with the IRZ having an increasing effect in stabilizing the flame. Increasing the amount of fuel in a combustion process results in a higher PFR due to the elevated concentration of fuel molecules available for reaction with the oxidizer. This increase in fuel concentration facilitates more collisions between fuel and oxidizer molecules, resulting in a faster rate of product formation. Additionally, the higher fuel input contributes to greater heat release, leading to elevated temperatures that further accelerate the reaction rates and increase the product formation rates. Also, increasing the HF in the flame leads to an increase in PFR around the non-premixed hydrogen jets, which act as supportive elements for flame stabilization. However, at the highest equivalence ratio, the PFR becomes highest on both the outer and inner shear layers of the primary flame, even with increasing the HF up to 25%, which indicates that the effectiveness of hydrogen addition in producing more radicals and stabilizing the flame becomes diminished at higher equivalence ratio.

5.5 Species Distributions

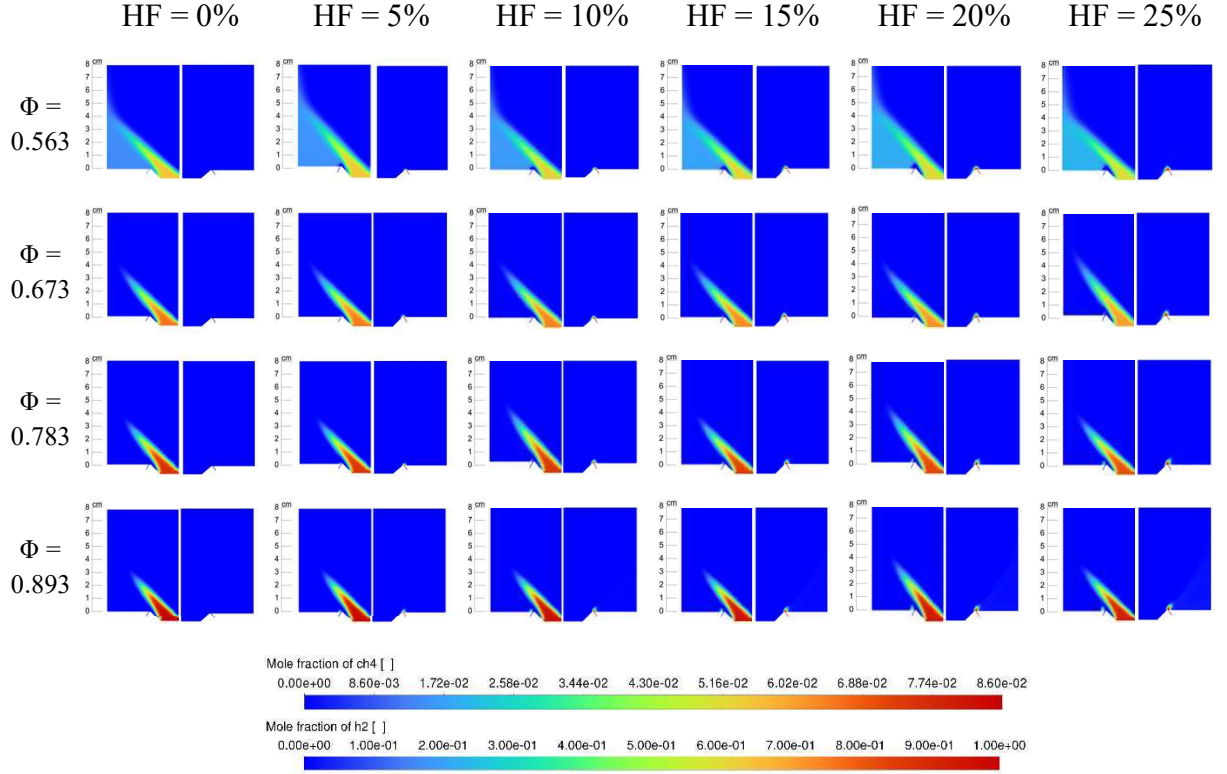
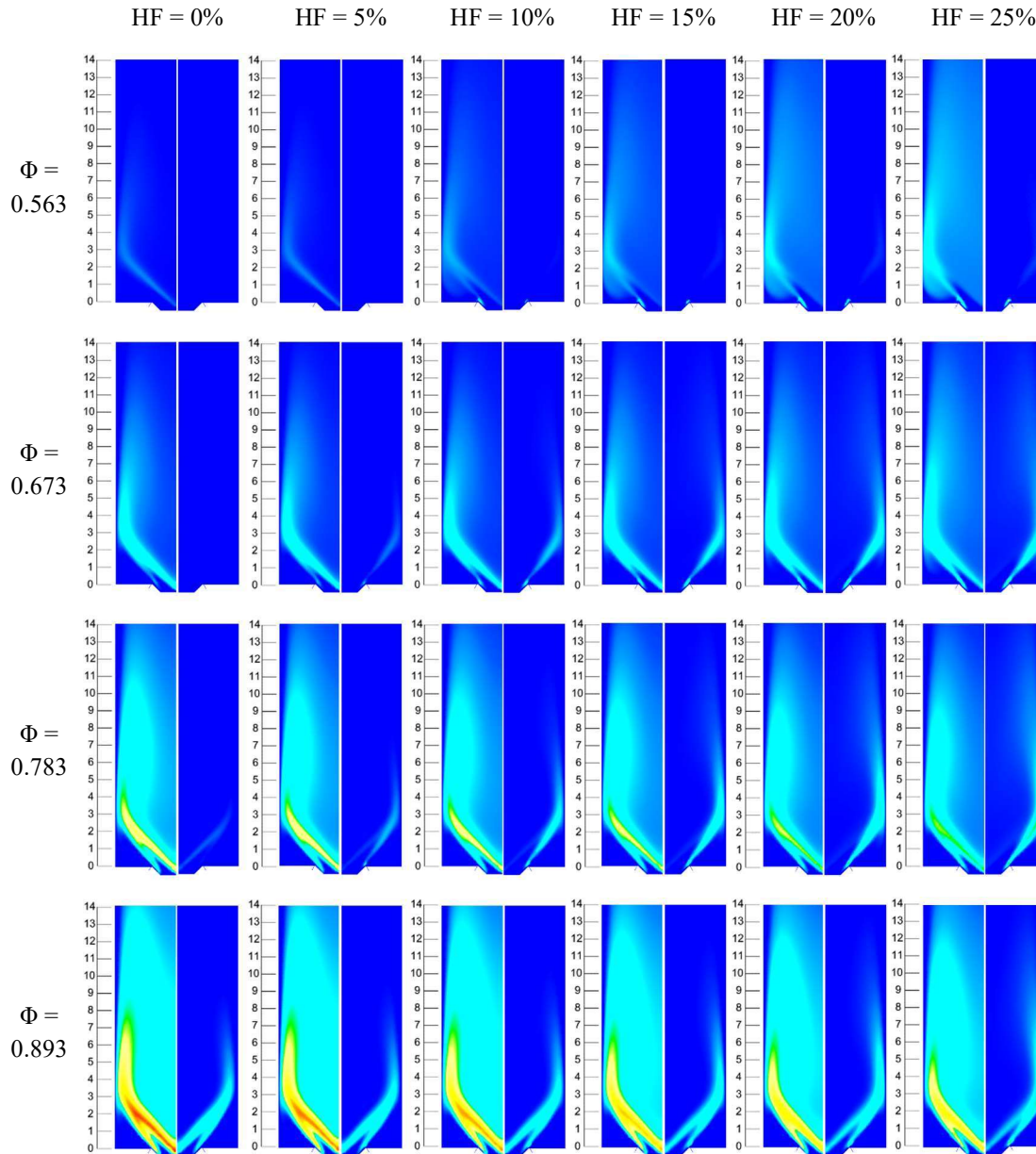


