

**NUMERICAL INVESTIGATION AND DESIGN OF
HYDROGEN-BASED BURNER FOR
CIVIL AIRCRAFT JET ENGINE**

**BY
HAFIDZ AZHAR JAKARIA**

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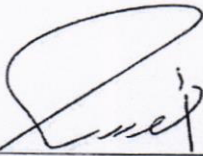
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KING FAHD UNIVERSITY OF PETROLEUM & MINERALS

DHAHRAN- 31261, SAUDI ARABIA

DEANSHIP OF GRADUATE STUDIES

This thesis, written by **Hafidz Azhar Jakaria** under the direction of his thesis advisor and approved by his thesis committee, has been presented and accepted by the Dean of Graduate Studies in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN AEROSPACE ENGINEERING**.



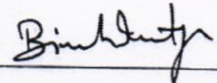
Dr. Ayman M. Abdallah
Department Chairman



Dr. Naef A. A. Qasem
(Advisor)

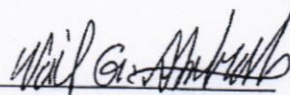


Prof. Suliman Al-Homidan
Dean of Graduate Studies



Dr. Binash Imteyaz
(Member)

Date



Dr. Wael G. AbdelRahman
(Member)



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I dedicate this thesis to my family, mentors, and friends whose unwavering support and encouragement made this journey possible |

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LIST OF ABBREVIATIONS

AFR	:	Air to Fuel Ratio
AFT	:	Adiabatic Flame Temperature
ASC	:	Axially Staged Combustors
ATM	:	Air Traffic Management
CAEE	:	Committee on Aviation Engine Emissions
CAEP	:	Committee on Aviation Environmental Protection
CAN	:	Committee on Aircraft Noise
CC	:	Combustion Chamber
CFD	:	Computational Fluid Dynamics
CO	:	Carbon Monoxide
COT	:	Combustor Outlet Temperature
CPU	:	Central Processing Unit
DAC	:	Double Annular Combustors
DO	:	Discrete Ordinate
DTRM	:	Discrete Transfer Radiation Model
EDC	:	Eddy Dissipation Concept
EDM	:	Eddy Dissipation Model

FAR	: Fuel-to-Air Ratio
GDP	: Gross Domestic Product
GHG	: Greenhouse Gas
GTE	: Gas Turbine Engine
HC	: Hydrocarbons
H ₂ FC	: Hydrogen Fuel Cell
ICAO	: International Civil Aviation Organization
IATA	: International Air Transport Association
ISR	: Intelligence, Surveillance, and Reconnaissance
LDI	: Lean Direct Injectors
LES	: Large Eddy Simulation
LH ₂	: Liquid Hydrogen
LPP	: Lean Premixed Prevaporised
LTO	: Landing Take-off
NO	: Nitric Oxide
NO ₂	: Nitrogen Dioxide
OPR	: Overall Pressure Ratio

PDF	: Probability Density Function
RANS	: Reynolds-averaged Navier Stokes
RSM	: Reynolds Stress Model
RTE	: Radiative Transfer Equation
RQL	: Rich-Burn Quick-quench Lean-burn
S2S	: Surface-to-Surface
SAF	: Sustainable Aviation Fuel
SFC	: Specific Fuel Consumption
SO _x	: Sulphur Oxides
TAPS	: Twin Annular Premixing Swirler
TBC	: Thermal Barrier Coating
TET	: Turbine Entry Temperature
TKE	: Turbulence Kinetic Energy
UHC	: Unburned Hydrocarbons
UAV	: Unmanned Aerial Vehicle
UV	: Ultraviolet
VGC	: Variable Geometry Combustors

WSGGM : Weighted Sum of Gray Gas Model

NOMENCLATURE

Symbol	Definition	Unit
a	Absorption coefficient	1/m
C_p	Specific heat	J/kg
$C_{p,i}$	Element specific heat	J/kg
d_h	Hub diameter	m
d_o	Swirl diameter	m
D_p	Mass of gaseous emission	g
f	Mixture fraction	---
F_{00}	Rated thrust	kN
G	Incident radiation	W/m ²
G_B	Turbulence generation due to buoyancy	m ² /s ³
g_i	Gravitational component	m/s ²
G_k	Turbulence generation due to velocity	m ² /s ³
$\tilde{H}$	Mean enthalpy	J
H_i	Element specific enthalpy	J/kg
k	Turbulent kinetic energy	J/kg
k_l	Laminar thermal conductivity	W/m.K
$\dot{m}_a$	Air mass flow rate	Kg/s
M_{air}	Air molar mass	g/mol
$\dot{m}_f$	Fuel mass flow rate	Kg/s
M_{fuel}	Fuel molar mass	g/mol
M_t	Turbulent Mach number	---
$p(f)$	Probability density function	---
PF	Pattern factor	---
ppm	Part per million	---
Pr_t	Prandtl number	---
q_r	Radiation flux	J/s
S_h	Radiation source energy	J
S_i	Reaction rate of an element	---
S_{ij}	Strain rate tensor	1/s
S_m	Mass flux due to the conversion liquid fuel droplet to the gas phase	Kg/s

S_N	Swirl number	---
T_3	Compressors exit air temperature	K
T_4	Average outlet combustor temperature	K
T_{max}	Maximum temperature in combustor	K
$\tilde{u}_i, \tilde{u}_j, \tilde{u}_k$	Favre-averaged velocity component	m/s
u'_i, u'_j	Velocity fluctuating component for Favre-averaged momentum equation	m/s
Y_M	Fluctuating dilatation component	m ² /s ³
Z_i	Mass fraction of an element	---
$Z_{i,fuel}$	Mass fraction of fuel at inlet	---
$Z_{i,ox}$	Mass fraction of oxidizer at inlet	---

Greek letters

ε	Turbulent dissipation rate	m ² /s ³
λ	Excess air coefficient	---
μ_t	Turbulent viscosity	Kg/m.s
ϕ	Equivalence ratio	---
$\bar{\phi}$	Density-weighted thermochemical scalar	Kg/m ³
π_{00}	Engine overall pressure ratio	---
$\bar{\rho}$	Averaged density	Kg/m ³
σ	Steffan-Boltzmann constant	---
θ	Swirl vanes angle	deg
$\overline{\chi_{st}}$	Mean scalar dissipation	1/s

ABSTRACT

Full Name : [Hafidz Azhar Jakaria]

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Switching to hydrogen as a clean and sustainable fuel for gas turbine engines offers a chance to minimize greenhouse gas emissions while maintaining excellent performance and dependability. This thesis investigates hydrogen combustion simulation in an annular aero gas turbine engine, aiming to reduce NO_x emissions while possibly achieving optimal flame temperature and stabilization using parametric analysis. First, the number of hydrogen injectors (1, 4, and 8) and their orientation (axial and transverse) are compared against the existing kerosene combustion. Next, the swirl angles for each injector setup are varied from 35° to 65°. Lastly, this study provides a sensibility test of equivalence ratios (ϕ) to comply with the landing take-off (LTO) cycle, ranging from 0.1 to 0.86, changing the fuel flow rate with a constant air flow. A detailed reaction mechanism is incorporated to capture the unique combustion characteristics of hydrogen fuel, such as high flame speed and low volumetric density. Simulation results show that altering the fuel composition, injector setups, swirl angles, and equivalence ratios significantly affects the combustion process in the recirculation zone (RZ) and combustor outlet. For instance, kerosene flame yields a maximum flame temperature of ~2200 K with an outlet NO_x level of 44 ppm. The hydrogen flame, however, demonstrates a higher flame temperature in RZ, reaching up to 2650 K. All different hydrogen injector configurations show higher NO_x emissions than kerosene. Still, the eight axial injectors produce the lowest NO_x of 66 ppm among other

injector modifications. Moreover, it shows moderate flame temperature in RZ (2400 K), which is slightly favorable to reduce thermal stresses. The four and eight transverse injectors exhibit higher flame temperature than the axial injectors, producing higher outlet NO_x. However, they may improve flame stabilization due to their inherent cross-flow fuel mixture. The same thing cannot be said when increasing the swirl angle. From the numerical results, flame instabilities are observed in transverse injectors at high swirl angles (55° and 65°), indicating transverse injectors may work well at low angles or none. Moreover, high swirl angles (55° and 65°) generate hotter and wider flames in RZ for axial and transverse injectors, producing higher NO_x of more than 200 ppm. In contrast, low NO_x emissions are observed at low swirl angles (35° and 40°). For example, eight axial injectors show the lowest NO_x (66 ppm) at 40° swirl angle, while eight transverse injectors show 74 ppm at 35°. In terms of ϕ , simulations reveal that a higher equivalence ratio exhibits an increased average velocity output, indicating increased output thrust, reflecting the aircraft engine's power demands. However, modification of the equivalence ratios shows different performances for axial and transverse injectors. For instance, transverse orientation generally shows higher flame temperature than axial injectors in the same number of injectors, producing more NO_x across various equivalence ratios. However, peak temperature occurs in the range $0.2 \leq \phi \leq 0.3$ for axial and transverse injectors, which may have been caused by optimum fuel residence and mixing. Therefore, flow recirculation and fuel mixing are crucial factors in achieving optimal flame structure and temperature while maintaining relatively low NO_x pollutants. These findings provide valuable insights for the design of hydrogen burners in next-generation aircraft engines.

Keywords:

Hydrogen, Aero Gas Turbine Engine, NO_x, Flame Temperature, Flame Stabilization, Fuel Injectors, Swirl Vanes Angle, Equivalence Ratio

ملخص الرسالة

الاسم الكامل: حافظ أزهر زكريا

عنوان الرسالة: دراسة عددية و تصميمية لغرفة الإحتراق الهيدروجينية لمحركات الطائرات المدنية النفثة

التخصص: هندسة الطيران والفضاء

تاريخ الدرجة العلمية: جماد الآخر 1446

التحول إلى استخدام الهيدروجين كوقود نظيف ومستدام لمحركات التوربينات الغازية يُمثل فرصة لتقليل انبعاثات غازات الاحتباس الحراري مع الحفاظ على الأداء العالي والموثوقية. تتناول هذه الأطروحة محاكاة احتراق الهيدروجين في محرك توربيني غازي هوائي دائري (Annular Aero Gas Turbine Engine) ، بهدف تقليل انبعاثات NOx مع تحقيق درجة حرارة مثلى للهب وضمان استقراره، وذلك من خلال تحليل بارامتري . في البداية تم مقارنة عدد حاقنات الهيدروجين (1، 4، و8) واتجاهها بشكل محوري ، وعرضي مع نظام احتراق الكيروسين التقليدي . بعد ذلك تم تغيير زوايا السحب الدوراني (Swirl Angles) لكل إعداد من الحاقنات بين 35° و 65°. وأخيراً، أُجري اختبار حساسية لنسب التكافؤ (ϕ) لتلبية متطلبات دورة ICAO's LTO، وذلك ضمن نطاق يتراوح بين 0.1 و 0.86 عن طريق تعديل معدل تدفق الوقود مع الحفاظ على معدل تدفق الهواء ثابتاً . تم اعتماد آلية تفاعل تفصيلية لتمثيل الخصائص الفريدة لاحتراق الهيدروجين، مثل سرعة اللهب العالية والكثافة الحجمية المنخفضة . أظهرت نتائج المحاكاة أن تغيير تركيبة الوقود ، إعدادات الحاقنات ، زوايا السحب الدوراني ونسب التكافؤ، يؤثر بشكل كبير على عملية الاحتراق في منطقة إعادة التدوير (Recirculation Zone - RZ) ومخرج غرفة الاحتراق . على سبيل المثال ، ينتج لهب الكيروسين درجة حرارة لهب قصوى تقارب K 2200 ، مع انبعاثات NOx عند المخرج تبلغ 44 ppm . أما لهب الهيدروجين، فقد أظهر درجة حرارة أعلى داخل الـ RZ تصل إلى K 2650 . أدت جميع تكوينات حاقنات الهيدروجين إلى انبعاثات NOx أعلى من تلك الناتجة عن الكيروسين ، إلا أن التكوين الذي يضم 8 حاقنات محورية (Axial Injectors) سجل أدنى مستوى NOx بلغ 66 ppm مقارنة ببقية التكوينات .

علاوة على ذلك ، أظهر هذا التكوين درجة حرارة لهب معتدلة داخل الـ RZ (حوالي K2400) ، وهي ميزة مرغوبة للحد من الإجهادات الحرارية . في المقابل ، سجلت الحاقنات العرضية (Transverse Injectors) ذات الأعداد 4 و 8 درجات حرارة لهب أعلى من المحورية ، مما أدى إلى انبعاثات NOx أعلى . ومع ذلك ، قد يكون لها دور في تحسين استقرار اللهب بفضل طبيعة خلط الوقود العرضي . لوحظ أن الوضع يختلف عند زيادة زوايا السحب الدوراني ؛ حيث أظهرت النتائج العددية وجود عدم استقرار في اللهب عند استخدام الحاقنات العرضية بزوايا كبيرة (55° و 65°) ، ما يشير إلى أنها تعمل بشكل أفضل عند الزوايا المنخفضة أو بدون سحب دوراني . أنتجت الزوايا العالية (55° و 65°) لهباً أوسع وأكثر سخونة داخل الـ RZ سواء باستخدام الحاقنات المحورية أو العرضية ، مما أدى إلى انبعاثات NOx تجاوزت 20 ppm . في المقابل تم تسجيل أدنى مستويات NOx عند الزوايا المنخفضة (35° و 40°) . على سبيل المثال ، سجلت الحاقنات المحورية الثمانية NOx بمعدل 66 ppm عند زاوية 40° ، بينما سجلت الحاقنات العرضية الثمانية 74 ppm عند زاوية 35° . أما بالنسبة لنسبة التكافؤ ϕ ، فقد كشفت المحاكاة أن زيادتها تؤدي إلى ارتفاع متوسط سرعة المخرج ، ما يشير إلى زيادة الدفع الناتج ، وهو ما يتماشى مع متطلبات الطاقة لمحركات الطائرات . لكن تأثير تعديل نسب ϕ يختلف بين التكوينات المحورية والعرضية . فمثلاً ، أظهرت الحاقنات العرضية عمومًا درجة حرارة لهب أعلى من المحورية عند نفس العدد ، مما أسفر عن انبعاثات NOx أعلى عبر مجموعة واسعة من نسب ϕ . ومع ذلك لوحظت درجات حرارة قصوى في النطاق 0,2 – 0,3 لكلا التكوينين، ويُحتمل أن يكون ذلك نتيجة لزمّن الإقامة المثالي و خلط الوقود الفعال . بالتالي تُعد إعادة تدوير التدفق وفعالية خلط الوقود عوامل جوهرية لتحقيق بنية لهب مثالية ودرجات حرارة مناسبة مع المحافظة على انبعاثات NOx عند مستويات منخفضة نسبيًا . تقدم هذه النتائج رؤى مهمة في تصميم حواقل وقود الهيدروجين لمحركات الطائرات في الجيل القادم .

الكلمات المفتاحية:

الهيدروجين، محرك توربيني غازي هوائي ، أكاسيد النيتروجين ، درجة حرارة اللهب ، تثبيت اللهب ، حاقنات الوقود ، زاوية ريش الدوامة ، نسبة التكافؤ

CHAPTER 1

INTRODUCTION

1.1. Motivation

The aviation sector is the cornerstone of human progress and worldwide connectivity. It has had a phenomenal upsurge in the last few years, erasing distances between individuals and locations worldwide. According to the International Civil Aviation Organization (ICAO), commercial air transport could be doubled by the mid-2030s, with an annual growth of 4.3% [1]. Moreover, for the next two decades, air travel is poised to be the fastest-growing industry in the world, driven by emerging-market economies [2]. It is reported that 3.6% of the world's gross domestic product (GDP) was generated by aviation in 2016, supporting 65.5 million employment and \$2.7 trillion in economic activity [3]. This trend will continue as aviation has always been at the forefront of technological innovations [4].

With the potential of ever-expanding fleet size in the foreseeable future, it is imminent that the aviation sector will consume fossil fuel rigorously. Recent studies stated that global airlines used about 200 megatons of fuel in 2015. In 2045, Fossil fuel expenditure is predicted to triple compared to 2015, depending on Air Traffic Management (ATM) and technological advances. Accordingly, the rise of traditional jet fuel consumption significantly contributes to atmospheric CO₂ emissions. International Aviation released approximately 600 megatons of carbon emissions throughout the year 2015, and it is predicted to triple that amount by 2045 [5]. Indeed, the main cause of the world's

greenhouse gas (GHG) emissions, identified as the key component causing global warming, is typically attributed to emissions from burning fossil fuels. Approximately 3% of the anthropogenic greenhouse effect is exacerbated by current air traffic [6]. Given that air travel represents one of the most difficult sectors to decarbonize, this percentage will inevitably rise. As a result, the persistent increase in aircraft emissions poses consequential challenges in complying with the Paris Agreement's GHG reduction and commitments [7].

The International Air Transport Association (IATA) has employed innovative tactics to minimize aircraft emissions with its new Fly Net Zero program to achieve net zero CO₂ emissions by 2050. Coordinated efforts from the whole industry, including airlines, airports, manufacturers, air navigation service providers, and strong government support, are mandatory, ensuring the program's effectiveness in achieving its goal. The program's strategy is divided into four methods: Sustainable Aviation Fuel (SAF), cutting-edge technologies, infrastructure and operational efficiencies, and offsets and carbon capture [8]. SAFs are considered sustainable because their source does not compete with agricultural products, nor do they necessitate additional resources involving water and deforestation. IATA projects that SAFs may provide around 65% of the carbon emissions reduction needed by aviation to achieve net zero in 2050, but a massive effort is compulsory to meet the requirement.

SAFs are useful because they offer short-term solutions for reducing aircraft emissions with little to no modifications of aircraft engines [4]. However, the operating cost of SAFs is more expensive than that of conventional jet fuel, compromising its short-term solution [9]. Hydrogen and ammonia offer potentially clean and renewable energy. In nature, ammonia is primarily formed through the decaying process of animal or plant matter [10].

However, hydrogen can be produced by man-made technology, including natural gas steam reforming, coal gasification, and electrolysis [11]. Despite this, hydrogen possesses more gravimetric energy six times and three times than ammonia and jet fuel, respectively [12], [13], [14].

Hydrogen's outstanding properties make it a highly promising fuel in future aviation. Currently, however, it also faces numerous drawbacks when applied to passenger jets, including safety concerns [15], storage and distribution, infrastructure development, cost of fuel production, innovative engine technology, and the necessity to modify aircraft design [16]. In the context of converting current gas turbines, the modification to the combustion technology must be adaptable under various operating loads, ensuring efficient, stable, and low NO_x combustion. Correspondingly, the control and metering unit system of the gas turbines needs to be adjusted to provide safe, rapid, and accurate operations [17], [18]. Current hydrogen aircraft research programs focus on providing feasible and sustainable hydrogen-powered aviation to overcome these concerns. Some notable projects, including Universal Hydrogen [19], ZeroAvia [20], and H2FLY [21] are testing hydrogen fuel cell (H₂FC) aircraft and will soon provide services in a small region. In the long run, Airbus revealed its ZEROe project in 2020, aiming to build carbon-free emissions aircraft by 2035 [22]. In Europe, several hydrogen aircraft designs have been proposed by the Clean Sky 2 Joint Undertaking [23], the Clean Aviation Joint Undertaking [24], and the FlyZero project [25].