Figure 47: The effect of overall equivalence ratio and hydrogen fraction on mole fraction of CH₄ (left)/H₂ (right).

Figure 47 illustrates the mole fractions of CH₄ and hydrogen fuels within the combustor under varying equivalence ratios and hydrogen fractions (HF). An elevation in equivalence ratio results in an increased CH₄ mole fraction in the flame, attributable to the heightened fuel-to-air ratio. Under extremely lean conditions, the flame stabilizes within the IRZ, causing CH₄ to disperse into the ORZ and consequently increasing its mole fraction in this region. The augmentation of the equivalence ratio sharpens the inner and outer shear layers, denoting the flame fronts. Additionally, an increase in equivalence ratio leads to a reduction in flame height, rendering it more compact. Conversely, an increase in HF results in a decrease in CH₄ mole fraction as a portion of the fuel transitions from CH₄ to hydrogen, causing a decline in the primary equivalence ratio. Notably, at lean conditions, HF significantly influences the flame shape. The heightened velocity of hydrogen jets, induced by increasing HF, leads to flame dispersion, elevating the concentration of CH₄ in the ORZ.

This effect diminishes at higher equivalence ratios, where the flame strengthens and stabilizes by both IRZ and ORZ. Regarding HF, higher equivalence ratios contribute to an increase in hydrogen volume flow rates, leading to elevated velocities of hydrogen jets and a more substantial penetration of hydrogen into the mixture.



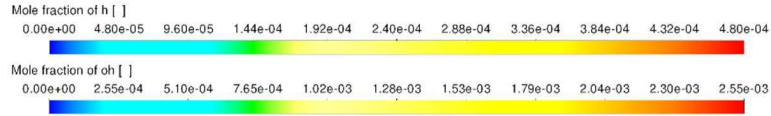


Figure 48: The effect of overall equivalence ratio and hydrogen fraction on mole fraction of OH (left) /H (right) radicals.

In Figure 48, the mole fractions of OH and H radicals within the flame are displayed in relation to variations in both equivalence ratio and hydrogen fraction (HF). An increase in equivalence ratio leads to a rise in OH radicals, attributed to two factors [285]–[287]. Firstly, the elevated equivalence ratio results in a greater presence of fuel in the mixture, providing more hydrogen atoms for the formation of OH radicals. Secondly, the higher equivalence ratio corresponds to an increased flame temperature, enhancing the rate of oxidation reactions responsible for OH radical production. On the other hand, an augmentation in HF under lean conditions results in an increase in OH radicals, particularly in the region around the hydrogen jets. This can be explained by the abundance of H and O moles and elevated temperatures near the hydrogen jet, fostering the dissociation of water molecules and, consequently, augmenting OH formation. However, at higher equivalence ratios, the positive impact of increasing HF on OH radical formation diminishes due to a reduction in flame temperatures.

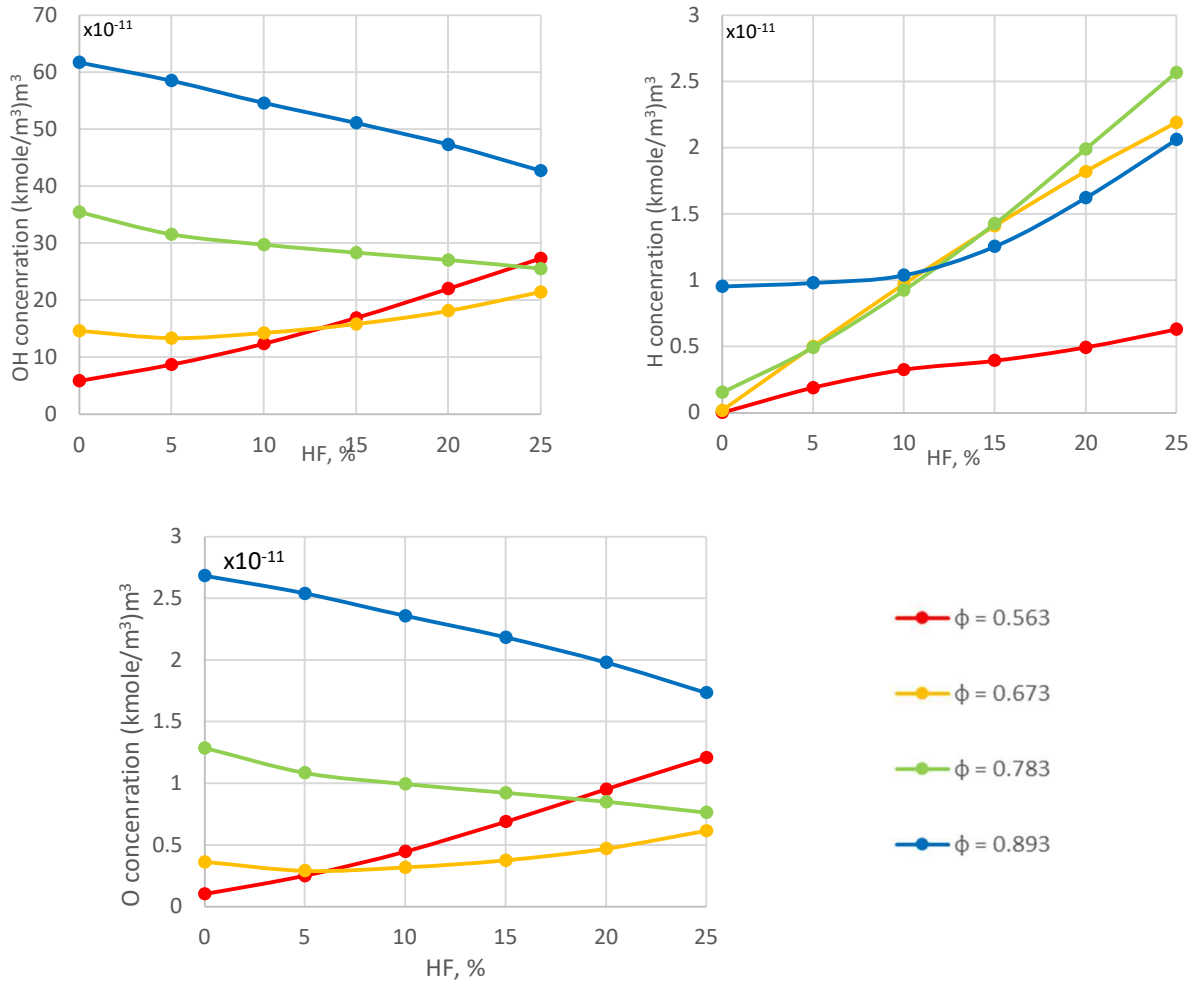
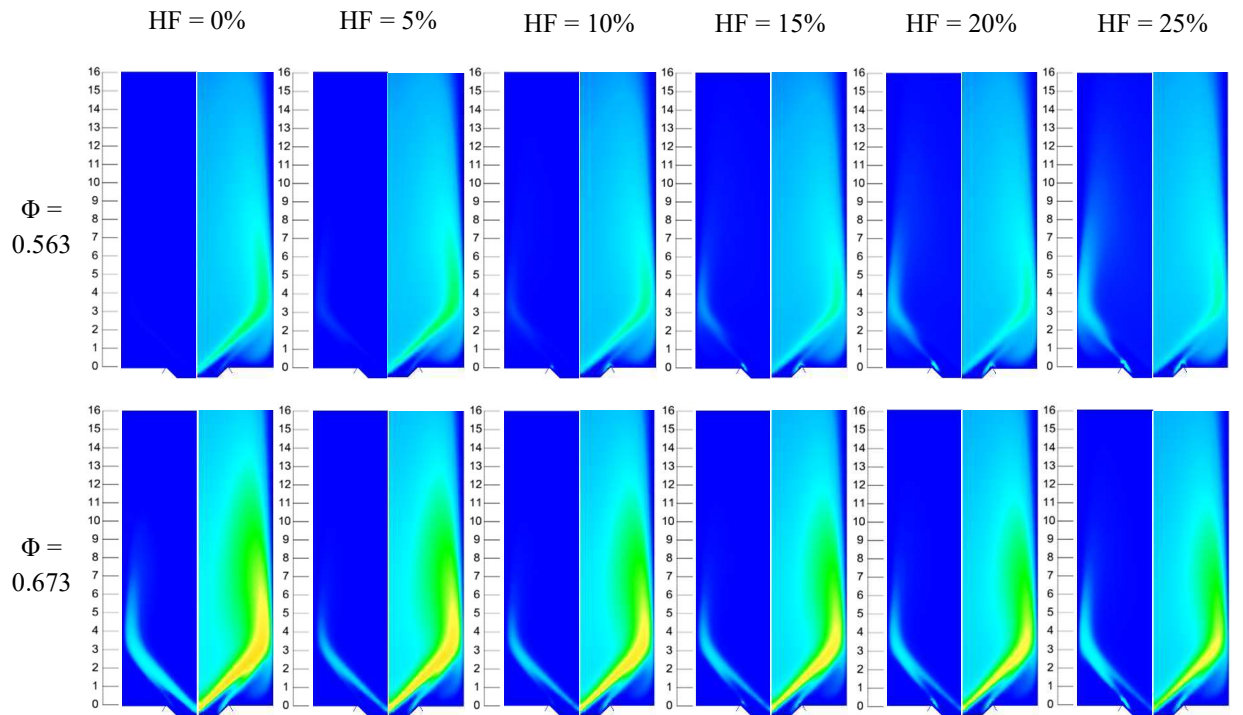


Figure 49: OH/H/O integral concentration over combustor volume with different overall equivalence ratios and hydrogen fractions.

The formation of H radicals is influenced by several factors, including the type of fuel, equivalence ratio, and flame temperature. Fuels with higher hydrogen content and elevated flame temperatures tend to yield greater concentrations of H radicals. The study's findings indicate a general increase in H radicals with both an elevation in equivalence ratio and hydrogen fraction (HF). However, within the range of equivalence ratios from 0.563 to 0.783, no significant alteration in the concentration of H radicals in the flame is observed, increasing equivalence ratio exhibited a stimulating effect on H radical formation with higher HF. Notably, the augmentation of HF is observed to enhance H radicals primarily

in the outer shear layer of the flame, where hydrogen jets interact with the main mixture. At the highest equivalence ratio ($\Phi = 0.893$) and 0% HF, a conspicuous increase in H radicals is evident in both the inner and outer shear layers of the flame. However, with increasing HF, H radicals intensify on the side of the hydrogen jets, corresponding to the outer shear layer, while experiencing a reduction in concentration within the inner shear layer. This reduction is attributed to the decrease in temperature associated with the addition of hydrogen to the main flame, as previously demonstrated. Additionally, Figure 49, depicting the volume integral of OH, H, and O radicals in the combustor, underscores that the formation of OH radicals surpasses both H and O radicals in magnitude.