1.2. Gas Turbine Aero-Engine

A gas turbine aero-engine, commonly known as a jet engine, generates thrust to propel an aircraft by expelling a high-speed stream of hot exhaust gases. Its operation is based on Newton's third law of motion, which states that every action has an equal and opposite reaction. Turbofan jet engines are commonly installed in modern subsonic aircraft owing to their compact design, high thrust, and high efficiency, which are fundamental requirements for any passenger aircraft [26]. A general schematic of a turbofan jet engine is illustrated in Figure 01. The turbofan draws and regulates the flow of ambient air. Some incoming air flows through the core compressor and burner, mixing fuel and air to produce combustion. The hot exhaust gas exits the exhaust nozzle after passing through the engine turbine, like the basic turbojet. The heat energy coming from the combustor is converted to mechanical energy via the turbine fan to generate power for the air compressor and other components. The rest of the incoming air flows around the fan and core engine in a manner similar to how air moves past a propeller. The airflow through the fan is only slightly accelerated, allowing the turbofan gas turbine to generate thrust from both the core engine and the fan. The bypass ratio refers to the ratio of air flowing around the engine to the air passing through the core [27].

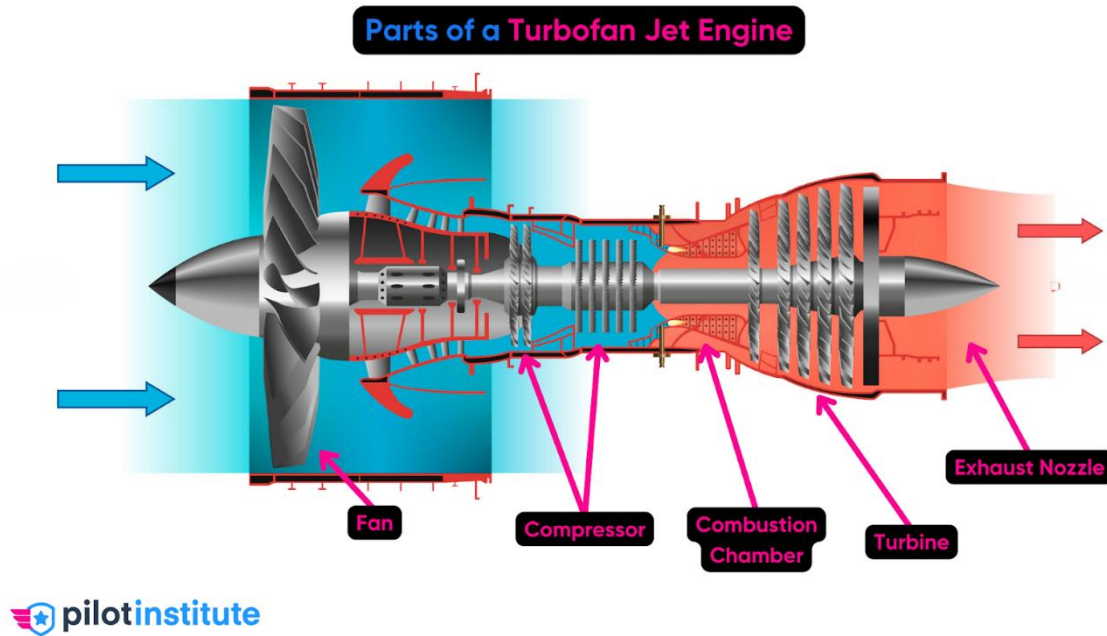


Figure 01 Standard schematic turbofan jet engine [28].

1.2.1. Gas Turbine Engine Cycle

The operating cycle of a gas turbine can be explained using the Joule-Brayton cycle, as shown in Figure 02. Generally, this cycle can be implemented as an open or closed cycle. However, aero-gas turbine engines are determined to be open cycles. In this case, the engine draws air from the surrounding atmosphere at ambient temperature and pressure. The exhaust nozzle discharges the combustion byproducts and unused air into the atmosphere [29].

In the Joule-Brayton cycle, point A represents the starting point under ambient conditions. The ambient air is compressed by the engine's compressor and reaches point B. In this stage (A-B), not only is air pressure increased, but also its temperature increases. Next, the compressed air is mixed with the fuel with an appropriate ratio in the engine combustion chamber, producing hot gases and releasing heat energy, ending at point C. In this stage

(B-C), the working fluid reaches significantly higher temperatures. Moreover, the change in composition of working fluid from air into combustion products increases the volume of the fluid. However, the total pressure is reduced because of the combustion process. The hot gas working fluid is then expanded through the engine turbine and exhaust nozzle, producing mechanical power for the compressor and propulsive jet for the aircraft.

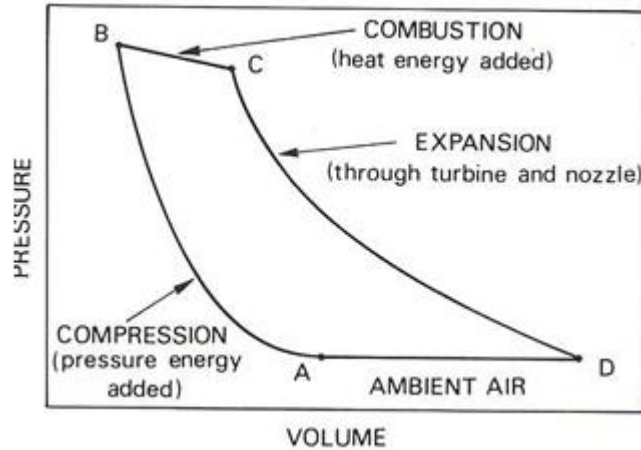


Figure 02 The Joule-Brayton cycle on a pressure-volume (P-V) diagram [30].

The Joule-Brayton cycle efficiency can be expressed as:

$$\eta_{GTE} = 1 - \frac{T_D - T_A}{T_C - T_B} \quad (1.1)$$

In this equation, T_A is the ambient static temperature, T_B is the combustor inlet temperature, T_C is the combustor exit temperature, and T_D is the turbine exit temperature. This formula concludes that increasing the combustor exit temperature will increase gas turbine thermal efficiency.

1.2.2. Combustor overview

The combustor is the key component of a gas turbine engine (GTE), providing sufficient heat energy by burning the fuel with an appropriate ratio of air, which is converted into mechanical energy by the engine turbine for other components. The remaining heat energy is used as a propulsive jet through the engine exhaust nozzle. In a gas turbine combustion chamber, the flow and burning rates are high due to the limited space, energy, and momentum requirements [29]. Moreover, high flame temperature is restricted to avoid thermal fatigue of the turbine blades since combustion in GTE is continuous once the spark plug is ignited [31], [32]. Therefore, retrofitting the current gas turbine design to accommodate hydrogen is daunting, considering hydrogen's low density and rapid burning rate. The details of combustor design requirements are explained in the following section.

Table 01 Typical design parameter for gas turbine engine using kerosene/jet fuel [29], [35], [36], [37], [38].

COMPANY	CFMI	CFMI	CFMI	CFMI	CFMI	IAE	Pratt & Whitney
Engine type	CFM 56	CFM 56	CFM 56	CFM 56	CFM 56	V2500	PW4000
Engine model	3C1	5A1	5B1	5C2	7B20	A1	-
Max thrust (lb)	23500	25000	27000	31200	20600	30000	60000
Bypass ratio	4.80	6.00	5.65	6.40	-	5.00	5.00
Total air mass flow (lb/s)	710	852	874	1065	-	781	-
SFC (lb/hr/lb)	0.33	0.33	0.34	0.32	0.36	0.35	-
Fuel flow (lb/s)	2.154167	2.291667	2.55	2.773333	2.06	2.916667	2.5346
Core airflow (lb/s)	122.4138	121.7143	131.4286	143.9189	-	130.1667	254
Fuel flow (kg/s)	0.977113	1.039482	1.15666	1.257962	1.284	1.322977	1.1497

Core airflow (kg/s)	55.52592	55.20863	59.61495	65.28047	56.8	59.04256	115.2124
Combustor air inlet temperature (K)	743.91	-	811.15	-	793.58	854.26	841.48
Combustor air outlet temperature (K)	1649.94	-	1509.15	-	1624	1727.594	1827.594
Combustor inlet pressure (Kpa)	2343.34	-	-	-	3313.32	3316.38	3247.43
Combustor outlet pressure (Kpa)	2226.1	-	-	-	-	-	-
Liner length (m)	0.208	-	-	-	-	0.2032	-
Liner height (m)	0.09	-	-	-	-	-	-

1.2.3. Combustor design requirement

The combustor must meet various requirements. The basic requirements are defined as follows [33]:

1. High combustion efficiency, where the fuel must be fully combusted to produce the maximum thermal energy.
2. Consistent and dependable ignition both on the ground and at high altitudes in the event of a flameout.
3. Excellent flame stability, in which the combustion flame should remain light over various air pressures and fuel-to-air ratios (FAR).
4. Low combustor pressure loss occurs due to flame diffusion, friction, and fluid momentum in the combustion chamber [34].
5. The optimal pattern factor is where the outlet combustor temperature must be regulated to minimize thermal stresses and extend the lifespan of the turbine blades. Minimum hazardous pollutants and emissions—conventional fossil fuels produce carbon gas emissions, which significantly contribute to climate change. However, hydrogen fuel supposedly only produces water vapor as a byproduct.
6. Good maintainability and endurance—gas turbine engines are prone to pressure pulsations and combustion instability.
7. Minimum cost and ease of manufacturing.

8. Multi-fuel capacity – Hydrocarbons, synthetic, hydrogen, and bio derivatives fuel

Table 01 depicts the design parameters for modern aircraft combustors.

1.2.4. Combustor fundamental design

The basic design of the combustor plays a crucial role in determining its performance to satisfy the design requirements outlined in the previous section. Moreover, it can carry out the needed modifications to accommodate good combustion performance. Achieving high combustion efficiency relies on effective air-fuel mixing, and when using liquid fuel, the injection method must be suitable to ensure the fuel droplets are well-atomized. Furthermore, appropriate combustor inlet temperature and turbulence are necessary to reduce ignition delay, providing the fuel-air mixture has sufficient residence time to burn [29].

Figure 03a illustrates the basic layout of the combustor, where the fuel is injected into the center of the straight-walled duct. Unfortunately, this basic configuration is impractical because of considerable pressure loss. This pressure loss harms gas turbine engines, mainly reducing efficiency and power output. The pressure loss of the illustrated simple design is excessive, approximately 30% of the air pressure achieved in the compressor. In Figure 03b, the diffuser is introduced to mitigate the pressure loss by a factor of 5 by reducing the stream velocity. However, a flow reversal must be created in this design to anchor the flame using a plain baffle, as shown in Figure 03c. This setup's remaining flaw is that the total air/fuel ratio is between 30 and 40, far higher than the flammability limit for a hydrocarbon-air mixture to generate the desired combustion temperature. The general AFR in the CC

primary zone should be around 18. To overcome this problem, a continuous recirculatory flow is introduced to maintain combustion, as depicted in Figure 03d.

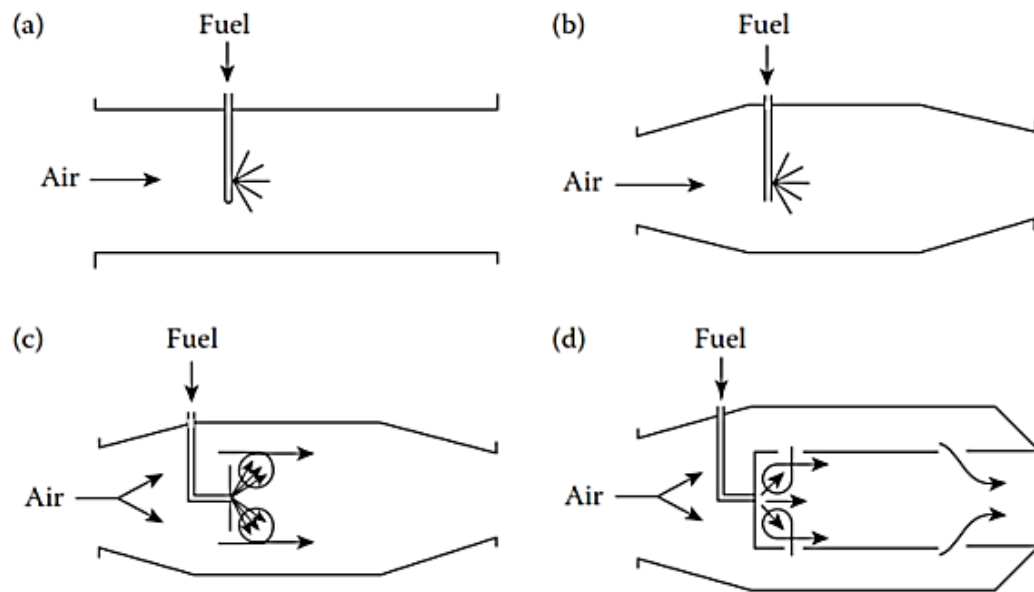


Figure 03 Evolution stages of traditional combustor design [33].

1.2.5. Common combustor types

A certain combustor type and configuration are chosen mostly based on the engine design and the requirements. Gas turbine combustors have three combustor layouts: can, cannular/tuboannular, and annular, as shown in Figure 04.

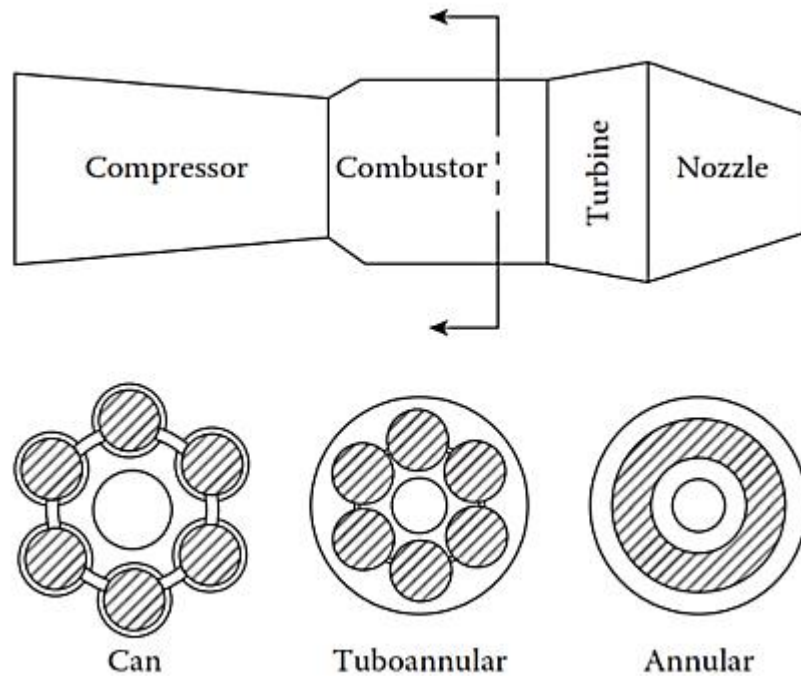


Figure 04 Common types of gas turbine combustor [33].

1.2.5.1. Tubular/Can

The tubular, sometimes called a can combustor, is the simplest design used in early jet engines. A can combustor consists of a cylindrical liner placed concentrically within a cylindrical casing, as depicted in Figure 05. The primary benefit of can combustors is that they can be used in comparatively little time and cost associated with their manufacturing. Moreover, they are used primarily in the industrial environment where ease of maintenance and accessibility are important factors. They are rarely, however, used in modern aircraft engines due to excessive weight and length [33].

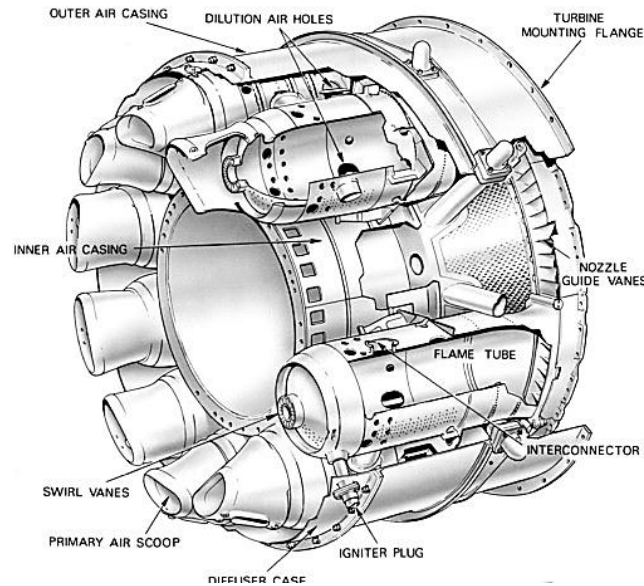


Figure 05 Can combustor design [39].

1.2.5.2. Annular

This design features an annular liner mounted concentrically within an annular casing, as shown in Figure 06. This chamber type is appropriate for aircraft engines for its efficient aerodynamic properties, resulting in less pressure loss and compact design than other combustor configurations. In the same mass flow, an annular combustor only necessitates half the diameter of the can combustor. However, the drawback comes as a heavy buckling load on the outer liner. Hence, annular combustors were installed in low-pressure ratio engines, including the Westinghouse J30, BMW 003, and the Metrovick Beryl. Slight modifications to the geometry design can interfere with the flow velocity profile, eventually disturbing the combustor outlet's temperature distribution. Another drawback is the high cost of testing annular combustors, which requires substantial air pressure, temperature, and flow rate under full-load conditions. Additionally, only a few facilities worldwide are equipped to accommodate these requirements.

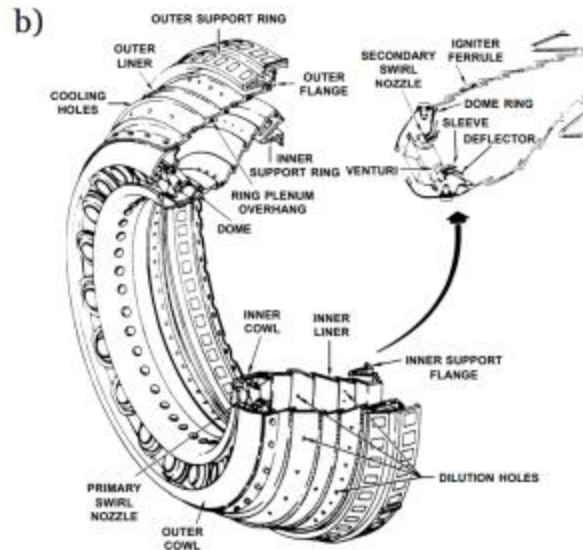


Figure 06 Annular combustor design based on CFM56-3 engine [40].

1.2.5.3. Can-annular

The cannular, sometimes called ‘tuboannular,’ is the hybrid of the can and annular combustor type, aiming to mitigate the drawbacks and improve the ease of maintenance and testing of the two designs. The cannular combustor consists of tubular liners fitted in a single annular casing, as depicted in Figure 07.