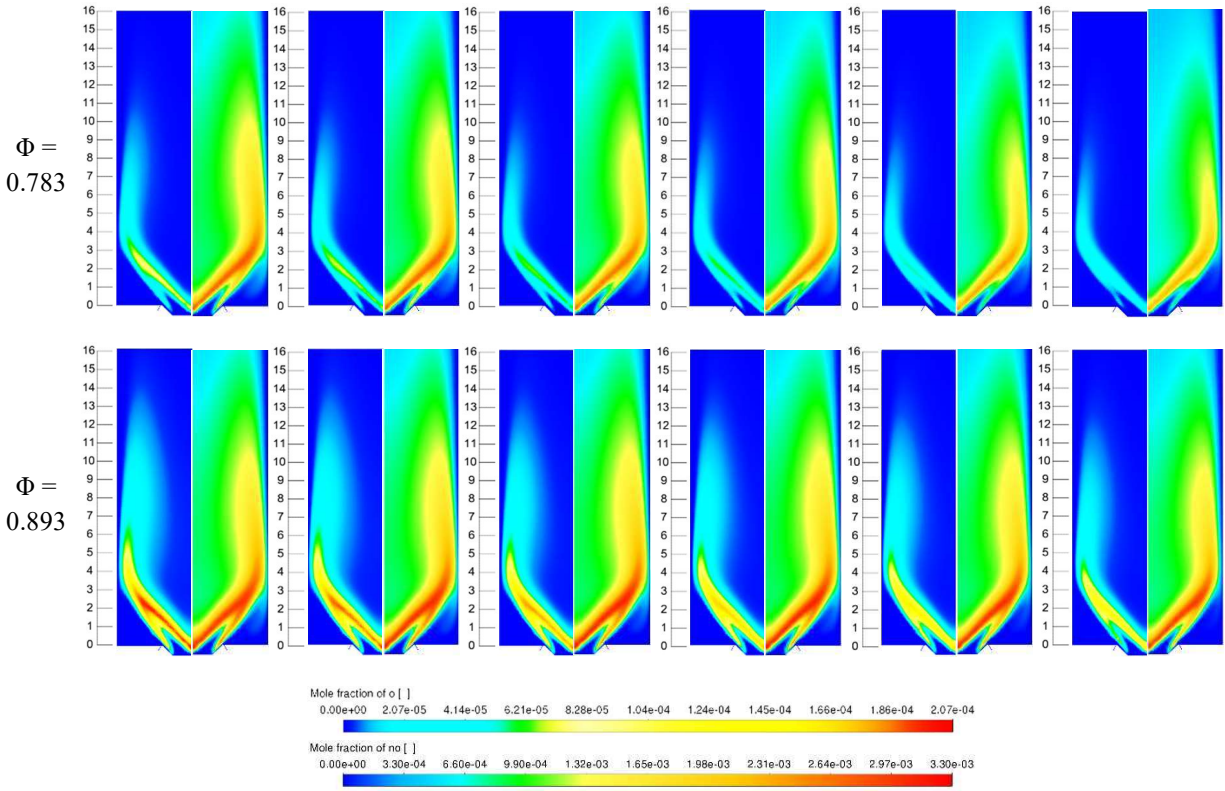


Figure 50: The effect of overall equivalence ratio and hydrogen fraction on mole fraction of O (left)/NO (right) radicals.

The primary contributor to NO_x emissions during combustion is nitric oxide (NO), which is illustrated in Figure 50 within the combustor. An increase in equivalence ratio is observed to correspond with elevated NO emissions in the combustor. This is attributed to the higher equivalence ratio, signifying an increased availability of fuel for combustion. Consequently, there is an augmentation in the HRR and flame temperature, facilitating the thermal dissociation of O₂ molecules into O atoms. These oxygen atoms can then react with N₂ molecules, resulting in the formation of NO [288]. At lean conditions, where the flame is relatively weak, the influence of hydrogen fraction (HF) becomes noticeable. The addition of hydrogen in lean conditions has several effects, including an increase in HC radicals, thereby enhancing the formation of NO_x emissions, particularly prompt NO_x. Additionally, the elevated jet of the flame contributes to the dispersion of NO throughout

the flame, rather than concentrating it in the flame core. Conversely, at higher equivalence ratios, an increase in HF leads to a reduction in NO_x emissions. This is attributed to HF reducing the flame temperature and the presence of HC radicals, which, in turn, diminishes the formation of NO. At the highest equivalence ratio ($\Phi = 0.893$), the influence of HF weakens, demonstrating almost constant NO levels in the flame with minimal reductions observed at HF = 20% and HF = 25%. Despite HF reducing flame temperature and consequently thermal NO_x, the presence of high fractions of HC radicals enhances prompt NO_x formation. These two opposing effects almost balance, with a slight advantage for the temperature effect at higher HF values.

Oxygen radicals (O radicals) are also depicted in Figure 50, showcasing their behavior with varying equivalence ratios and hydrogen fraction (HF). An increase in equivalence ratio is associated with a rise in O radicals, attributed to the heightened availability of fuel for combustion. This increase in fuel availability augments the HRR and flame temperature, fostering the thermal dissociation of O₂ molecules into O atoms. Additionally, elevated equivalence ratios lead to an increased concentration of CO₂ in the products, serving as sources of O radicals through $\text{CO}_2 + \text{M} \rightarrow \text{CO} + \text{O} + \text{M}$ reaction [289].

The behavior of O radicals with increasing HF exhibits a non-monotonic trend. At very lean conditions ($\Phi = 0.563$), increasing HF results in an augmentation of O radicals in the flame, particularly around the hydrogen jets, due to the elevated temperature promoting the thermal dissociation of O₂ molecules. As the equivalence ratio increases to $\Phi = 0.673$, O radicals in the flame increase at the inner shear layer. However, the addition of hydrogen introduces two contradictory changes: a reduction in flame temperature leading to a decrease in O radicals in the main flame, and an increase in O radicals near the hydrogen

jets, contributing to an overall reduction followed by an increase in O radicals in the flame, as depicted in Figure 50. At the highest equivalence ratios ($\Phi = 0.783$ and 0.893), increasing HF leads to a decrease in O radicals in the flame, a consequence of reduced flame temperatures, with this effect becoming more pronounced at the higher equivalence ratio of $\Phi = 0.893$.

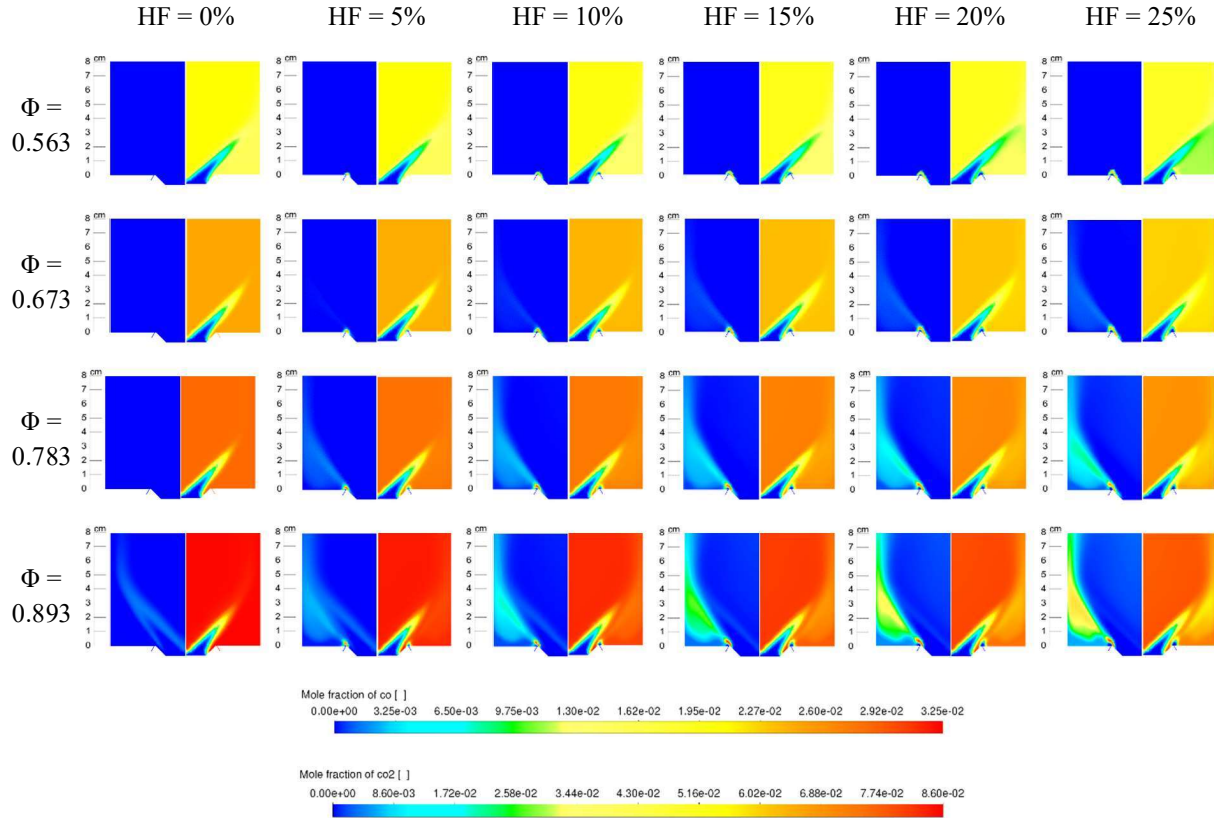
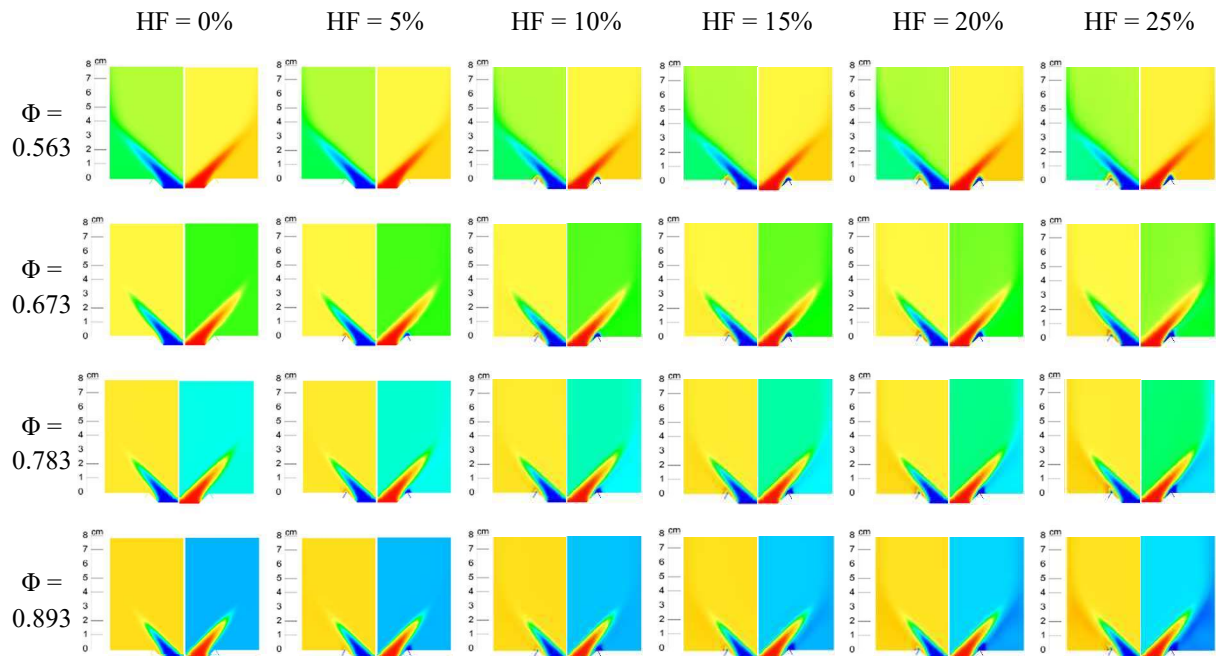


Figure 51: The effect of overall equivalence ratio and hydrogen fraction on mole fraction of CO (left) /CO₂ (right).

Figure 51 presents the formation of carbon monoxide (CO) and carbon dioxide (CO₂) in the combustor concerning varying equivalence ratios and hydrogen fraction (HF). An increase in equivalence ratio corresponds to an elevation in the fuel-to-air ratio, consequently amplifying CO₂ emissions. However, substituting a portion of the main CH₄-air mixture with hydrogen results in a reduction in CO₂ emissions, given hydrogen's status

as a carbon-free fuel. This reduction becomes more pronounced at higher equivalence ratios, where the proportion of CH_4 replaced by hydrogen is increased.

The influence of equivalence ratio on carbon monoxide (CO) formation is negligible due to the lean combustion conditions and the abundance of oxygen in the mixture to support complete combustion. However, at the highest equivalence ratio, a slight increase in CO is observed, attributed to the dissociation of carbon dioxide (CO_2) at elevated flame temperatures. Conversely, an escalation in hydrogen fraction (HF) leads to an increase in CO emissions. This is primarily attributed to the heightened flame temperature of the hydrogen jet, promoting the dissociation of CO_2 in its vicinity, and resulting in CO emissions. Additionally, hydrogen's greater affinity for oxygen, stemming from its faster kinetics and higher reactivity compared to CH_4 , contributes to an elevated production of CO, particularly in the ORZ near the hydrogen jet. This effect becomes more pronounced at higher equivalence ratios, where the decrease in oxygen-to-fuel ratio leads to a substantial increase in CO emissions, particularly noticeable in the ORZ.



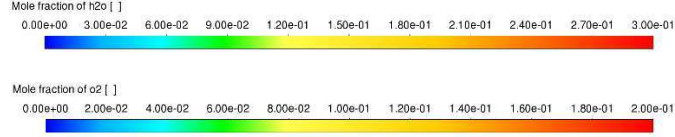


Figure 52: The effect of overall equivalence ratio and hydrogen fraction on mole fraction of H₂O (left)/O₂ (right).