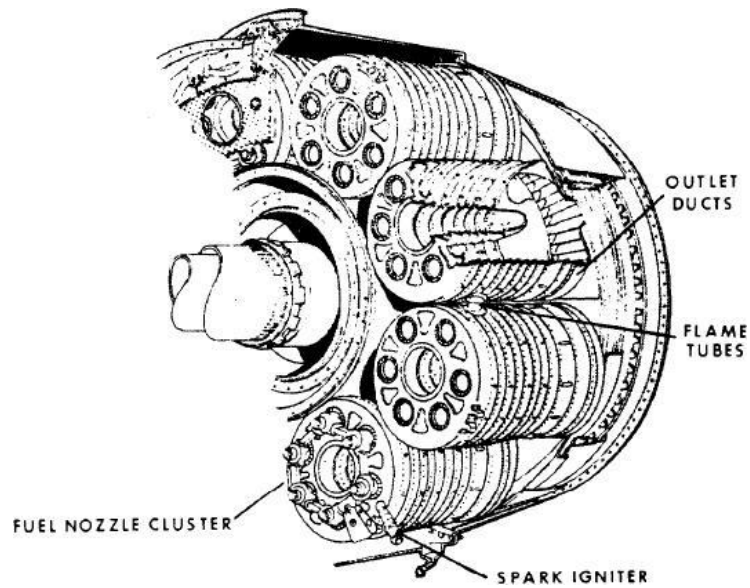


Figure 07 Cannular combustor arrangement [41].

The cannular combustor arrangement can be easily developed, considering the rig testing only carries out a single combustion chamber, like a can combustor. Moreover, testing can be done with a moderate amount of air supplies. However, it is struggling to obtain the desired consistent airflow pattern.

1.2.6. Combustion chamber components and zones

Conventional combustion chamber can be divided into several zones and parts, as depicted in Figure 08. Each has its own set of substantial functions for flame stabilization and control.

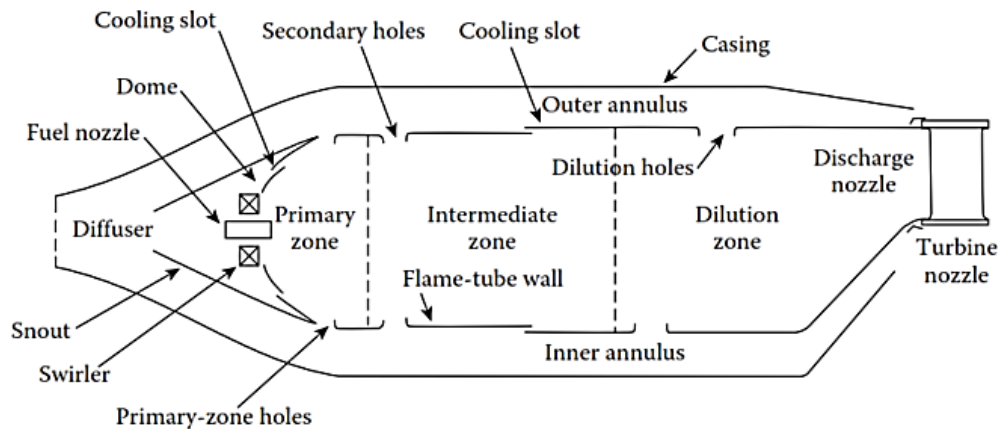


Figure 08 General annular combustion chamber layout [33].

1.2.6.1. Primary zone

The main purpose of the primary zone is to stabilize the flame and generate sufficient turbulence, heat, and residence time for the incoming fuel-air mixture to burn almost completely. The airflow pattern in the primary zone is critical for determining flame stabilization and ensuring complete combustion. The general flow pattern introduces toroidal flow reversal, which recirculates some hot combustion gases to ignite the incoming fuel-air mixture continuously, as shown in Figure 09. This toroidal flow reversal combines the air swirler and the primary air jets. If used properly, these two separate mode air injections will create air flow that complements each other. As a result, a robust and steady primary zone airflow pattern enables wide flammability limits and effective ignition [33].

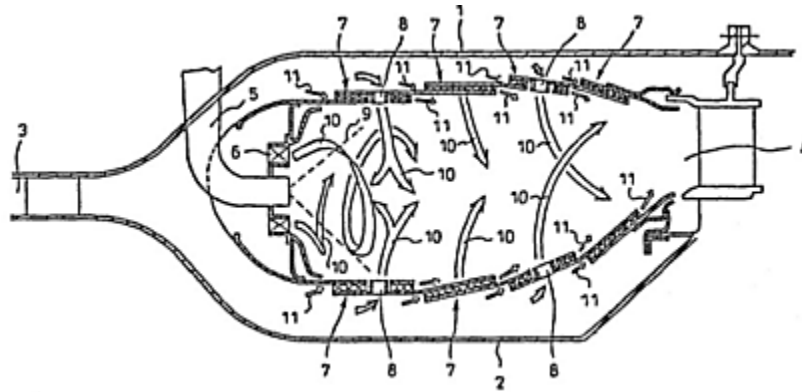


Figure 09 Combustion chamber with air swirler [33].

1.2.6.2. Swirler

One of the most effective methods for generating recirculation flow in the primary zone is by mounting an air swirler around the fuel injector. Vortex breakdown occurs when the circumferential velocity imparted to the flow is high, causing recirculation in the center region, as demonstrated in Figure 10. This flow recirculation is characterized by high turbulence, intense shear regions, and enhanced mixing rates.

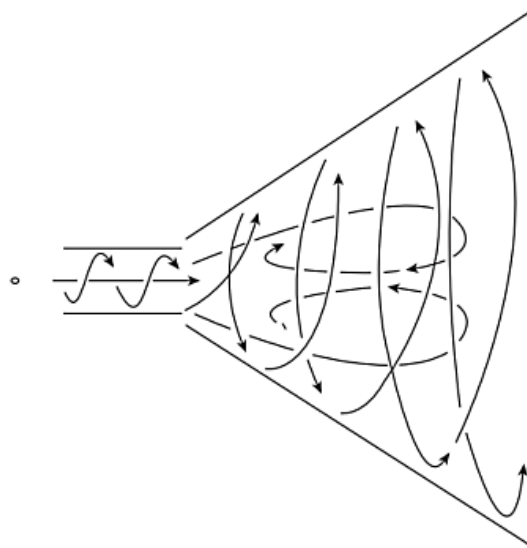


Figure 10 Steady flow circulation in the recirculation or primary zone [42].

The intensity of the swirl determines the swirl motion effectiveness, known as the swirl number (S_N) [43]:

$$S_N = \frac{2}{3} \left[\frac{1 - \left(\frac{d_h}{d_o}\right)^3}{1 - \left(\frac{d_h}{d_o}\right)^2} \right] \tan\theta \quad (1. 2)$$

here d_h represents the hub diameter while d_o represents the outer diameters of the swirler, and θ represents the swirl vane angle. To achieve a strong swirl effect, the swirl number must be greater than 0.6. Below 0.4, no recirculation flow is achieved.

1.2.6.3. Secondary zone

The secondary zone is essential for ensuring efficient combustion, controlling emissions, and maintaining the overall stability of the flame. Its primary function is ensuring complete combustion if the temperature in the primary zone exceeds 2000 K. Dissociation reactions take place when the combustion temperature surpasses 2000K, leading to high concentrations of carbon monoxide (CO) and nitric oxide (NO) when using hydrocarbon and hydrocarbon fuels. Introducing cooled air into the secondary zone aids in the recombination of dissociated species prior to reaching the dilution zone [33]. It is imperative to guarantee the presence of a lean mixture in the secondary zone, along with sufficient residence time to facilitate complete chemical reactions [44].

1.2.6.4. Dilution zone

The combustion gases from the secondary zone will be approximately 1800K and may be excessively hot for the turbine entry. Hence, the dilution zone must ensure that the temperature distribution of the stream is suitable for the turbine by allowing the remaining

air from the compressor to mix with combustion products. The pattern factor (PF) is a variable that determines how effective the dilution zone did the mixing and can be defined as [45]:

$$PF = \frac{T_{max} - T_4}{T_4 - T_3} \quad (1.3)$$

Where T_{max} is the maximum temperature observed, T_3 is the air inlet temperature fed to the combustor, and T_4 is the average outlet combustor temperature. $PF = 0.25$ for modern gas turbine engine [44]. Figure 11 shows the typical temperature profile at the combustor exit. The design process seeks homogeneous temperature distribution at the combustor outlet, avoiding hot spots that can increase the turbine blade's life span.

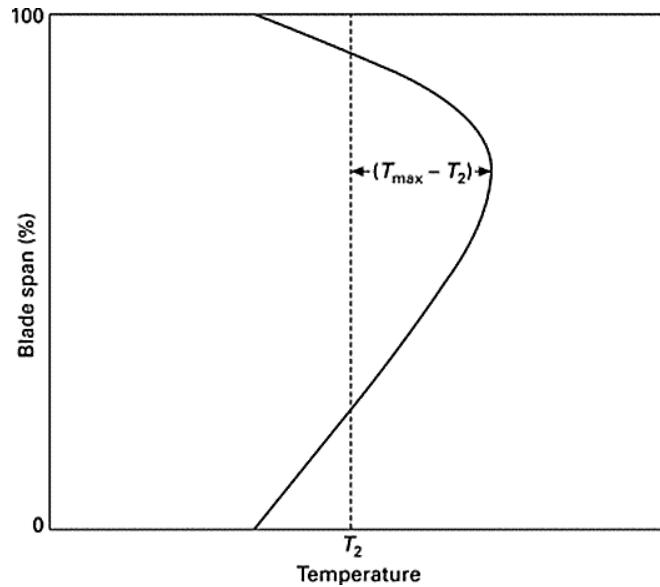


Figure 11 Temperature profile at the gas turbine combustor exit [45].

1.2.6.5. Wall cooling slot

The primary function of the liner walls is to contain the combustion flame and ensure proper air distribution across the designated zones. However, liner walls must be thermally

resistant and structurally robust to handle high temperatures and pressure variations. This is achieved by using high-temperature, oxidant-resistant liner walls and utilizing cooling air efficiently. In practice, the liner-wall temperature is determined by a mix of heat acquired from the hot gas through convection and radiation, and the heat transmitted by radiation and convection to the annulus air [33].

Thermal wall protection can be achieved through various techniques, including machined rings' slots and thermal barrier coating (TBC). Figure 12 depicts the "machined rings" method, which consists of rows of tiny holes in the liner walls that allow annulus air to enter the combustion zone.

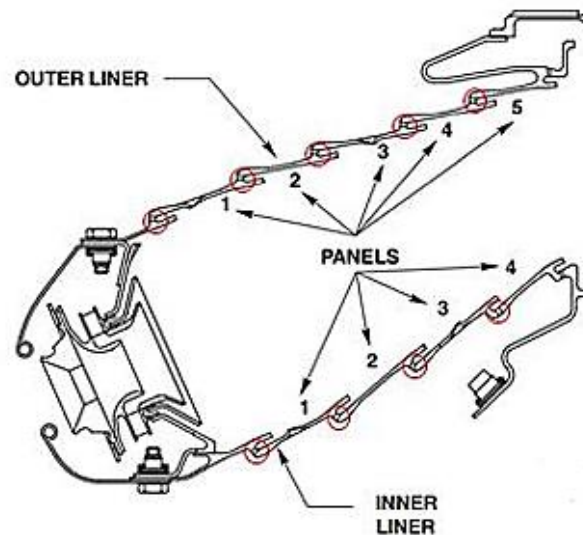


Figure 12 Location of the cooling film slots of CFM56-3 combustion chamber [40].

1.2.7. Regulation and emission analysis for conventional annular combustor

The primary pollutants released by airplanes are Unburned Hydrocarbons (UHC), NO_x (NO and NO₂), Sulphur Oxides (Sox), Carbon Monoxide (CO), and soot. Aviation emissions often have two major effects: local air quality, particularly near airports, and global climate change. Aircraft NO_x emissions account for 70-80% of total airport NO_x pollutants [46]. Unfortunately, this condition will have an impact on human health, such as lung inflammation and decreased immunity to respiratory infections. Other main combustion emissions and their impact on human health can be seen in [46]. The Committee on Aviation Environmental Protection (CAEP) predicted that in the next three decades, nitrogen oxides (NO_x) released below 3000 feet will rise from 0.25 million metric tons (Mt) to 0.72 Mt [47]. Furthermore, ozone depletion produced by high-altitude NO_x emissions contributes to an increase in surface UV radiation.

Over the last five decades, the airline industry has been able to lower fuel consumption by 70% while concurrently managing noise and reducing gaseous CO and HC emissions by approximately 50% and 90%, respectively. Material and cooling technology advancements allowed the engine to operate at greater Turbine Entry Temperature (TET) and Overall Pressure Ratio (OPR), enhancing thermal efficiency and lowering specific fuel consumption (SFC). However, these environmental and economic gains obtained by a higher combustion temperature and efficiency result in a rise in gaseous NO_x emissions [46].

In 1981, the ICAO Committee on Aviation Engine Emissions (CAEE) established the first ICAO standard to regulate aircraft emissions. Over the next two years, CAEE was

combined with the Committee on Aviation Environmental Protection (CAEP) and the Committee on Aircraft Noise (CAN). CAEP meets every three years to continuously develop and revise the emission limits to lessen the environmental impact of aircraft emissions, as shown Figure 13.

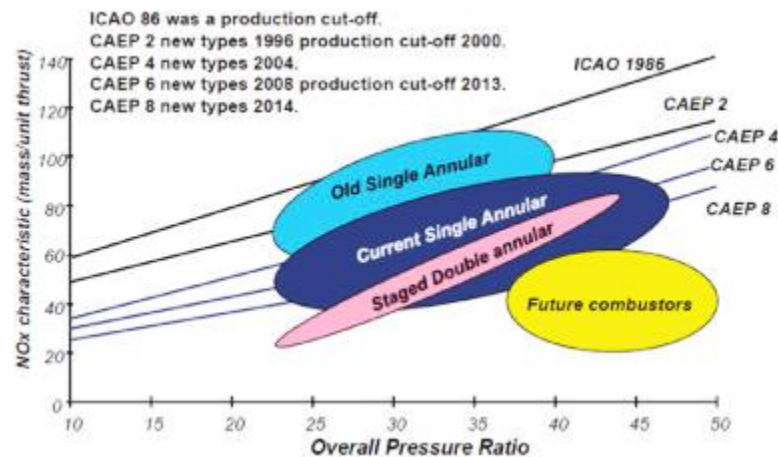


Figure 13 Low NOx combustors with ICAO standards [48].

The International Civil Aviation Organization (ICAO) establishes aircraft emissions regulations using a standard landing take-off (LTO) cycle that replicates aircraft operations at altitudes below 3000 feet (914.4 m). For subsonic aircraft, these flight stages are taxi/idle, take-off, and climb-out, as depicted in Figure 14.

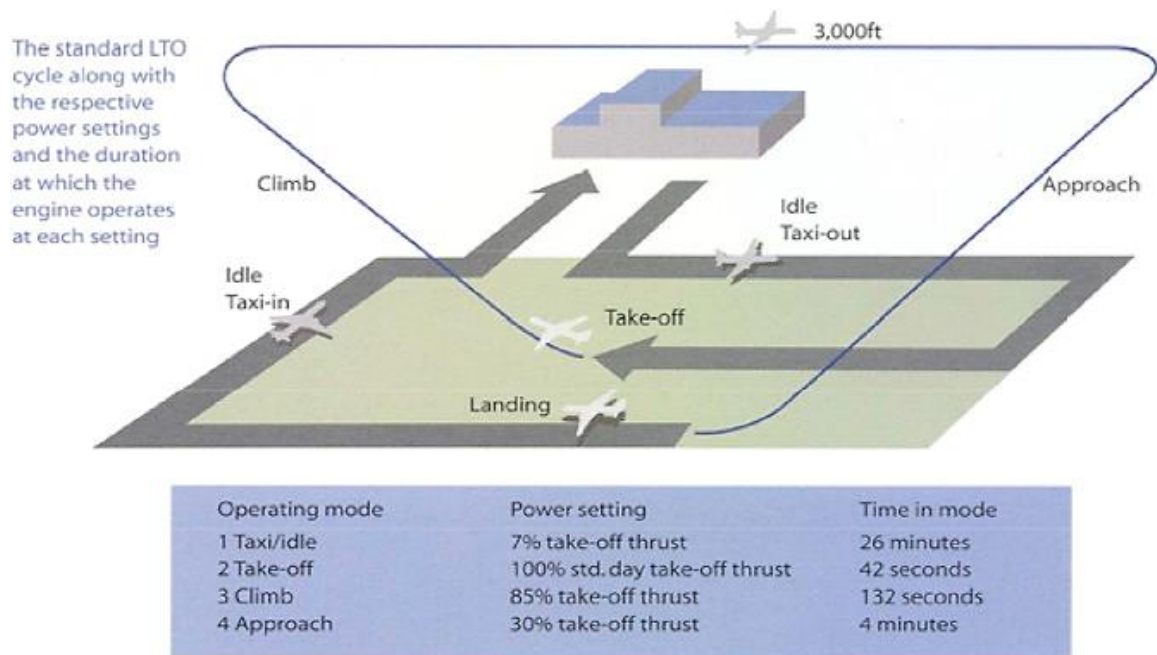


Figure 14 ICAO landing take-off cycle (LTO) [48].

1.2.8. Design for low-emissions combustor

The flame temperature in the primary zone is the most significant factor affecting the emissions from gas turbine combustors [46]. Figure 15 shows emissions related to combustion temperature in the primary zone and the excess air. A significant NO_x level is produced when flame temperatures exceed 1900 K, while an excessive amount of CO is formed when below 1670 K. There is a small range between 1670 K and 1900 K when CO and NO_x levels are comparatively low. Therefore, limiting the primary zone flame temperature within this narrow range is the main strategy for controlling pollutant emissions. However, in this work, the main concern is the reduction of NO_x emissions, which can be achieved using the following methods [46]:

- Rich burn or lean burn in the primary zone. In the former strategy, the residual air is directed through cooling holes to complete the combustion process. However, combustion instabilities may occur when using a lean burn strategy.
- Fuel staging, retaining the local equivalence ratio near the stoichiometric values in the combustion zone to achieve maximum combustion efficiency. Effective fuel-air mixing, using appropriate air swirler and primary jet inlet.
- Appropriate flow residence time, ensuring complete combustion occurs in the chamber.

Many developments in low-emissions combustor technology have occurred in the past five decades. They are: Rich-Burn Quick-quench lean-burn combustor (RQL) [49], Double annular combustors (DAC) [50], Axially staged combustors (ASC) [51], Twin Annular

Premixing Swirler (TAPS) [52], Lean Direct Injectors (LDI) [53], [54], Lean Premixed Prevaporised (LPP) [33], and Variable Geometry Combustors (VGC) [55]. Their technology readiness and detailed assessment can be seen in Ref. [46].