Figure 52 illustrates the mole fractions of H₂O/O₂ within the combustor under various equivalence ratios and hydrogen fractions. An elevation in equivalence ratio induces a reduction in the oxygen fraction, stemming from the increased proportion of fuel relative to the available oxygen. This shift results in a diminished concentration of remaining oxygen within the combustion mixture. Conversely, an increase in hydrogen fraction (HF) renders the primary flame leaner, leading to higher oxygen fractions within the flame. Near the hydrogen jet, the oxygen fraction is diminished as hydrogen, present in non-premixed jets, draws the required oxygen for combustion from the remaining oxygen in the main flame, primarily within the ORZ. Moreover, escalating the equivalence ratio induces a rise in the H₂O fraction within the flame, as increased fuel combustion generates additional combustion products, including CO₂ and H₂O. Increasing HF contributes to a leaner primary flame, yielding lower H₂O fractions within the flame. Nonetheless, in the vicinity of hydrogen jets, and owing to the complete combustion of hydrogen yielding H₂O as a primary product, mole fractions of H₂O experience an increase.

5.6 Emissions

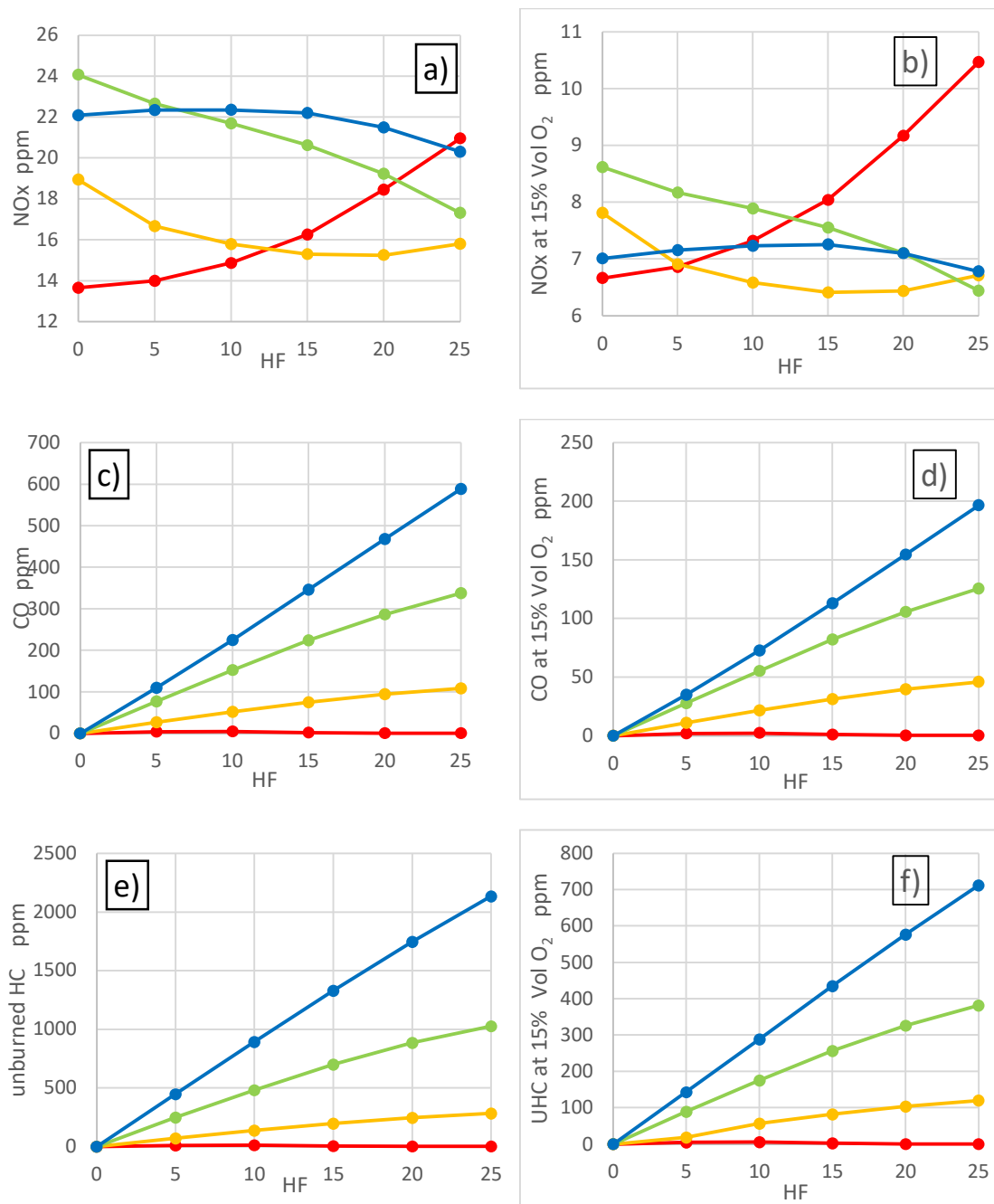
Figure 53 depicts flame emissions (NO_x, CO, CO₂, UHC, and O₂) at the burner exit, based on the average area integral. Specifically, Figure 53a presents NO_x emissions under varying hydrogen fractions (HF) and equivalence ratios. The results illustrate an increase in NO_x emissions with the equivalence ratio, showcasing a non-monotonic trend with HF. The NO_x emissions in the combustion process primarily stem from two sources: Thermal

NO_x, resulting from the dissociation and reaction of atmospheric nitrogen at elevated flame temperatures, and Prompt NO_x, instantaneously formed in the presence of CH radicals. At 0% HF, an escalation in equivalence ratio leads to heightened NO_x emission due to increased fuel availability, elevated HRR, and enhanced flame temperature, facilitating both thermal and prompt NO_x formation. Upon the introduction of hydrogen under lean conditions, prompt NO_x becomes dominant, with an increasing hydrogen fraction resulting in elevated HC radical production that notably enhances NO_x emissions, while the impact on thermal NO_x remains minimal. However, at higher equivalence ratios, augmenting the hydrogen fraction leads to reduced NO_x emissions. This reduction is attributed to the introduction of hydrogen causing a decrease in the main flame temperature, as demonstrated earlier, consequently diminishing thermal NO_x formation. Additionally, the lower temperature diminishes the concentration of HC radicals, suppressing prompt NO_x formation [290]. At the highest equivalence ratio ($\Phi = 0.893$), the influence of hydrogen fraction weakens, showcasing nearly constant NO levels in the flame, with marginal reductions observed at HF = 20% and HF = 25%. Despite HF reducing flame temperature and, consequently, thermal NO_x, the prevalence of high fractions of HC radicals amplifies prompt NO_x formation. These counteracting effects nearly balance, with a slight inclination towards the temperature effect at higher HF values, offering a beneficial configuration for NO_x reduction. Figure 53b depicts the NO_x emissions subsequent to modification to incorporate a 15% oxygen dilution. Despite maintaining a consistent trajectory, post-adjustment of the NO_x emissions reveals that the apical NO_x emissions occur at an equivalence ratio of 0.783.