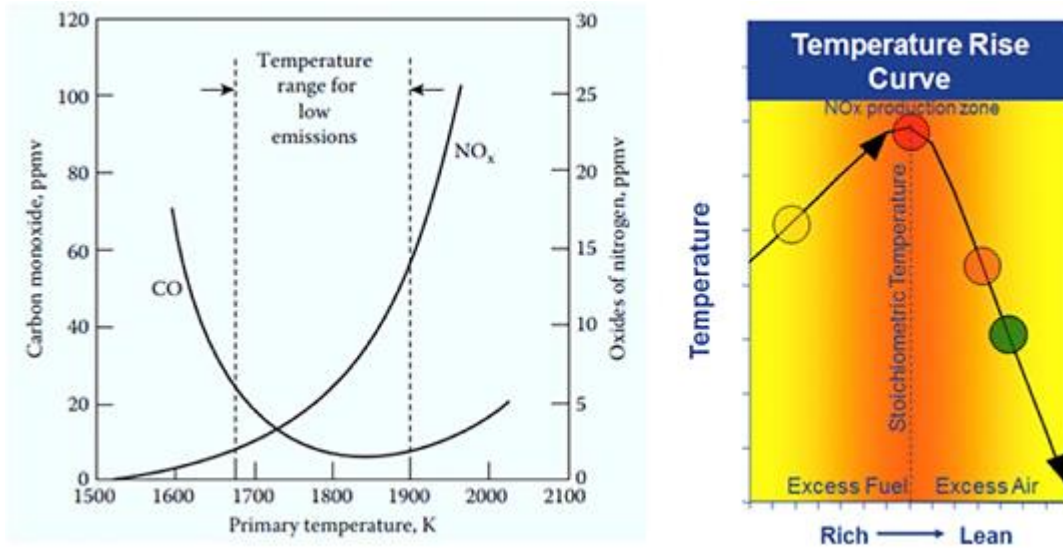


Figure 15 Carbon monoxide (CO) and NOx emissions vs temperature at the primary zone and excess air ratio (EAR) [33].

1.3. Historical Perspective of Hydrogen in Aviation

The concept of converting hydrogen as the primary energy source in aircraft is not new. It goes back to 1783, when Jacques Charles and Robert Brothers launched a hydrogen-fueled air balloon, deemed the first hydrogen-oriented air travel [56]. In the late 1890s, Germany and the United States patented Zeppelin. The Zeppelin's principal structural feature was a fabric-covered strong metal structure made of transverse rings and longitudinal girders that held several hydrogen gasbags [57]. In the late 1930s, the Heinkel He 118 dive bomber prototype was flown with hydrogen jet engines, but the engine's turbines eventually wore out [58]. In the 1950s, ground tests were established as a B-57 airplane, marking it the first jet aircraft to implement hydrogen fuel [59]. Another flight test was carried out in the 1980s using a modified Tu-154 [60]. However, in both projects, only a single engine was retrofitted to operate on cryogenic liquid hydrogen (LH2) [61]. Between 2000 and 2002, the European Commission funded the CRYOPLANE project, led by Airbus Deutschland, to design and investigate an LH2 fuel system for multiple aircraft configurations, including 12-passenger small business jet, 44-passenger regional airliners, 185 passengers medium and long-range aircraft [62]. In 2005, AeroVironment successfully manufactured the world's first hydrogen-powered Unmanned Aerial Vehicle (UAV). This aircraft was designated to operate at a high altitude with a long duration [63]. Boeing created a Diamond DA20, a small-scale propelled-based aircraft, which completed its maiden flight on April 3, 2008 [64]. Furthermore, in July 2012, the hydrogen-based Phantom Eye UAV was presented as the successor to the Diamond DA20 [65]. The first fixed-wing UAV to use liquid hydrogen fuel was intended for intelligence, surveillance, and reconnaissance (ISR) missions. On September 29, 2016, the Hy4 aircraft flew its maiden flight from Stuttgart

Airport [66]. It's the world's first four-seater passenger plane powered solely by hydrogen fuel cells. The plane was developed by DLR researchers, along with various industry and research partners. In 2021, HyFlyer was successfully flown, and a six-seater Cessna aircraft was retrofitted to accommodate hydrogen fuel cells [67].

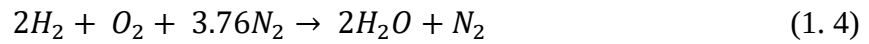
1.4. Hydrogen Fuels

Understanding the properties of hydrogen is crucial for using it as a primary fuel source. In recent decades, hydrogen fuel has been incorporated into various internal combustion engines due to its appealing characteristics. However, in this work, the author describes the performance of hydrogen flames exclusively for turbine gas uses.

Hydrogen is an eco-friendly fuel that may decrease pollutant emissions in gas turbine engines [33]. Hydrogen combustion in aircraft can minimize climate effects by up to 75% compared to fossil jet fuel [68]. This reduction in climate impact is caused by its combustion, which produces no carbon emissions. However, hydrogen combustion emits NO_x and water vapor since these are considered pollutants through their radiative forcing effects and contribute to climate change [69]. Initial research on hydrogen-fueled aircraft indicates that lean-mixture fuel can cut NO_x emissions up to 70% without significantly reducing combustion efficiency [23]. Despite producing almost three times the amount of water vapor than kerosene, hydrogen combustion does not emit soot. However, unlike NO_x emissions, water vapor does not stay long as it can condense and precipitate out as snow or rain within days. Thus, the primary purpose of this project is to reduce or limit the quantity of NO_x created by hydrogen combustion. In the following subsections, all relevant parameters and considerations are discussed.

1.4.1. Reaction mechanisms

Chemical reactions are accomplished in an appropriate condition between two species or more. To react, these species must engage with sufficient kinetic energy (i.e., the Activation energy, E_{act}) and proper geometrical orientation. The produced collision is then forming a new species. The stoichiometric chemical equation for hydrogen (H_2) and air combustion is expressed as follows:



The chemical equation (1.4) is referred to as the global reaction. This reaction, however, does not illustrate the entire reaction mechanisms of hydrogen combustion. Since the hydrogen molecule is highly reactive and susceptible to molecular diffusion, the combustion process involves several intermediate species and elementary reactions. Hence, detailed kinetic mechanisms are pivotal to predicting emissions, auto-ignition, and flashback [70] within an engine. In addition, CFD can implement these mechanisms to simulate the rate of reaction of hydrogen and air.

In recent decades, various H_2/O_2 combustion mechanisms were published [71], [72], [73], [74], with the inclusion of syngas [75], [76], [77], [78], [79] and hydrocarbon oxidation mechanism [80], [81]. Olm et al. [82] compared the performance of these detailed mechanisms based on experimental data, experimental conditions, and dependence on accuracy. In his investigation, it is concluded that the detailed mechanism published in reference [75] demonstrated the highest performance compared to other hydrogen mechanisms. However, as an illustration, the detailed hydrogen/air reaction mechanism of work done in [71] is shown in Table 02.

Table 02 H₂/O₂ reaction mechanism (units: cm³, mol, s, kcal, K) [71].

	Reaction	A	N	E ^{act}	Ref
H ₂ /O ₂ chain reactions					
1	$\dot{\text{H}} + \text{O}_2 = \dot{\text{O}} + \dot{\text{O}}\text{H}$	1.91×10^{14}	0.00	16.44	[83]
2	$\dot{\text{O}} + \text{H}_2 = \dot{\text{H}} + \dot{\text{O}}\text{H}$	5.08×10^4	2.67	6.292	[84]
3	$\dot{\text{O}}\text{H} + \text{H}_2 = \dot{\text{H}} + \text{H}_2\text{O}$	2.16×10^8	1.51	3.43	[85]
4	$\dot{\text{O}} + \text{H}_2\text{O} = \dot{\text{O}}\text{H} + \dot{\text{O}}\text{H}$	2.97×10^6	2.02	13.4	[86]
H ₂ /O ₂ dissociation/recombination reactions					
5	$\text{H}_2 + \text{M} = \dot{\text{H}} + \dot{\text{H}} + \text{M}$	4.57×10^{19}	-1.40	105.1	[87]
6	$\dot{\text{O}} + \dot{\text{O}} + \text{M} = \text{O}_2 + \text{M}$	6.17×10^{15}	-0.50	0.00	[87]
7	$\dot{\text{O}} + \dot{\text{H}} + \text{M} = \text{O} \dot{\text{H}} + \text{M}$	4.72×10^{18}	-1.00	0.00	[87]
8	$\dot{\text{H}} + \dot{\text{O}}\text{H} + \text{M} = \text{H}_2\text{O} + \text{M}$	4.50×10^{22}	-2.00	0.00	[87]
Formation and consumption of H $\dot{\text{O}}_2$					
9	$\dot{\text{H}} + \text{O}_2 + \text{M} = \text{H}\dot{\text{O}}_2 + \text{M}$	3.48×10^{16}	-0.41	-1.12	[88]
	$\dot{\text{H}} + \text{O}_2 = \text{H}\dot{\text{O}}_2$	1.48×10^{12}	0.60	0.00	[89]
10	$\text{H}\dot{\text{O}}_2 + \dot{\text{H}} = \text{H}_2 + \text{O}_2$	1.66×10^{13}	0.00	0.82	[90]
11	$\text{H}\dot{\text{O}}_2 + \dot{\text{H}} = \dot{\text{O}}\text{H} + \dot{\text{O}}\text{H}$	7.08×10^{13}	0.00	0.30	[90]
12	$\text{H}\dot{\text{O}}_2 + \dot{\text{O}} = \dot{\text{O}}\text{H} + \text{O}_2$	3.25×10^{13}	0.00	0.00	[91]
13	$\text{H}\dot{\text{O}}_2 + \dot{\text{O}}\text{H} = \text{H}_2\text{O} + \text{O}_2$	2.89×10^{13}	0.00	-0.50	[91]
Formation and consumption of H ₂ O ₂					
14	$\text{H}\dot{\text{O}}_2 + \text{H}\dot{\text{O}}_2 = \text{H}_2\text{O}_2 + \text{O}_2$	4.2×10^{14}	0.00	11.98	[92]
	$\text{H}\dot{\text{O}}_2 + \text{H}\dot{\text{O}}_2 = \text{H}_2\text{O}_2 + \text{O}_2$	1.3×10^{11}	0.00	-1.629	[92]

15	$\text{H}_2\text{O}_2 + \text{M} = \dot{\text{O}}\text{H} + \text{O}\dot{\text{H}} + \text{M}$	1.27×10^{17}	0.00	45.5	
	$\text{H}_2\text{O}_2 = \dot{\text{O}}\text{H} + \text{O}\dot{\text{H}}$	2.95×10^{14}	0.00	48.4	[93]
16	$\text{H}_2\text{O}_2 + \dot{\text{H}} = \text{H}_2\text{O} + \dot{\text{O}}\text{H}$	2.41×10^{13}	0.00	3.97	[87]
17	$\text{H}_2\text{O}_2 + \dot{\text{H}} = \text{H}_2 + \text{H}\dot{\text{O}}_2$	6.03×10^{13}	0.00	7.95	[87]
18	$\text{H}_2\text{O}_2 + \dot{\text{O}} = \dot{\text{O}}\text{H} + \text{H}\dot{\text{O}}_2$	9.55×10^6	2.00	3.97	[87]
19	$\text{H}_2\text{O}_2 + \dot{\text{O}}\text{H} = \text{H}_2\text{O} + \text{H}\dot{\text{O}}_2$	1.0×10^{12}	0.00	0.00	[94]
	$\text{H}_2\text{O}_2 + \dot{\text{O}}\text{H} = \text{H}_2\text{O} + \text{H}\dot{\text{O}}_2$	5.8×10^{14}	0.00	9.56	[94]
Efficiency factors and other parameters are described in [71]					

1.4.1.1. Mixture ratios and combustion stoichiometry

The mixture ratio is the ratio of fuel and oxidizer in the combustion zone. In a premixed flame, the mixture ratio is constant throughout the system. However, diffusion flame allows various mixture ratios [29]. The mixture ratio is often expressed as the fuel-to-air ratio (FAR) or air-to-fuel ratio (AFR). Another relevant term is the equivalence ratio. The equivalence ratio represents the actual FAR or AFR ratio to the stoichiometric value, respectively. The FAR can be formulated by the following equation [29]:

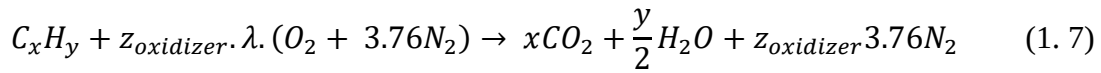
$$FAR = \frac{\dot{m}_f}{\dot{m}_a} = \frac{1}{AFR} \quad (1.5)$$

Here, $\dot{m}_f$ represents the fuel mass flow rate and $\dot{m}_a$ is defined as the air mass flow rate.

While the equivalence ratio (ϕ) may be expressed as:

$$\phi = \frac{FAR_{actual}}{FAR_{stoichiometric}} = \frac{\left(\frac{\dot{m}_f}{\dot{m}_a}\right)_{actual}}{\left(\frac{\dot{m}_f}{\dot{m}_a}\right)_{stoichiometric}} \quad (1.6)$$

A stoichiometric mixture means $\phi = 1$; a lean mixture $\phi < 1$; while a rich mixture $\phi > 1$. A stoichiometric reaction occurs when the amount of oxidizer is sufficient to burn the fuel fully [95]. In theory, this reaction is the most economical. In hydrocarbon combustion, a stoichiometric reaction indicates the byproducts of combustion are carbon dioxide, water vapor, and inert nitrogen gas, as given in the equation below:



Where: $z_{oxidizer} = x + y/4$. λ is the excess air coefficient for stoichiometric reaction $\lambda = 1$.

In eq. (1.7), for 1 mole of C_xH_y , it requires a total amount of $z_{oxidizer}$ a mole of air ($O_2 + 3.76N_2$) to have a stoichiometric reaction. The value of 3.76 moles of nitrogen is the ratio of 79% nitrogen to 21% oxygen in the air. Based on eq. (1.9), the stoichiometric FAR can be formulated as:

$$(FAR)_{stoich} = \left(\frac{\dot{m}_f}{\dot{m}_a} \right)_{stoich} = \frac{1}{4.762z_{oxidizer}} \frac{M_{fuel}}{M_{air}} \quad (1.8)$$

In this equation, M_{fuel} is the molar mass of the fuel, while M_{air} is the molar mass of the air/oxidizer. $(FAR)_{stoich}$ both for jet A and hydrogen fuel can be seen in Table 03.

1.4.1.2. Thermal NOx formation

NOx emissions are mostly composed of nitric oxide (NO), with smaller amounts of nitrous oxide (N₂O) and nitrogen dioxide (NO₂). NOx contributes to photochemical smog, causes acid rain, and depletes the ozone layer, making it a significant pollutant [96].

The formation of NO_x in a turbulent flame is often caused by four distinct mechanisms: thermal NO_x, prompt NO_x, fuel NO_x, and intermediate N₂O. For hydrogen flames, the relevant NO_x mechanisms are associated with thermal NO_x and intermediate N₂O [29]. The extended Zeldovich mechanism determines the generation of thermal NO_x through a series of highly local temperature-dependent chemical processes. The key processes involved for the generation of thermal NO_x are listed below [96]:



The net rate formation of thermal NO_x via reactions (1.9) - (1.11) is given by:

$$\frac{d[NO]}{dt} = k_{f,1}[O][N_2] + k_{f,2}[N][O_2] + k_{f,3}[N][OH] - k_{r,1}[NO][N] - k_{r,2}[NO][O] - k_{r,3}[NO][H] \quad (1.12)$$

Where: $k_{f,1} = 1.8 \times 10^8 e^{-38370/T}$, $k_{f,2} = 1.8 \times 10^4 e^{-4680/T}$, $k_{f,3} = 7.1 \times 10^7 e^{-450/T}$, $k_{r,1} = 3.8 \times 10^7 e^{-425/T}$, $k_{r,2} = 3.81 \times 10^3 T e^{-20820/T}$, and $k_{r,3} = 1.7 \times 10^8 e^{-24560/T}$.

For a lean mixture, the steady state assumption can be established. Then the NO formation rate becomes:

$$\frac{d[NO]}{dt} = k_{f,1}[O][N_2] \frac{\left(1 - \frac{k_{r,1}k_{r,2}[NO]^2}{k_{f,1}[N_2]k_{f,2}[O_2]}\right)}{\left(1 + \frac{k_{r,1}[NO]}{k_{f,2}[O_2] + k_{f,3}[OH]}\right)} \left(\frac{gmol}{m^3s}\right) \quad (1.13)$$

1.4.1.3. Intermediate N₂O

Malte and Pratt [97] hypothesized the first intermediate pathway of NO_x synthesis from molecular nitrogen (N₂) using nitrous oxide (N₂O). Nitrogen is primarily part of the

combustion and dilution of air. However, under certain circumstances, such as high pressures and oxygen levels, this intermediary process may account for up to 90% of the NO_x produced during combustion. Hence, this is relevant in machinery like compression ignition and gas turbine engines. The N₂O-intermediate pathway has been found to account for approximately thirty percent of the overall NO_x generated by these systems.

The most fundamental model of the intermediate N₂O process involves two reversible reactions [97]:



For elevated pressure:



The rate of NO_x formation through intermediate N₂O mechanism:

$$\frac{d[NO]}{dt} = 2(k_{f,2}[N_2O][O] - k_{r,2}[NO]^2) \text{ gmol/m}^3\text{s} \quad (1.17)$$

At quasi-steady state:

$$[N_2O] = \frac{k_{f,1}[N_2][O][M] + k_{r,2}[NO]^2}{k_{r,1}[M] + k_{f,2}[O]} \quad (1.18)$$

Where: $k_{f,1} = 4.44 \times 10^{32} T^{-8.358} e^{-28234/T}$, $k_{f,2} = 2.9 \times 10^7 e^{-11651/T}$, $k_{r,1} = 4.0 \times 10^8 e^{-28234/T}$, and $k_{r,2} = 1.45 \times 10^{-29} T^{9.259} e^{-11651/T}$.

1.4.2. Hydrogen fuel properties

1.4.2.1. General comparison to Jet A fuel and consideration of fitting hydrogen fuel into gas turbine engine

"Jet fuel" generally refers to aviation fuels used in gas turbine engine aircraft. It is traditionally known as kerosene fuel, derived from the kerosene fraction obtained during the distillation of crude oil (~150-275 °C) [66]. Typical jet fuel contains thousands of chemical compounds, up to 20% being aromatic [67], [68]. Since the late 1930s, the two primary types of jet fuel have been Jet A, mainly used in the United States, and Jet A-1, which is commonly used in other regions of the world. The key difference is that Jet A-1 has a lower freezing point than Jet A, which is -47 °C and -41 °C, respectively [69]. However, both possess the same minimum flash point of 38 °C.

In contrast to kerosene fuel, hydrogen is the universe's most fundamental and ubiquitous chemical substance. Under ideal circumstances, it exists as a diatomic gas (H_2), having the lowest gravimetric density among other gaseous chemical elements. Today, hydrogen is a feasible alternative for conventional jet fuel since it has a high heating value with low-carbon emissions, provides energy security, and reduces particulate matter [98]. As shown in Table 03, hydrogen fuel offers almost triple the gravimetric energy density of jet A fuel. Furthermore, it provides a wider flammability limit range under sea-level conditions. However, the obvious concern regarding hydrogen fuel is that it requires a much larger storage tank due to its low volumetric density. All these drawbacks, unfortunately, compensate for the gravimetric energy density of hydrogen fuel, reducing the economic efficiency of long-range hydrogen-powered aircraft [23], [69]. To benefit fully from hydrogen fuel, aircraft need to undergo major modifications. This includes redesigning all

aircraft systems, such as propulsion systems, fuel tanks and supply, and fuselage configuration [23].

Integrating hydrogen fuel into existing gas turbine engines requires significant consideration. Key modifications include the fuel injection method and the fuel evaporation system. Additionally, the combustion chamber must be redesigned to enhance combustion performance. As Haglind and Singh [101] stated, the net thrust or the combustor outlet temperature (COT) can be retained when switching to hydrogen fuel.

Boggia and Jackson [99] suggest that hydrogen fuel enhances performance due to changes in combustion products within the turbines. However, this improvement is offset by a reduction in mass flow, which negatively impacts performance. A decrease in mass flow into the turbines reduces thrust power for two reasons. Firstly, if there is no variation in exhaust gas composition, reduced fuel flow decreases total exhaust mass flow accordingly. Secondly, reduced mass flow leads to a larger total temperature and pressure drop. However, the composition change in the hydrogen combustion product compensates for the reduced fluid flow. It is worth noting that, theoretically, the only combustion product of hydrogen flame is water vapor (H_2O). Under fixed power, the water vapor (H_2O) increases the thrust output, lowers the total pressure, and temperature drops, owing to its higher c_p than carbon dioxide (CO_2). In summary, improved c_p overcomes the reduced mass flow thrust output, enhancing net thrust and maintaining the COT.

Table 03 Jet A and hydrogen fuel properties comparison [100], [101].

Properties	Jet A (Kerosene)	Hydrogen
Carbon content	12	0
Stoichiometric AFR	14.6	34.3
Stoichiometric FAR	0.0685	0.0291
Stoichiometric fuel fraction (%)	1.2	29.6
Flammability limits within air mixture (vol%) at sea level	0.6-5	4-75
Density at gas phase (kg/m ³)	7.1	0.08
The gravimetric energy density (MJ/kg)	43.24	120.0
Volumetric energy density (MJ/L)	34.2	8.4
Minimum ignition energy (mJ)	2	0.018
Flame speed (cm/s)	60	250
Adiabatic Flame Temperature (K)	2419	2525

1.4.2.2. Laminar burning velocity

Laminar burning velocity refers to the speed at which a planar flame moves into an unburned mixture under defined pressure and temperature conditions [102]. A high laminar burning velocity would generate rapid combustion. Exact measurements of burning speed are critical in validating the computational model as well as in practical systems [103]. Specifically, the burning velocities of the H₂-air mixture are instrumental in devising the pertinent application [104].

Ghosh et al. [105] studied the laminar burning velocity of H₂ /air flames at near-cryogenic temperatures across different equivalence ratios. In his study, the initial temperature for fuel-air mixture reaches as low as 160K, considering that hydrogen-powered aircraft

operate on cryogenic fuel tanks to minimize the required volume for hydrogen storage systems [106]. Figure 16 shows the impact of the equivalence ratio on the laminar burning velocities of hydrogen, methane, ethylene, and propane flames at room temperature and atmospheric pressure. It is well agreed that a lean fuel-air mixture decreases the laminar burning velocities, including the hydrogen fuel. Correspondingly, lowering the temperature of the mix abates the flame propagation to the unburned blend, as shown in Figure 17.

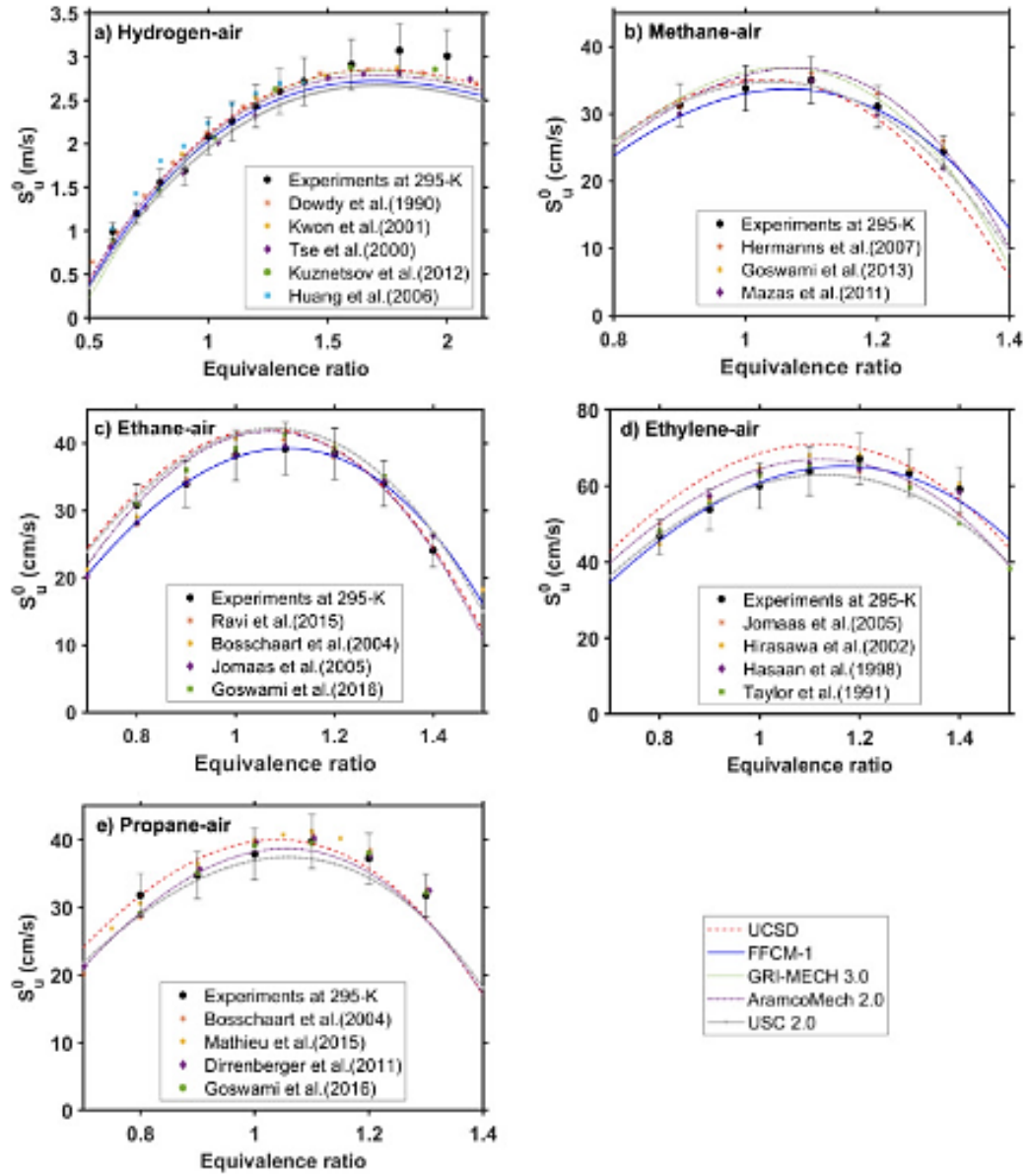


Figure 16 The laminar burning velocity of several fuels at different equivalence ratios at atmospheric pressure and temperature [105].

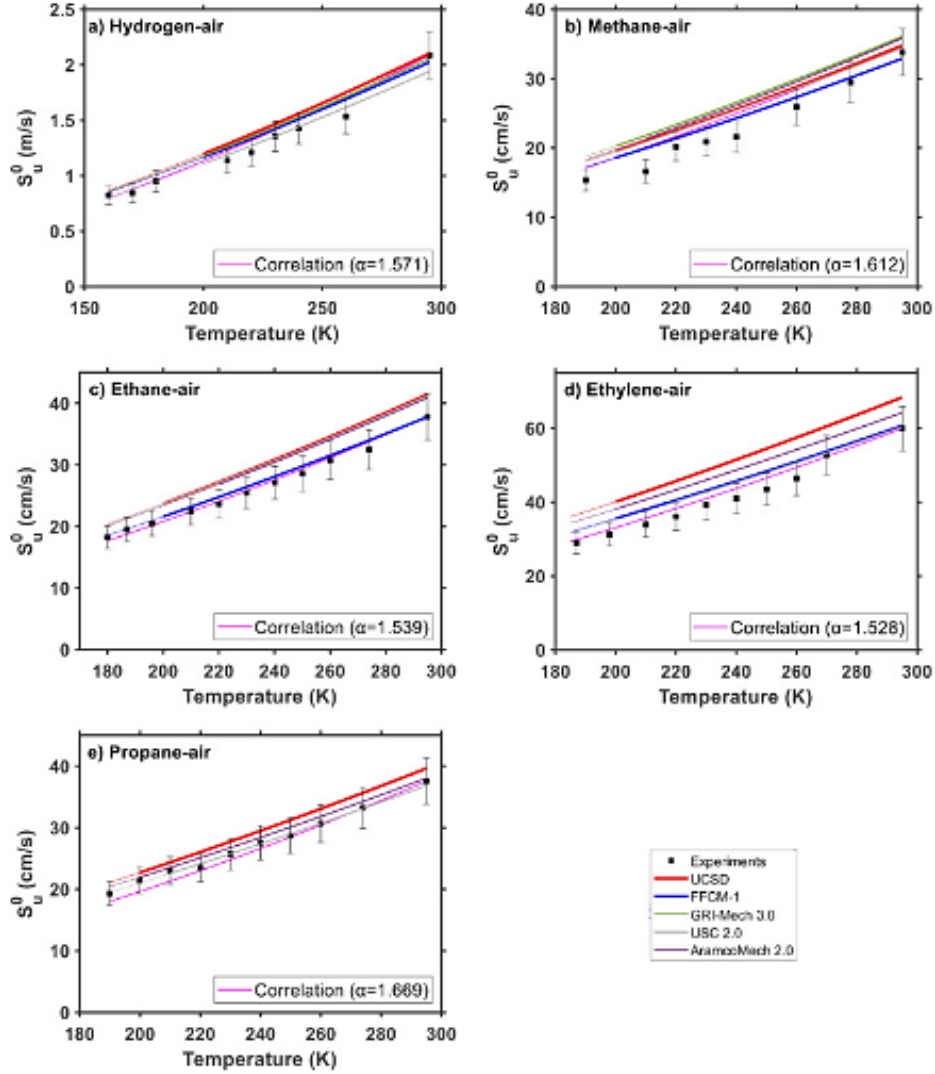


Figure 17 Laminar burning velocities at fixed stoichiometric ratio and difference in temperature [105].

1.4.2.3. Detailed hydrogen adiabatic flame temperature

The theoretical maximum temperature produced inside the combustion chamber where no heat exchange occurs with the surroundings is identified as adiabatic flame temperature (AFT) [107]. In other words, the system is insulated, preventing heat from escaping or entering the system. In real-life scenarios, however, heat exchange is inevitable during combustion, leading to lower combustion temperatures than AFT. When the flame temperature exceeds 1800K, combustion products undergo dissociation, developing

radicals and highly diffusive species. These dissociation reactions are called endothermic reactions, in which heat energy is absorbed, thus lowering the flame temperature [45].

Figure 18 presents AFT for several fuels at different equivalence ratios, including hydrogen [108]. Figure 19 illustrates the influence of hydrogen blends on the AFT of methane/air combustion for turbine gas application [109]. Hydrogen fuel holds a high adiabatic flame temperature relative to other natural gas. Moreover, hydrogen enrichment of syngas-air combustion increases AFT due to accelerated reaction rate, leading to higher combustion efficiency. However, hydrogen enrichment into the mixture consequently increases the pollutant NO emissions [110]. Hence, a leaner fuel regime may suppress NO_x formation [109].

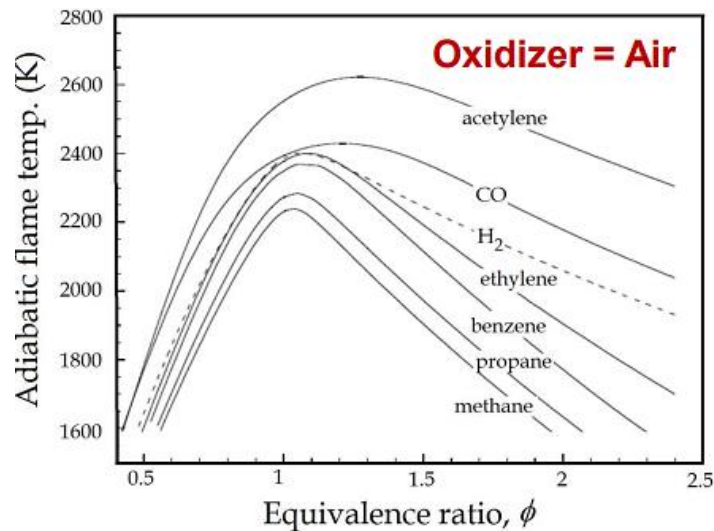


Figure 18 Adiabatic flame temperature of acetylene, CO, hydrogen, ethylene, benzene, propane, and methane over various equivalence ratios [108].

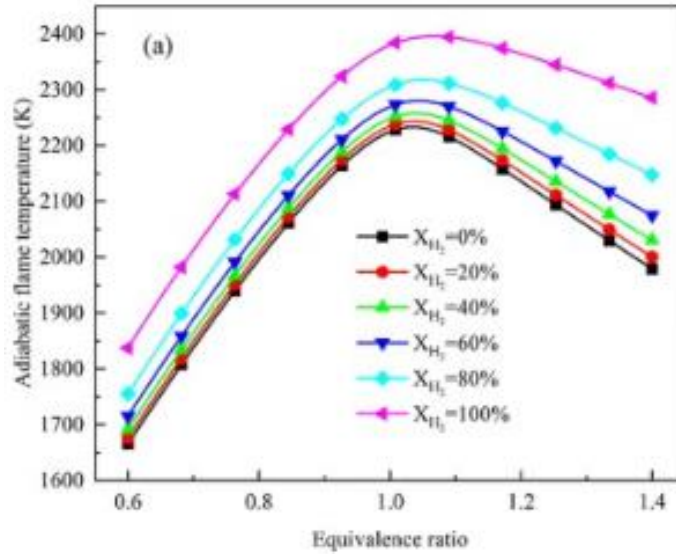


Figure 19 Adiabatic flame temperature of methane-air combustion with hydrogen enrichment at difference equivalence ratios [109].

1.2.5.4. Flame shape

This section provides a visual representation of flame shapes to gain more insight into hydrogen combustion. The effect of hydrogen enrichment on methane-air combustion with an equivalence ratio of 1.0 is presented in Figure 20. This figure shows that hydrogen addition holds significant importance to the flame structure. Using pure methane, it is observable that the flames extend across the combustor base, conforming to the vessel's shape. In contrast, a higher hydrogen content is characterized by more intense and concentrated flames, indicating faster reactions and higher flame speeds. Additionally, a greater hydrogen percentage results in increased audible noise related to combustion dynamics. As throat velocities increase, the noise level also rises due to the higher turbulent flame speed, which leads to a greater risk of flashback [111].

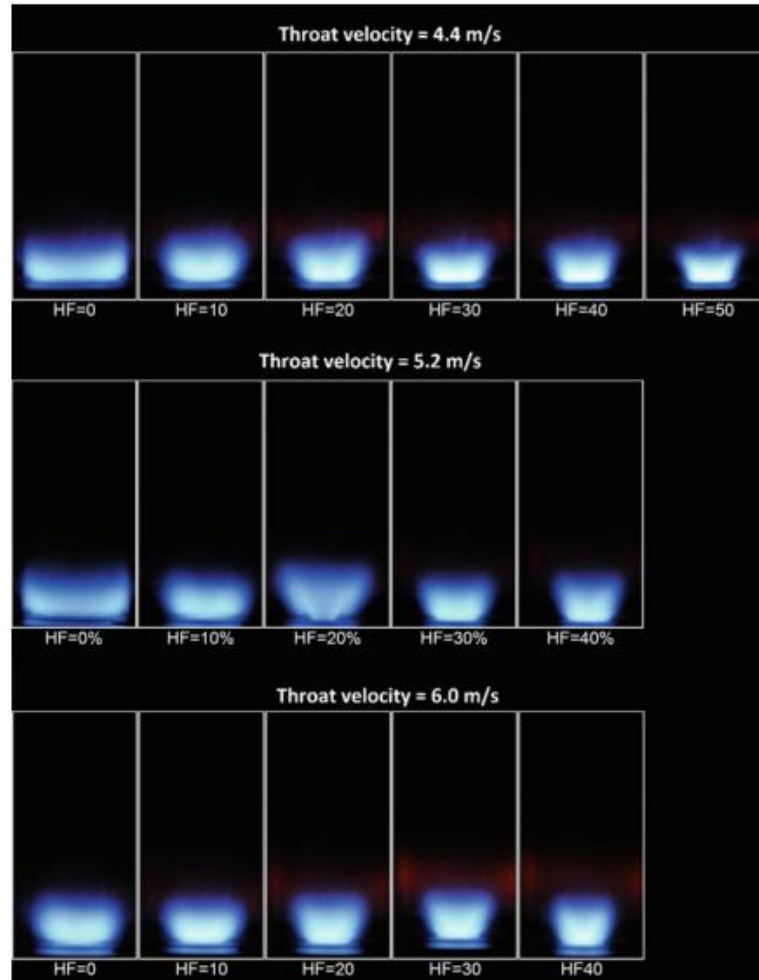


Figure 20 Flame shapes of methane-hydrogen-air at an equivalence ratio of 1.0 over different throat velocities and hydrogen fractions [112].

1.5. Thesis Objective

Based on the reviewed literature and identified gaps, the primary goal of this thesis is to numerically assess the feasibility of a hydrogen-based burner for jet engines and compare its performance with Jet A fuel. To achieve this, the following objectives are essential for studying the behavior of hydrogen combustion in an annular combustor.