Figure 53c and Figure 53e illustrate the impact of hydrogen fraction addition and equivalence ratio on CO and Unburned Hydro-Carbons (UHC) emissions. At 0% HF, CO and UHC levels remain nearly constant at a very low value with an increase in equivalence ratio, attributable to the abundance of oxygen facilitating complete combustion. As the hydrogen fraction is introduced, CO and UHC emissions experience an elevation, with a more pronounced effect observed at higher equivalence ratios. This phenomenon can be attributed to hydrogen's higher affinity for oxygen compared to CH_4 , resulting from its faster kinetics and heightened reactivity. The swift combustion characteristics of hydrogen restrict the availability of oxygen for the main flame's combustion, leading to incomplete combustion and the formation of unburned HCs. While the impact of hydrogen on CO and UHC is less noticeable in lean conditions, it becomes prominent at higher equivalence ratios, where the reduced oxygen-to-fuel ratio substantially increases CO and UHC emissions, especially with higher HF. Figure 53d and figure 53f show the modified CO and UHC emissions at 15% oxygen dilution.

The provided data includes Oxygen fractions, as depicted in Figure 53e, offering insights for comparisons with systems featuring comparable oxygen dilution levels. An increase in equivalence ratio is associated with a decrease in the oxygen fraction at the burner exit. This phenomenon is a consequence of the heightened proportion of fuel in relation to available oxygen, leading to a reduction in the residual oxygen concentration at the burner exit. Additionally, the inclusion of hydrogen, with its higher air-to-fuel ratio by volume compared to CH_4 , contributes to an increase in oxygen fractions within the flame. In Figure 53h, the variations in CO_2 emissions concerning equivalence ratio and HF are presented. The elevation of the equivalence ratio results in an increased fuel-to-air ratio, subsequently

leading to an augmentation in CO₂ emissions. Conversely, substituting a portion of the main CH₄ mixture with hydrogen induces a reduction in CO₂ emissions, as hydrogen serves as a carbon-free fuel.



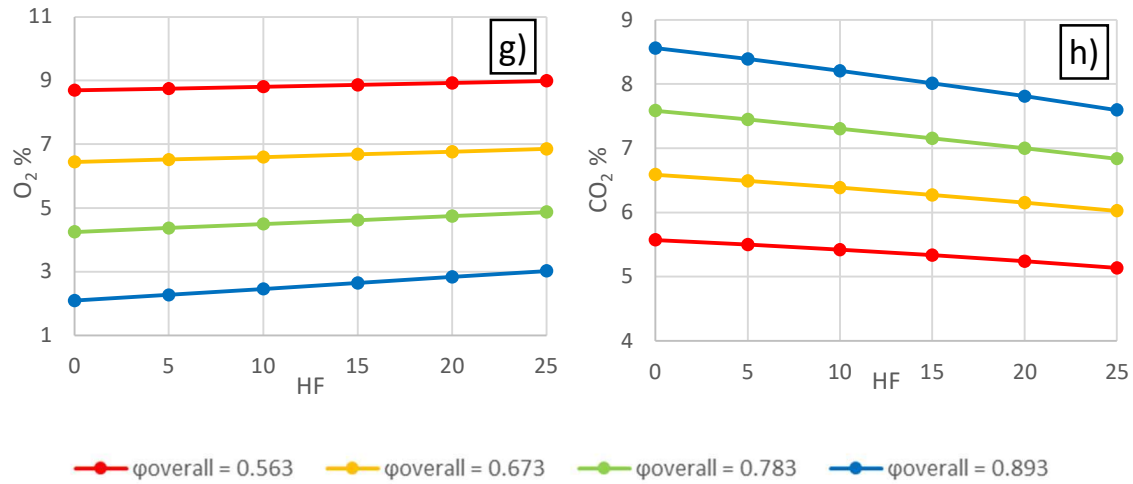


Figure 53: The effect of overall equivalence ratio and hydrogen fraction on Flame emissions (NOx, CO, CO₂, unburned hydrocarbons and O₂) at burner exit based on average area integral.

CHAPTER 6

Conclusion and Recommendations

This study examines, experimentally and numerically, combining the concepts of stratification and hydrogen-enrichment to enhance the lean stability of a premixed swirl-stabilized CH₄/air flame in a burner geometry that mimics Dual Annular Counter-Rotating Swirl (DACRS) burners in actual aeroderivative GTs. Stratification is achieved by introducing enrichment H₂ in non-premixed mode in form of eight peripheral jets at the base of the CH₄/air flame. Hydrogen fractions (HFs) added are up to 25% which, according to literature, doesn't affect NO_x emissions. Stability map, flame imaging and temperatures profiles are obtained experimentally to show the effect of hydrogen addition and equivalence ratio on these parameters. Numerical simulations also were conducted on the combustor to augment the existing dataset and scrutinize the influence of hydrogen fraction (HF) and equivalence ratio on a range of parameters. The primary objective was to elucidate their effects on emissions of CO, NO_x, UHC, O₂, and CO₂, as well as examine the velocity and temperature distributions, concentrations of OH, H, and O radicals, progress variable, product formation rates, flame thickness, flame speed, critical strain rate, and concentrations of CH₄, H₂, CO, NO, O₂, H₂O, NO, and CO₂ throughout the investigated domain. For the studied combustor, results show the following points:

- The introduction of hydrogen through non-premixed non-swirling jets yields conflicting outcomes in combustion dynamics. On one hand, hydrogen enhances reaction kinetics and flame speed, resulting in a more compact, shorter, and

brighter primary flame anchored around the hydrogen non-premixed pilot flames. Conversely, the increased momentum of the hydrogen jets, driven by higher velocities, counteracts the swirling action, dispersing the primary flame and extending its recirculation zones downstream, leading to a taller and paler appearance. Despite these opposing effects, the combustor LBO limit remains relatively unaffected by hydrogen addition, remaining nearly constant at an overall equivalence ratio (ϕ_{overall}) of 0.5. Consequently, introducing hydrogen from the non-premixed fuel circuit of the DACRS burner proves ineffective in enhancing the LBO limit, suggesting that hydrogen enrichment is more effective when premixed with the primary swirling reactants. The interplay of these effects is contingent on both ϕ_{overall} and hydrogen fraction (HF), with the momentum effect becoming pronounced at lower ϕ_{overall} . At higher ϕ_{overall} , the momentum effect emerges as a viable technique to mitigate flashback, offering a strategic approach to reducing flashback risk.