- Investigate the combustion process of the hydrogen-based burner of a jet engine.
- Evaluate the combustion emissions, especially NO_x formation, compared to existing jet engines.
- Investigate the influence of the number and orientation of fuel injectors.
- Investigate the influence of the swirling vane angles.

| CHAPTER 2 |

| LITERATURE REVIEW

2.1.Literature for Hydrogen Injection Method

Over the past few decades, many authors have examined potential approaches to abate carbon and NO_x emissions in gas turbine systems. Ziemann et al. [113] investigated the fuel injector method for lean hydrogen combustion with two concepts, namely premixed and non-premixed combustors for aero engines. This study concluded that NO_x emission can be mitigated depending on the premixing capability. Smith et al. [38] studied several burner designs to be adopted in high-pressure ratio aero engines. His investigation suggested that lean premixed pre-vaporized and lean catalytic are deemed unfeasible for jet engines. Instead, he concluded that lean direct injection (LDI) with multiple injectors is highly promising in the foreseeable future. This conclusion was concurred with the study conducted by Haglind and Singh [114]. Adapting a conventional combustion chamber for hydrogen use involves replacing the injection system, as kerosene is injected in a liquid state, whereas hydrogen is introduced in its gaseous form. Marek et al. [115] experimented with five LDI configurations to study lean hydrogen combustion performance. Tests were established at different inlet temperatures ranging from 600° to 1000° F, inlet pressure ranging from 60 to 200 psi, and equivalence ratio up to 0.48. This experiment demonstrated that the combustion was steady, and NO_x emissions were comparable to jet A combustion. Zareei et al. [116] discovered that increasing the number of fuel injectors can boost the performance while decreasing emissions of internal combustion engines. Domingues and Brójo [117] concluded that, theoretically, Retrofitting a CFM56-3 combustor to use

hydrogen fuel requires modifying the injection system. However, the NO_x emissions generated from burning hydrogen are estimated to be nearly twice as high as those produced by Jet A. Lei and Khandelwal [118] investigated different angles of hydrogen fuel injectors to reduce NO_x emissions. It was found that the introduction of an angled air inlet resulted in an increased airflow rotation, enhancing the blending intensity of fuel and oxidizer. Joshi et al. [119] designed a modified fuel injection system for a DACRS premixer. In this design, fuel injectors are perpendicular to the main airflow, which promotes rapid and thorough mixing of fuel and air. Their experiment observed that single-digit NO_x emissions were produced using the transverse fuel injection method. Dahl and Suttrop [17] developed a hydrogen micromix module into an Auxiliary Power Unit (APU) of the GTCP 36-300 engine. This approach allows the phenomenon of jet-in-crossflow of fuel and oxidizer, similar to what has been showed by Joshi et al. [119]. However, this design also enables the miniaturization of flamelets, reducing NO_x pollutants considerably [120]. Moreover, the risk of flashback can be avoided because of the absence of a flammable fuel-air mixture before the injectors. Pourhoseini et al. [121] demonstrated through their experiment that large swirl angle vanes decrease NO_x emissions.

2.2.Literature for Simulation Methods

Many have utilized different approaches to predict turbulence behavior for gas turbine burners. Jiang [122] explored and validated six commonly used Reynolds-Averaged Navier-Stokes (RANS) turbulence models. The validation process involves a comprehensive comparison against the experimental database from the related combustor model. This study revealed that the Reynolds Stress Model (RSM) produced the highest accuracy, where it was the only model that could simulate the recirculation zone accurately. However, the $k-\varepsilon$ model can give similar results under the same configuration and operating conditions. Boudier et al. [123] compared the accuracy of Large Eddy Simulation (LES) and RANS turbulence solver against the experimental data of an aero gas turbine burner. This study concluded that LES provides incredible applicability for industrial purposes, given its ability to predict highly accurate unsteady turbulence reacting flows. Additionally, it can predict temperature fields and velocity profiles to a much higher degree. However, the LES model is deemed computationally expensive compared to other turbulence models under the same geometry, number of meshing, and boundary conditions [124]. Therefore, the RANS model, specifically $k-\varepsilon$, was opted to solve the reacting flow for the gas turbine burner, given its sufficient results in the free stream region [125]. According to Jakaria et al. [126], the realizable $k-\varepsilon$ is sufficient to simulate turbulent hydrogen flame.

The turbulent-combustion interaction is one of the most complicated studies in this domain. Numerous models are offered for modeling non-premixed turbulent flames, with significant differences in processing costs, accuracy, and intricacy [127]. The Eddy dissipation model (EDM) and presumed PDF (Probability Density Function) are two

affordable computational combustion non-premixed models widely used in many engineering applications. Rohani et al. [127] compared the EDM and PDF models for non-premixed methane flame against experimental data. His study concluded that the presumed PDF model shows better agreement with the experimental value regarding combustion temperature. Lau [128] compared the PDF model and EDM performance for propane jet flame. Using a PDF model, his investigation accurately predicted the combustion products: CO, CO₂, and NO. Benim and Pfeiffelmann [129] analyzed three different combustion models, including EDM, PDF, and Eddy dissipation concept (EDC) for lifted hydrogen flames using the RANS turbulence model. Their study concluded that incorporating a PDF combustion model is better for the whole range of experiment data.

There are various radiation models available in Fluent, namely the Discrete Transfer Radiation Model (DTRM) [130], P-1 radiation model [131], Rosseland radiation model [131], Surface-to-Surface (S2S) radiation model [131], and Discrete Ordinate (DO) radiation model [132]. Each of these methods has its advantages and drawbacks. For instance, the P-1 radiation model is the simplest case of the more general P-N model and requires little central processing unit (CPU) demand. However, for complicated geometry, there might be a loss of accuracy and tends to over-predict radiative fluxes [96]. Gamil et al. [133] compared the P-1 and DO radiation models on the flame and liner walls of the Rolls-Royce-RB-183 combustion chamber. In his investigation, the DO was more accurate in estimating the combustor wall and flow temperatures than the P-1 radiation method. However, it requires more CPU power.

CHAPTER 3

NUMERICAL METHODOLOGY

In this work, a numerical setup was conducted with three steps, as shown in Figure 21. First, the simulation of non-premixed turbulent simple flame using hydrogen, as shown in the work of [134], [135], [136]. Second, the simulation of non-premixed kerosene in an annular combustion chamber is similar to the work in [44], [137]. This method was selected mainly because of the lack of experimental and numerical data on hydrogen flames in annular combustion chambers. Another reason is that the turbulence and energy models employed in the simple non-premixed hydrogen flame can be justified and later used in the annular combustion chamber.

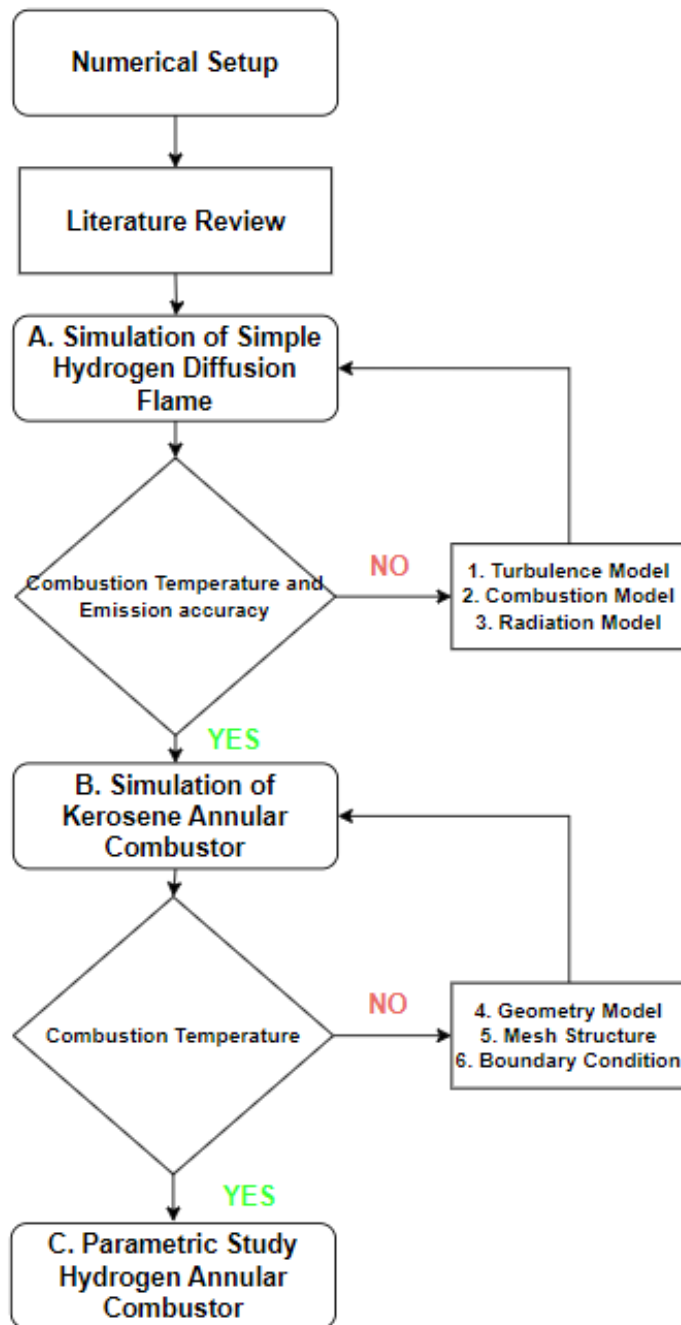


Figure 21 Steps of numerical setup for hydrogen annular combustion chamber.

3.1. Governing Equations

The governing equations for non-premixed combustion involve the conservation of mass, momentum, and energy [138]. RANS governs the Navier-Stokes equation into averaged and fluctuating components [96].

3.1.1. Conservation of mass, momentum, and turbulence model

Conservation of mass can be formulated as follows [139]:

$$\frac{\partial \bar{\rho}}{\partial t} + \frac{\partial}{\partial x_i} (\bar{\rho} \tilde{u}_i) = 0 \quad (3.1)$$

where the term $\bar{\rho}$ is defined as the mean density, while $\tilde{u}_i$ refers to the velocity vector.

The conservation of momentum can be expressed as:

$$\begin{aligned} \frac{\partial (\bar{\rho} \tilde{u}_i)}{\partial t} + \frac{\partial (\bar{\rho} \tilde{u}_i \tilde{u}_j)}{\partial x_j} \\ = - \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial \tilde{u}_k}{\partial x_k} \right) \right] \\ + \frac{\partial}{\partial x_j} (-\overline{\rho u'_i u'_j}) \end{aligned} \quad (3.2)$$

Here, the term $\tilde{u}_i, \tilde{u}_j$, and $\tilde{u}_k$ represent the Favre-averaged velocity components. The symbols u'_i and u'_j are described as the fluctuating term. The term $\bar{p}$ is defined as the time-averaged statistic pressure, while μ is the molecular viscosity. Eq. (3.1) and Eq. (3.2) are described as the RANS equations.

The Reynolds stresses $(-\overline{\rho u'_i u'_j})$ must be modeled to close Eq. (3.2) by using the Boussinesq hypothesis with the following formula:

$$-\overline{\rho u'_i u'_j} \approx \mu_t \left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial \tilde{u}_k}{\partial x_k} \right) - \frac{2}{3} \bar{\rho} k \delta_{ij} \quad (3.3)$$

The term turbulent viscosity (μ_t) is modeled using the following equation:

$$\mu_t = \bar{\rho} C_\mu \frac{k^2}{\varepsilon} \quad (3.4)$$

Here, the symbol k and ε are defined as the turbulence kinetic energy (TKE) and dissipation rate. Constants $C_\mu = 0.09$ [96].

Transport equations for TKE and dissipation rate are solved by the realizable k - ε turbulent model. These equations are [96]:

$$\frac{\partial(\bar{\rho}k)}{\partial t} + \frac{\partial(\bar{\rho}k\tilde{u}_i)}{\partial x_i} = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho\varepsilon - Y_M + S_k \quad (3.5)$$

$$\begin{aligned} \frac{\partial(\bar{\rho}\varepsilon)}{\partial t} + \frac{\partial(\bar{\rho}\varepsilon\tilde{u}_i)}{\partial x_i} &= \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_j} \right] + \bar{\rho} C_{1\varepsilon} S \varepsilon - \bar{\rho} C_2 \frac{\varepsilon^2}{k + \sqrt{\nu \varepsilon}} \\ &+ C_{1\varepsilon} \frac{\varepsilon}{k} C_{\varepsilon b} G_b + S_\varepsilon \end{aligned} \quad (3.6)$$

In Eq. (3.5) and Eq. (3.6), the constants are $C_2 = 1.9$, $\sigma_k = 1.0$, $\sigma_\varepsilon = 1.2$. The constant $C_{1\varepsilon}$ is expressed by:

$$C_{1\varepsilon} = \max \left[0.43, \frac{\eta}{\eta + 5} \right] \quad (3.7)$$

where $\eta = S \frac{k}{\varepsilon}$ and $S = \sqrt{2S_{ij}S_{ij}}$.

and

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \quad (3.8)$$

The production of turbulence (G_k) due to mean velocity can be expressed as:

$$G_k = -\rho \overline{u'_i u'_j} \frac{\partial u_j}{\partial x_i} \quad (3.9)$$

The production of turbulence due to buoyancy (G_B) can be expressed as:

$$G_B = \beta g_i \frac{\mu_t}{Pr_t} \frac{\partial T}{\partial x_i} \quad (3.10)$$

where g_i is the gravitational component. However, for hydrogen combustion, the effects of gravitational force are negligible [140].

The fluctuating dilatation contribution (Y_M) can be expressed as:

$$Y_M = 2\rho\varepsilon M_t^2 \quad (3.11)$$

where M_t is defined as the turbulent Mach number, which can be expressed as:

$$M_t = \sqrt{\frac{k}{a^2}} \quad (3.12)$$

and a is described as the speed of sound.

3.1.2. Heat transfer model

The conservation of energy with radiation source term for a non-premixed combustion model is formulated as follows [96]:

$$\frac{\partial}{\partial t}(\bar{\rho}\tilde{H}) + \frac{\partial}{\partial x_i}(\bar{\rho}\tilde{u}_i\tilde{H}) = \frac{\partial}{\partial x_i}\left(\frac{\mu_t}{Pr_t}\frac{\partial\tilde{H}}{\partial x_i}\right) + S_h \quad (3.13)$$

where $\tilde{H}$ is described as the mean enthalpy, Pr_t is the Prandtl number, which is set to 0.85, and S_h is the term for radiation source.

3.1.2.1. P-1 radiation model

For the hydrogen diffusion flame case study, the P-1 radiation model is selected for the heat transfer model. The P-1 radiation model is the simplest P-N model. For gray radiation modeling, the radiation flux (q_r) is expressed as:

$$-\nabla \cdot \mathbf{q}_r = aG - 4an^2\sigma T^4 \quad (3.14)$$

where the term a is defined as the absorption coefficient, G is the incident radiation, n is the refractive index, σ is the Steffan-Boltzmann constant ($5.6704 \times 10^{-8} W/m^2 \cdot K^4$) and the T is the local temperature. The Eq. (3.14) is then substituted into the Eq. (3.13) accounting for the radiation source.

Water vapor (H₂O) is chosen as the radiating species, considering that the bypass product of hydrogen combustion is H₂O. Many works [137], [138], [143] also recommend this assumption for non-premixed turbulent hydrogen flames. The plank mean absorption coefficient of water vapor is found in Ref. [141].

3.1.2.2. Discrete ordinate radiation model

For the kerosene annular combustion chamber case, the discrete ordinate (DO) method was selected for the radiation model, incorporating the weighted sum of the gray gas model (WSGGM) for the absorption coefficient. DO governs the radiative transfer equation (RTE) for a finite number of discrete solid angles. The DO model can be written in the direction of $\vec{s}$ in the cartesian system, as follows [131]:

$$\nabla \cdot (I(\vec{r}, \vec{s})\vec{s}) + (a + \sigma_s)I(\vec{r}, \vec{s}) = an^2 \frac{\sigma T^4}{\pi} + \frac{\sigma_s}{4\pi} \int_0^{4\pi} I(\vec{r}, \vec{s}') \Phi(\vec{s}, \vec{s}') d\Omega' \quad (3. 15)$$

Here, I is defined as the radiative intensity.

3.1.3. Combustion-chemistry modeling

Modeling for turbulent combustion is known for its complexity [142], considering its highly non-linearity functions of temperature and species concentrations in the chemical reactions between species and flow field [143]. For simple fuels such as hydrogen, generally, only ten species interact through a twenty-step reaction to describe the complex reaction effects. However, for hydrogen carbon fuels, the number of species and reactions significantly increases [144], [145].

3.1.3.1. PDF combustion model

Under a set of simplification assumptions for a non-premixed combustion, mixture fraction (f) is described as the fluid's instantaneous thermochemical state associated with a conserved scalar quantity. Thermochemical scalars are the species mass fractions and temperature. The mixture fraction is expressed in terms of mass fraction [146]:

$$f = \frac{Z_i - Z_{i,ox}}{Z_{i,fuel} - Z_{i,ox}} \quad (3.16)$$

In the expression above, the term Z_i is defined as the mass fraction of an element, i . The subscripts ox and $fuel$ denote the value at the oxidizer inlet and fuel inlet, respectively. The transport equation for the Favre-averaged mixture fraction ($\bar{f}$) and its variance ($\overline{f'^2}$) [147] can be modeled as:

$$\frac{\partial}{\partial t}(\rho \bar{f}) + \nabla \cdot (\rho \vec{v} \bar{f}) = \nabla \cdot \left(\left(\frac{k_l}{C_p} + \frac{\mu_t}{\sigma_t} \right) \nabla \bar{f} \right) + S_m \quad (3.17)$$

$$\begin{aligned} \frac{\partial}{\partial t}(\rho \overline{f'^2}) + \nabla \cdot (\rho \vec{v} \overline{f'^2}) \\ = \nabla \cdot \left(\left(\frac{k}{C_p} + \frac{\mu_t}{\sigma_t} \right) \nabla \overline{f'^2} \right) + C_g \mu_t \cdot (\nabla \bar{f})^2 - C_d \rho \frac{\varepsilon}{k} \overline{f'^2} \end{aligned} \quad (3.18)$$

In Eq. (3.16) and Eq. (3.17), k is the laminar thermal conductivity, C_p is the specific heat of the mixture, and S_m is the mass flux due to liquid fuel droplets into the gas phase. The constants are $\sigma_t = 0.85$, $C_g = 2.86$, and $C_d = 2.0$.

In this thesis work, a steady diffusion flamelet model is adopted. This approach considers the turbulent flame an ensemble of discrete steady laminar flames. Hence, for a steady diffusion flamelet model, the density-weighted thermochemical scalars ($\bar{\phi}$) are modeled as follows:

$$\bar{\phi} = \int \int \phi(f, \chi_{st}) p(f, \chi_{st}) df d\chi_{st} \quad (3.19)$$

Where:

$$p(f, \chi_{st}) = p_f(f) p_\chi(\chi_{st}) \quad (3.20)$$

The *beta-PDF* assumption is used to solve the probability density function $p(f)$ by the following equation:

$$p(f) = \frac{f^{\alpha-1} (1-f)^{\beta-1}}{\int f^{\alpha-1} (1-f)^{\beta-1} df} \quad (3.21)$$

$$\alpha = \bar{f} \left[\frac{\bar{f}(1-\bar{f})}{\bar{f}'^2} - 1 \right] \text{ and } \beta = (1-\bar{f}) \left[\frac{\bar{f}(1-\bar{f})}{\bar{f}'^2} - 1 \right] \quad (3.22)$$

The term p_χ in Eq. (3.19) is calculated using the following equation:

$$p_\chi(\chi_{st}) = \delta(\chi - \overline{\chi_{st}}) \quad (3.23)$$

In this equation, $\overline{\chi_{st}}$ is referred to as mean scalar dissipation, which may be formulated by:

$$\overline{\chi_{st}} = \frac{C_\chi \overline{\varepsilon f'^2}}{k} \quad (3.24)$$

Constant $C_\chi = 2.0$.

The following formula can calculate the transport equation for laminar flamelets [148]:

$$\rho \frac{\partial Y_i}{\partial t} = \frac{1}{2} \rho \chi \frac{\partial^2 Y_i}{\partial f^2} + S_i \quad (3.25)$$

$$\rho \frac{\partial T}{\partial t} = \frac{1}{2} \rho \chi \frac{\partial^2 T_i}{\partial f^2} - \frac{1}{C_p} \sum_i H_i S_i + \frac{1}{2C_p} \rho \chi \left[\frac{\partial C_p}{\partial f} + \sum_i C_{p,i} \frac{\partial Y_i}{\partial f} \right] \frac{\partial T}{\partial f} \quad (3.26)$$

Where $C_{p,i}$, H_i , and S_i are the i^{th} element-specific heat, specific enthalpy, and reaction rate, respectively.

The term scalar dissipation considers the variable density, χ , is expressed as [149]:

$$\chi(f) = \frac{a_s}{4\pi} \frac{3(\sqrt{\rho_\infty/\rho} + 1)^2}{2\sqrt{\rho_\infty/\rho} + 1} \exp(-2[\operatorname{erfc}^{-1}(2f)]^2) \quad (3.27)$$

3.1.3.2. Eddy dissipation model

Magnussen and Hjertager [150] proposed an eddy-dissipation combustion model, where turbulence is assumed to control the reaction rate. Turbulence gradually mixes fuel and oxidizer into the reaction zones, which combust rapidly in a diffusion flame. In this case, the expensive Arrhenius chemical kinetic calculations can be neglected, reducing

computational cost. However, it is recommended to use one or two-step reaction mechanisms to obtain accurate results. The net rate production of species i because of reaction r , can be expressed as:

$$R_{i,r} = v'_{i,r} M_{w,i} A \rho \frac{\varepsilon}{k} \min \left(\frac{Y_{\mathcal{R}}}{v'_{\mathcal{R},r} M_{w,\mathcal{R}}} \right) \quad (3.28)$$

$$R_{i,r} = v'_{i,r} M_{w,i} A B \rho \frac{\varepsilon}{k} \frac{\sum_P Y_P}{\sum_j^N v''_{j,r} M_{w,j}} \quad (3.29)$$

In these equations, $v'_{i,r}$ is the stoichiometric coefficient for reactant i in reaction r . $M_{w,i}$ refers to the molecular weight of species i . Y_p is the mass fraction of any production species denoted by P , while $Y_{\mathcal{R}}$ is the mass fraction of a reactant, $\mathcal{R}$. $A = 4.0$ and $B = 0.5$.

3.2. Turbulent Hydrogen Diffusion Vertical Flame

3.2.1. Geometry and boundary condition setup

As shown in Figure 21, in this step, various models, including the turbulence, combustion, and radiation models, must be selected appropriately for the hydrogen diffusion flame. Although these models are not strictly implemented in the hydrogen annular combustion chamber, they may give helpful insight into the numerical setup in further parametric study.

A simple hydrogen diffusion flame was obtained from the experimental study done by Barlow and Carter [134]. In their investigation, undiluted hydrogen was injected via a vertical round jet with an inner diameter of 3.75mm and an outer diameter of 4.8mm. The fuel was surrounded by the co-flowing air coming from a wind tunnel. The numerical domain can be seen in Figure 22, having an axial distance of 1m and a radial distance of 0.3m. The flow domain can be considered an axisymmetric case to reduce the mesh and the CPU demand. Boundary conditions for this setup are depicted in Table 04. Boundary conditions for vertical turbulent hydrogen diffusion flame. Various turbulence models were applied, including the standard $k-\varepsilon$ turbulence model, modified $k-\varepsilon$ turbulence model (changing constant to $C_{\varepsilon 1} = 1.6$), the realizable $k-\varepsilon$ turbulence model, and Pope correction for $k-\varepsilon$ turbulence model. For the combustion model, the PDF model was selected with a steady laminar flamelet accordingly. The P-1 radiation model was chosen to solve the radiative transfer equation, as stated in the previous subchapter.

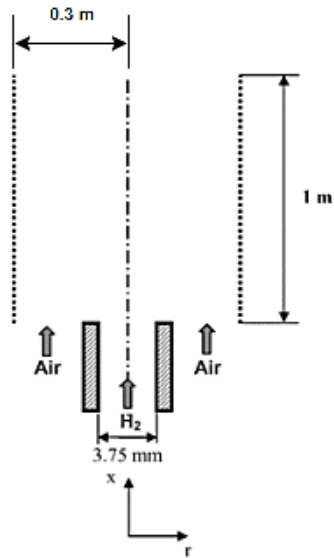


Figure 22 Flame setup for non-premixed turbulent hydrogen flame [136].

Table 04 Boundary conditions for vertical turbulent hydrogen diffusion flame.

Parameter	Value	Unit
Fuel inlet speed	296	m/s
Air inlet speed	1	m/s
Operating temperature for air	300	K
Operating pressure for air	1	atm

3.2.2. Mesh study and generation

Three total numbers of cells were tested for the hydrogen diffusion flame to conduct a mesh independence study; they are 16,000, 80,000, and 322,000 cells. Each generated number of cells contains a minimum orthogonality of 0.9 and a maximum aspect ratio of 4.4. The testing domain is at the centerline, specifically for their mean temperature, as shown in Figure 23. Hence, based on that, 80,000 cells were chosen, and its mesh structure is depicted in Figure 24.

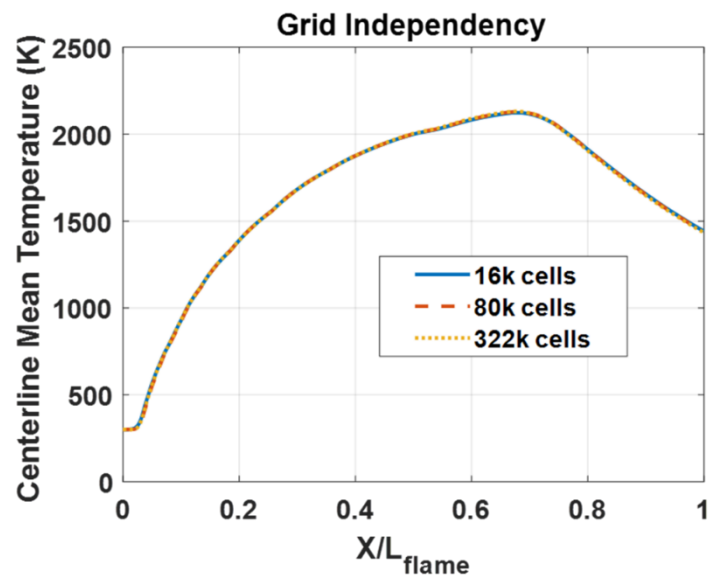


Figure 23 Mesh study for non-premixed turbulent hydrogen flame

3.2.3. Result

It can be observed from Figure 25 that near the fuel injector exit, the modified standard $k-\varepsilon$ turbulence model ($C_{\varepsilon 1} = 1.6$) shows the best prediction. However, the realizable $k-\varepsilon$ turbulence model can accurately predict further downstream flame temperature. Therefore, for the hydrogen annular combustor simulation, the realizable $k-\varepsilon$ turbulence model is fixed. It is also worth noting that this turbulence model can handle swirled flow compared to the standard $k-\varepsilon$ model [96].

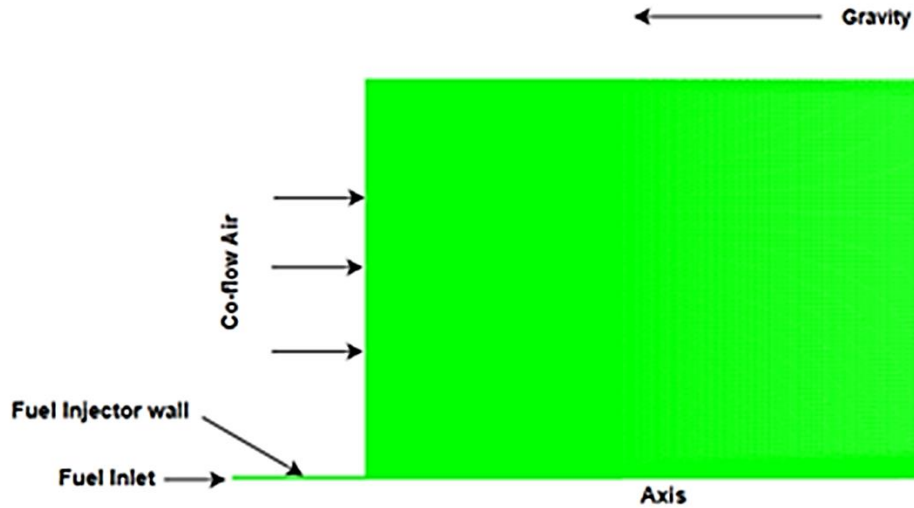


Figure 24 Mesh structure for the non-premixed turbulent hydrogen flame.

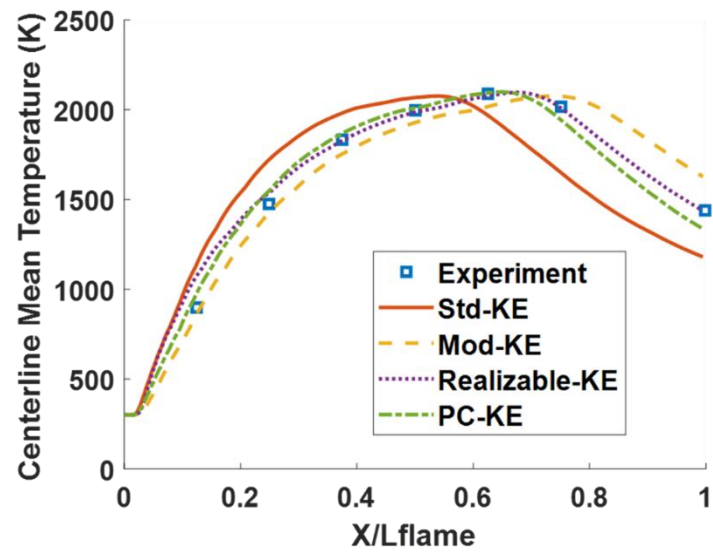


Figure 25 Centerline temperature of simulated vertical turbulent hydrogen diffusion flame.

3.3.Kerosene Annular Combustion Chamber

3.3.1. Geometry setup and boundary conditions

Initially, the author attempted to replicate the geometry setup of the CFM56-3 annular combustion chamber, as shown in the work [29], [151]. However, after preliminary tests, it is deemed arduous to replicate the same model since the author does not possess the pertaining blueprint because of the manufacturer's confidentiality. Hence, in this thesis, geometry is modeled based on the work done in Ref. [44], [137], an annular combustion chamber using kerosene ($C_{12}H_{23}$). The main goal of this step is to validate the geometry model of a somewhat realistic annular combustor. Moreover, the mesh structure of this annular combustor will be used for the hydrogen annular combustor. The combustor geometry is depicted in Figure 26 and Figure 27. Despite this, the author could not replicate the entire combustor, namely the swirler geometry, the air jet's inlet diameter, and the fuel inlet diameter. But they are assumed to be close enough for the current work. Furthermore, this geometry will be validated against the study done in [137]. The combustor is designed using commercially available software and presents only 1/18 circular pieces of the original combustor, simplifying the model and reducing the computational run time.

The initial design parameters for the kerosene annular combustor are based on the work of Ilbas et al. [44], [137], a low bypass turbofan GTE is shown in Table 05. Hence, the air distribution for each air inlet is depicted in Table 06. Detailed boundary conditions for the annular combustor are shown in Table 07. Here, the swirler angle vanes are assumed to be 40° with a thickness of 0.7mm and 12 12-piece blades. Here, the calculated swirl number is 0.65 [137].

For validation purposes, a simplified kerosene ($C_{12}H_{23}$) reaction mechanism is used. This chemical reaction is based on a one-step mechanism, as shown in Eq. (3.30) since the EDM combustion model can handle one or two-step reactions accurately. Moreover, this model is also used by Ref. [44], [137]. Kerosene fuel is available in the Fluent code database. The equivalent ratio of each zone is shown in

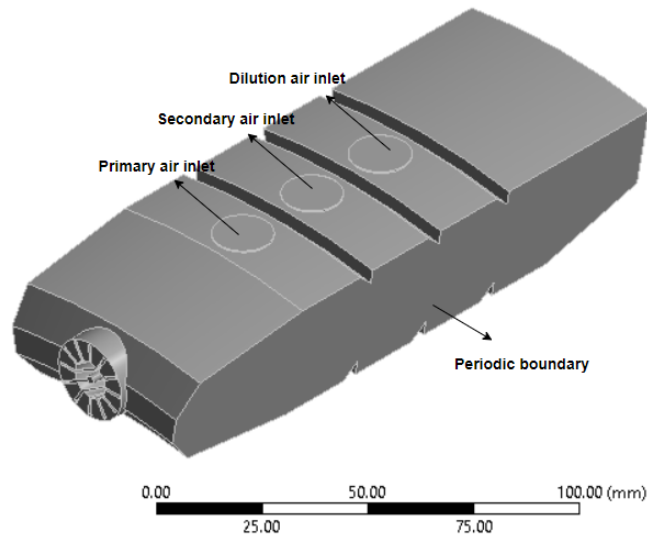
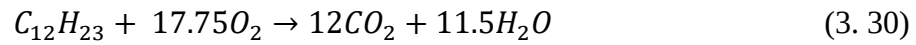


Figure 26 Isometric view of the kerosene annular combustion chamber.

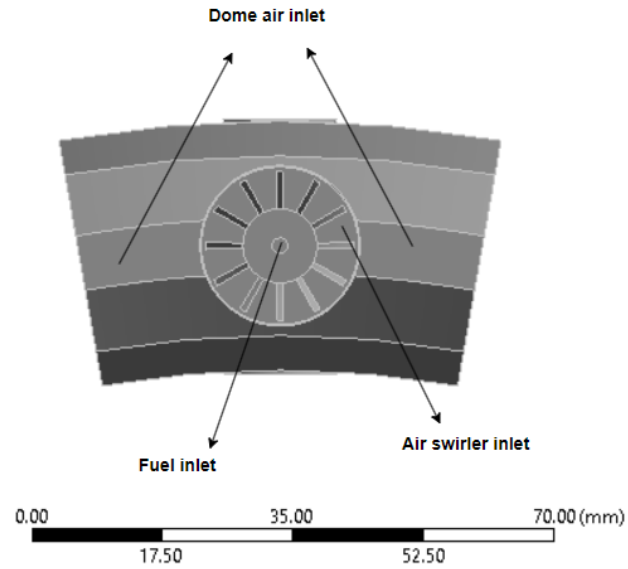


Figure 27 Front view of the kerosene annular combustion chamber.

Table 05 Initial design parameters for the kerosene annular combustor [44], [137].

Parameter	Value	Units
Air mass rate	28.7103	kg/s
Kerosene fuel mass rate	0.25818	kg/s
Compressors exit pressure	2083450	Pa
Compressors exit temperature	743.352	K
Liner length	157.19	mm
Liner height	40.26	mm

Table 06 Air distribution for the kerosene annular combustor [44], [137].

Component	Percentage distribution (%)
Swirler inlet	12
Cooling dome inlet	8
Primary jet inlet	20
Secondary jet inlet	50
Dilution jet inlet	10

Table 07 Boundary conditions for kerosene combustor.

Description	Area each inlet (mm ²)	The mass flow rate of each inlet (kg/s)
Fuel inlet	3.4636	0.0143
Swirler inlet	225.38	0.1914
Dome dilution inlet	242.51	0.0638
Primary jet inlet	173.43	0.1595
Secondary jet inlet	173.43	0.3987
Dilution jet inlet	179.08	0.0797

Table 08 FAR and Equivalence ratio for kerosene annular combustor.

Location	Fuel-to-air ratio (FAR)	Equivalence ratio (Φ)
Recirculation zone	0.0449	0.6563
Primary zone	0.0224	0.3281
Secondary zone	0.0099	0.1458
Dilution zone	0.0089	0.1312

3.3.2. Mesh study and generation

Four cells were tested for the kerosene annular combustor to conduct a mesh independence study, including 1 million, 1.82 million, 2.5 million, and 4.2 million cells. Each generated number of cells contains a minimum orthogonality of 0.2 and a maximum aspect ratio of 30. Mesh study was done at different sections of the combustor, specifically the radial velocity profile for a cold flow, as shown in Figure 28, Figure 29, Figure 30, and Figure 31. Cold flow tests were performed by turning off the volumetric species transport. Hence, based on these results, it was decided to use 2.5million cells for further study. The generated mesh structure for 2.5million cells can be seen in Figure 32 and Figure 33. Periodic boundary condition was utilized instead of symmetric boundary condition to fully capture the flow behavior inside the combustor, as shown in Figure 34.

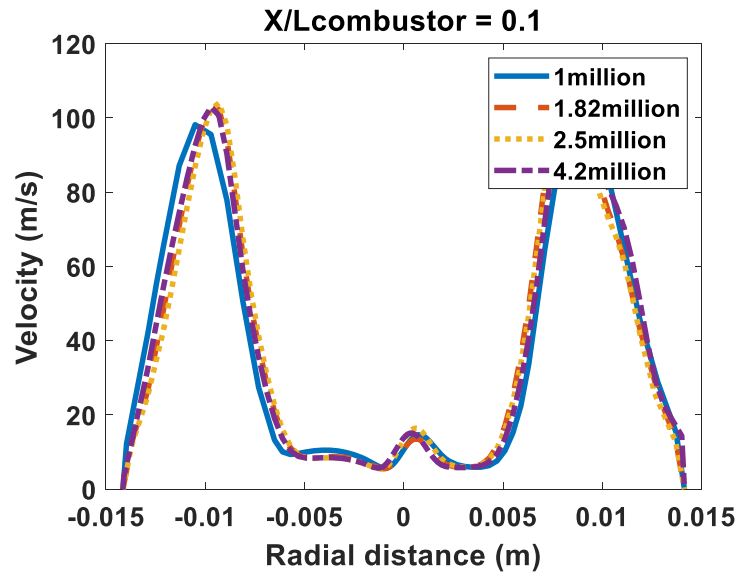


Figure 28 Cold flow radial velocity at $X/L_{\text{combustor}} = 0.1$ with different total number of cells.

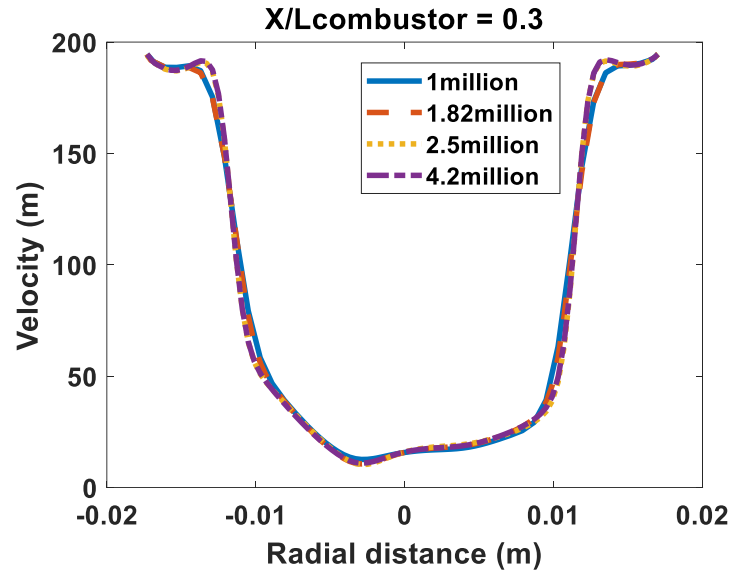


Figure 29 Cold flow radial velocity at $X/L_{\text{combustor}} = 0.3$ with different total number of cells.