- According to experimental readings, hydrogen fractions (HF) up to 20% exhibit no significant impact on flame temperature, aligning with previous literature, and consequently, NO_x emissions remain unaffected within this range. The flame temperature is predominantly influenced by the overall equivalence ratio (ϕ_{overall}) rather than HF. Under lean operating conditions, characterized by a ϕ_{overall} of 0.644, NO_x emissions approach zero at HF up to 20%, while CO emissions remain around 3 ppm. Increasing HF has minimal effects on CO emissions, but NO_x emissions decrease due to a reduction in nitrogen and hydrogen radicals, resulting in reduced NO formation through prompt mechanisms. Hydrocarbon (HC)

emissions increase with higher HF, attributed to the adverse impact of hydrogen jet velocity, shifting a portion of the primary flame downstream. The equivalence ratio emerges as the primary determinant of flame emissions, with low ϕ_{overall} near blowout leading to fluctuating and high-frequency CO and HC emissions due to flame instability. Conversely, higher ϕ_{overall} results in elevated NO_x emissions, driven by increased temperature promoting thermal NO_x formation.

- Numerical results show that temperature is primarily influenced by the equivalence ratio, leading to increased reaction rates and temperatures with higher values. In contrast, variations in hydrogen fraction result in a localized temperature rise around hydrogen jets but an overall lower flame temperature. The configuration effectively introduces hydrogen without a simultaneous elevation in flame temperature, suggesting a promising strategy for emission reduction, especially in mitigating NO_x emissions. The velocity field, maintained at a constant inlet velocity of 6 m/s, displays distinct IRZ and ORZ in the swirler combustor. Equivalence ratio augmentation increases reaction rates, temperatures, and the size of the IRZ, while hydrogen fraction variations have minimal impact on the velocity field.
- Two distinct flame fronts are identified, each with corresponding values. An increased equivalence ratio results in higher flame speed due to elevated fuel availability and heat release, while hydrogen introduction reduces the primary flame speed. Notably, a high flame speed is observed near the hydrogen jet, peaking at leaner equivalence ratios. The primary flame thickness decreases with higher equivalence ratios but increases with higher hydrogen fractions. The

hydrogen flame has a smaller thickness than the primary mixture. Critical strain rates for primary flame decrease in leaner conditions, making combustion more susceptible to turbulence, while higher flame speeds near hydrogen jets elevate critical strain rates, indicating increased turbulence-induced distortion. Understanding these parameters is crucial for stable combustion in practical applications.

- Very lean equivalence ratios exhibit incomplete flames in the ORZ, with hydrogen aiding completion around non-premixed hydrogen jets. Higher equivalence ratios show minimal impact from increased hydrogen enrichment. Increasing equivalence ratio slightly reduces flame length, indicating faster reactions. PFR increases notably in the inner thin layer at low equivalence ratios, with hydrogen fraction enhancement aiding flame stabilization. At higher equivalence ratios, both inner and outer shear layers show increased PFR, indicating more intense and compact flames. Increasing hydrogen fraction enhances PFR around non-premixed hydrogen jets, but at the highest equivalence ratio, the impact diminishes, suggesting reduced effectiveness in radical production and flame stabilization.
- Illustrating CH_4 and hydrogen mole fractions in the combustor under varying equivalence ratios and hydrogen fractions (HF), higher equivalence ratios increase CH_4 mole fraction, stabilizing the flame in the IRZ. Conversely, increasing HF reduces CH_4 mole fraction. For OH radicals, higher equivalence ratios increase OH radicals. HF under lean conditions enhances OH radicals around hydrogen jets, but at higher equivalence ratios, the positive impact diminishes. The

formation of H radicals increases with both equivalence ratio and HF, primarily in the outer shear layer with higher HF. Oxygen radicals (O radicals) increase with equivalence ratio, and HF exhibits a non-monotonic trend, indicating that OH radicals surpass H and O radicals in magnitude.

- NO_x emissions exhibit a non-monotonic trend with hydrogen fraction (HF) and increase with equivalence ratio. Higher equivalence ratios raise NO_x due to increased fuel availability and elevated flame temperature. Introducing hydrogen under lean conditions elevates prompt NO_x, but at higher equivalence ratios, higher HF reduces NO_x emissions by lowering the main flame temperature. CO₂ emissions increase with equivalence ratio, while substituting CH₄ with hydrogen decreases CO₂ emissions. CO and Unburned Hydro-Carbons (UHC) emissions increase with HF, especially at higher equivalence ratios. The higher reactivity of hydrogen leads to incomplete combustion, raising CO and UHC emissions. Oxygen fractions decrease with equivalence ratio, and oxygen fractions within the flame increase due to hydrogen inclusion. The mole fractions of H₂O /O₂ illustrate that increasing in equivalence ratio reduces oxygen fraction and increases H₂O fraction.

6.1 Recommendations for Future Work

Nevertheless, the application of pilot fuel jets serves as an augmented methodology for enhancing the lean blowout limit in various industrial burners, including DACRS burners. Contrary to expectations, our findings indicate that the utilization of tilted hydrogen jets does not contribute to the improvement of the blowout limit. Instead, it leads to an increase in carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions. In considering

future research directions, it is advisable to broaden the investigation by exploring additional fuel mixtures, providing comprehensive insights into diverse combustion behaviors. This extension should encompass a variety of alternative fuel combinations to systematically analyze their influence on flame characteristics. Simultaneously, the study could delve into the effect of injection angles and positions on flame dynamics, constituting an intriguing avenue for further inquiry. Scrutinizing how these parameters affect flame characteristics could yield nuanced insights, contributing to an enhanced understanding and optimization of combustion systems. Moreover, integrating an examination of acoustic instabilities into this research framework adds another layer of complexity, offering the opportunity to explore the interplay between combustion and acoustics. By incorporating acoustics instabilities into the study, it becomes possible to gain a holistic understanding of the factors influencing combustion dynamics, ultimately contributing to advancements in both academic knowledge and practical combustion technologies. These multifaceted aspects—exploration of different fuel mixtures, examination of injection angles and positions, and integration of acoustics instabilities—emerge as promising directions for future academic research.

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