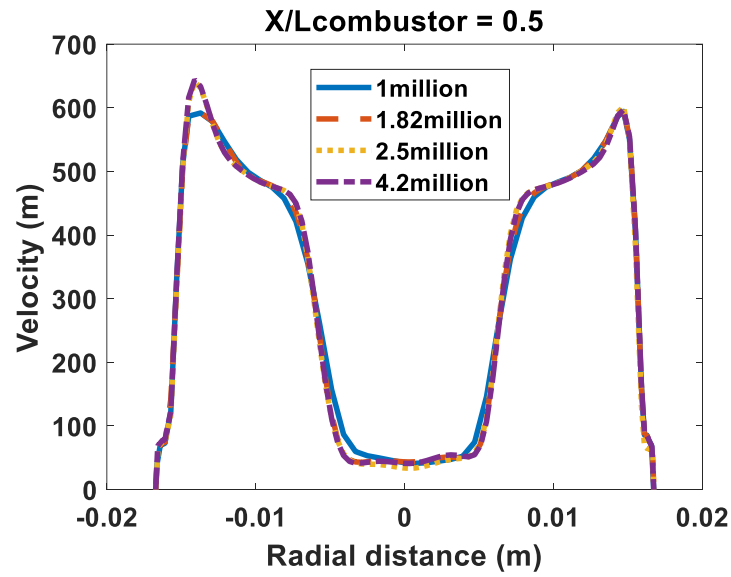


Figure 30 Cold flow radial velocity at $X/L_{\text{combustor}} = 0.5$ with different total number of cells.

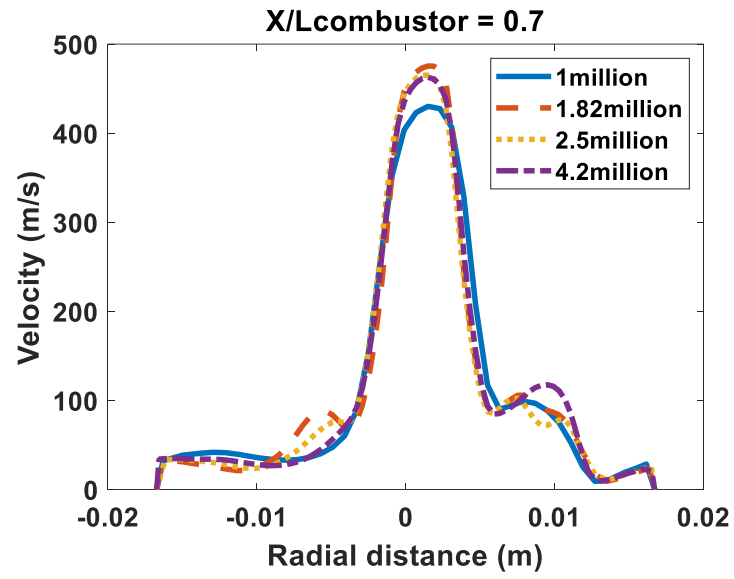


Figure 31 Cold flow radial velocity at $X/L_{\text{combustor}} = 0.7$ with different total number of cells.

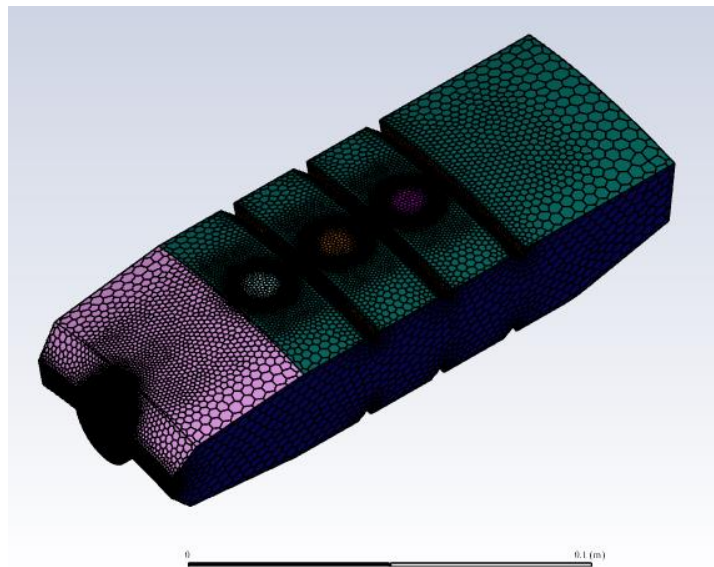


Figure 32 Isometric view 2.5million cells for kerosene annular combustor

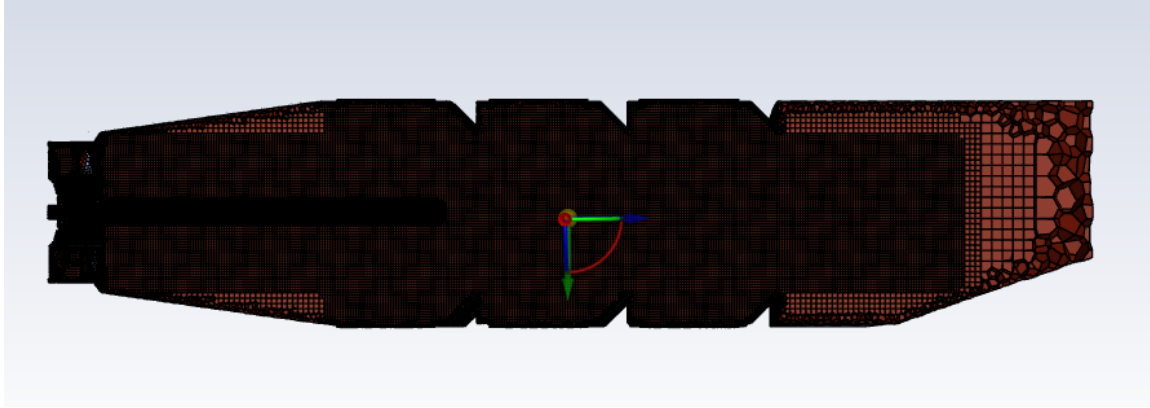


Figure 33 Cut view of 2.5 million cells for kerosene annular combustor.

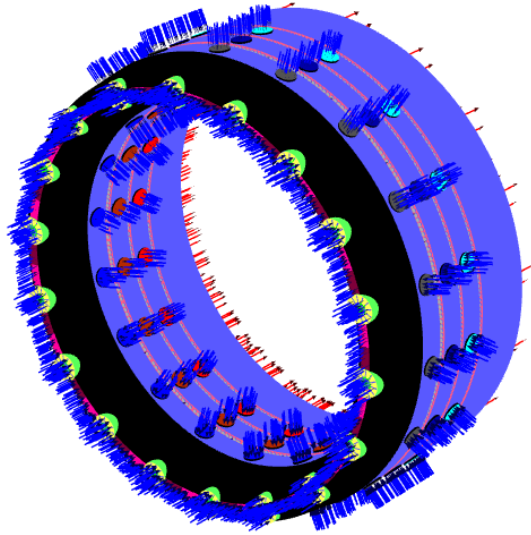


Figure 34 Full-scale kerosene annular combustor inside Fluent using periodic boundary condition.

3.3.3. Result

It can be observed from Figure 35, in the recirculation zone, the centerline temperature profile was slightly different from that of Ilbas et al. [137], this might have been caused by the geometry of the swirler. However, further downstream, the simulated kerosene flame shows good agreement. Moreover, it can capture the maximum centerline temperature. Therefore, this geometry and boundary condition will be the benchmark for the hydrogen annular combustion chamber simulation.

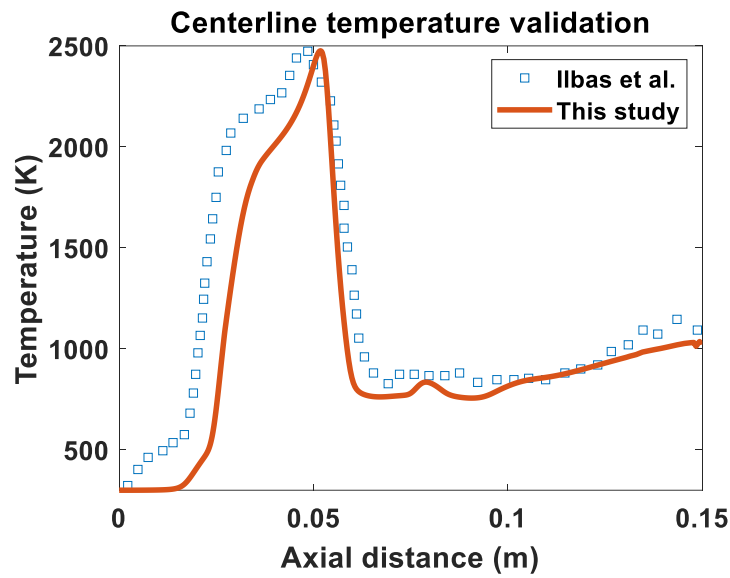


Figure 35 Simulation validation for kerosene annular combustor.

3.4. Hydrogen Annular Combustion Chamber

Based on the literature and thesis objective explained in Chapter 1, it is then summarized in Table 09 to give a clearer problem setup for the hydrogen annular combustor and Table 10 for the design parameter. Here, the design parameters are the same as Ref. [44] and [137]. However, the fuel mass flow rate will be reduced to a third because of hydrogen's high gravimetric energy density compared to kerosene fuel. The quantity of hydrogen fuel was calculated based on the ratio of hydrogen's LHV and kerosene LHV, as shown in the following equation:

$$\dot{m}_{hydrogen} = \dot{m}_{kerosene} \times \frac{LHV_{kerosene}}{LHV_{hydrogen}} \quad (3.31)$$

Based on the literature review, a parametric study was done by changing the number of fuel injectors, swirl angle vanes, and equivalence ratio. Three different hydrogen injectors are considered, including four fuel injectors, eight fuel injectors, and eight fuel injectors with a transverse system. Fuel injectors were added to ensure the fuel has sufficient residence time to burn with the oxidizer inside the combustor, considering hydrogen's low volumetric density. As seen in Figure 36, the velocity magnitude of fuel flow is significantly high, resulting in instability of flame generation.

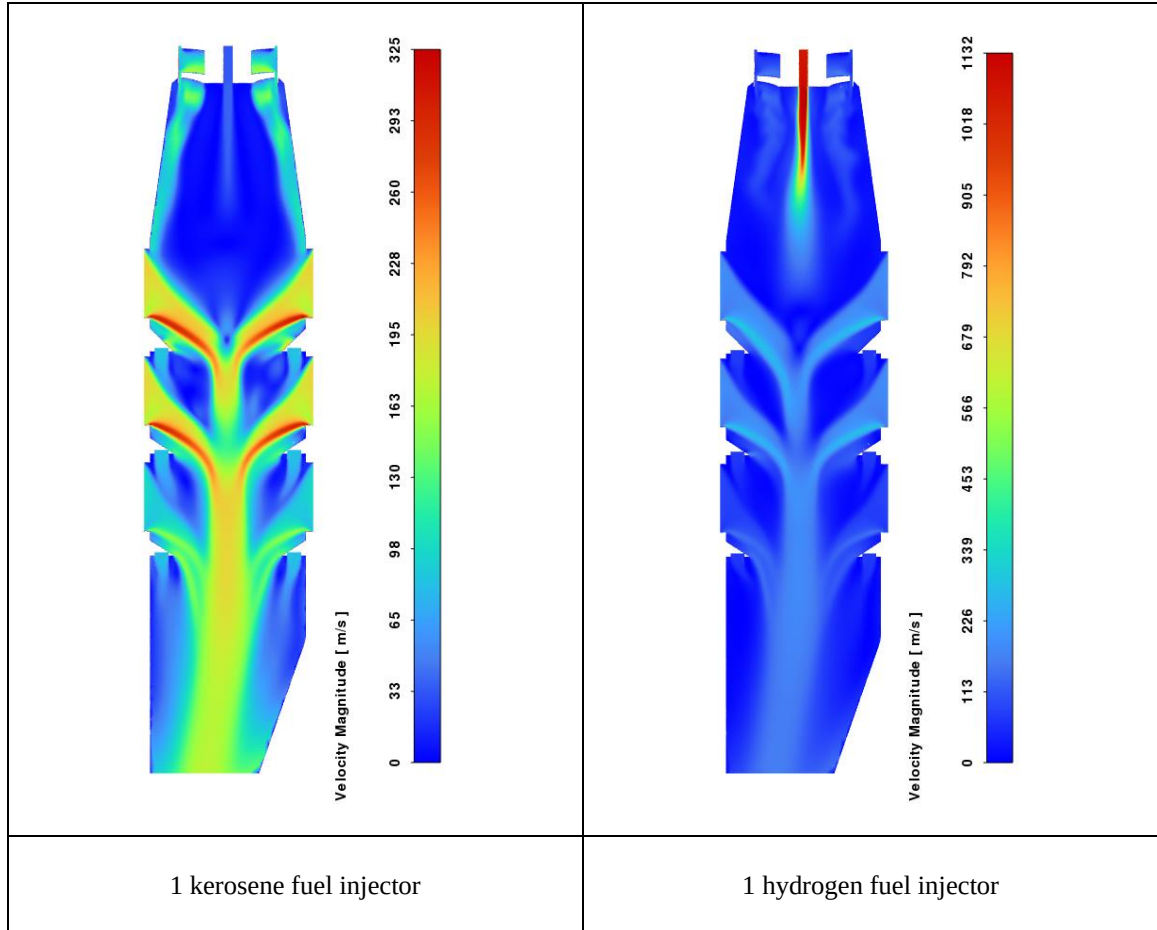


Figure 36 Velocity magnitude contour comparison using 1 injector.

Each of these fuel injectors has a diameter of 2mm. Once a suitable fuel injector system is obtained based on NO_x emissions and temperature distribution, the swirl vanes angle is then varied, ranging from 35° to 65°. The sensibility test for equivalence ratio was done to comply with the ICAO's LTO cycle, which has also been adjusted to accommodate hydrogen fuel.

Table 09 Problem setup for hydrogen annular combustor.

Design parameters	Parametric study	Performance parameters
-Inlet temperature (T_3)	-Fuel injector configurations (axial injectors: 1,4, and 8; transverse injectors: 4 and 8) -Swirl vanes angle (35-65°)	-Outlet averaged velocity
-Inlet pressure (P_3)		-NO _x emissions
-Fuel mass flow (m_{fuel})		-Max flame temperature

-Air mass flow (m_{fuel})	-Equivalence ratio (0.1-0.86)	-Max outlet temperature
-Combustor length and height		

Table 10 Design parameters for hydrogen annular combustor.

Parameter	Value	Units
Air mass rate	28.7103	kg/s
Hydrogen fuel mass rate	0.0930	kg/s
Compressors exit pressure	2083450	Pa
Compressors exit temperature	743.352	K
Liner length	157.19	mm
Liner height	40.26	mm

3.4.1. Geometry modification

As previously mentioned, modifications to the fuel injectors are done to ensure fuel has sufficient residence time burn and enhance proper mixing with the oxidizer by using additional fuel injectors, as shown in Figure 37, Figure 38, Figure 39, and Figure 40. Moreover, the hydrogen burner is equipped with rows of cooling/bleeding air inlets, minimizing hot spots near the liner walls, as depicted in Figure 41 and Figure 42. The first, second, and third rows have a total of 1620 cooling air inlets. Each cooling hole has a diameter of 3mm.

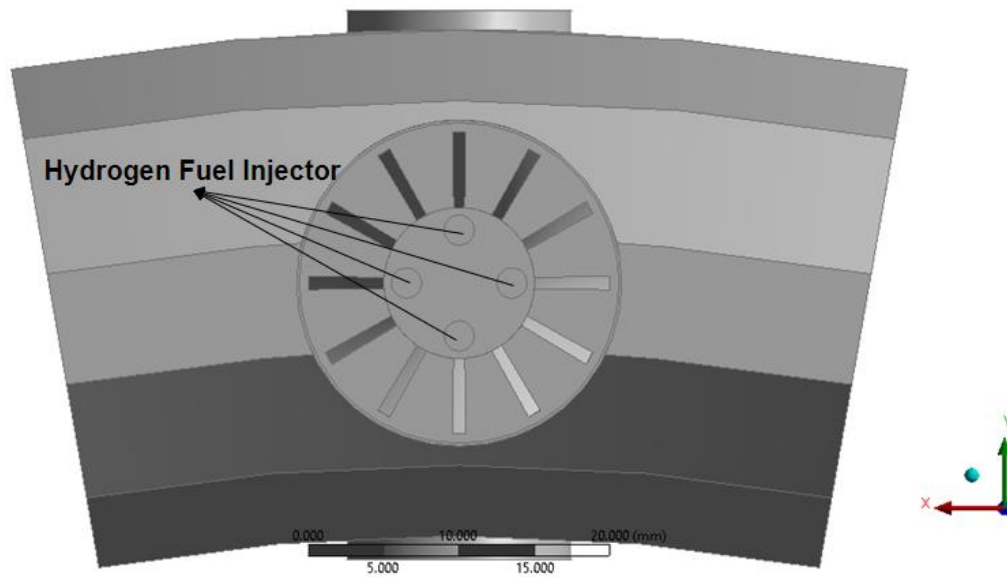


Figure 37 Four fuel injectors, all with a 2mm diameter.

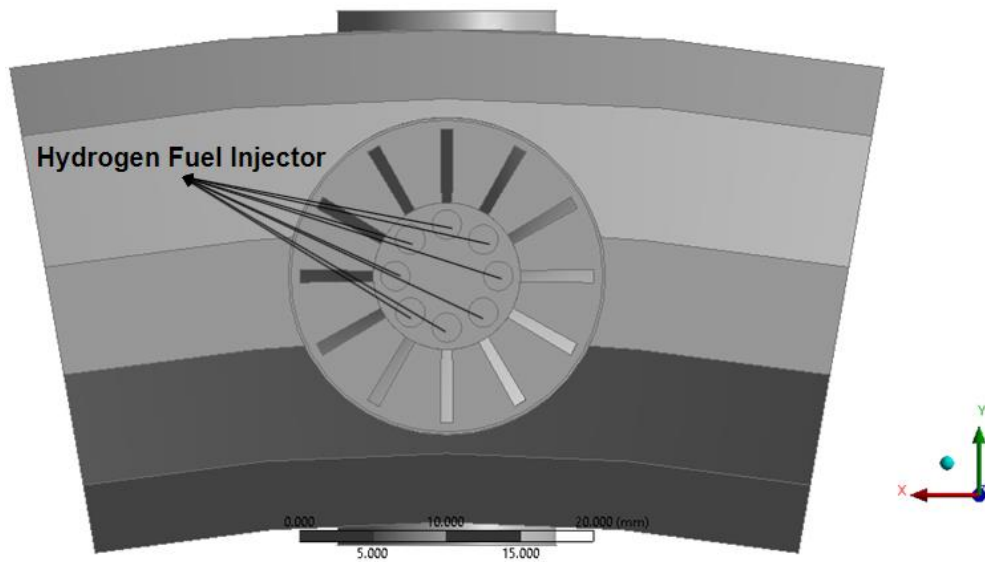


Figure 38 Eight fuel injectors, all with a 2mm diameter.

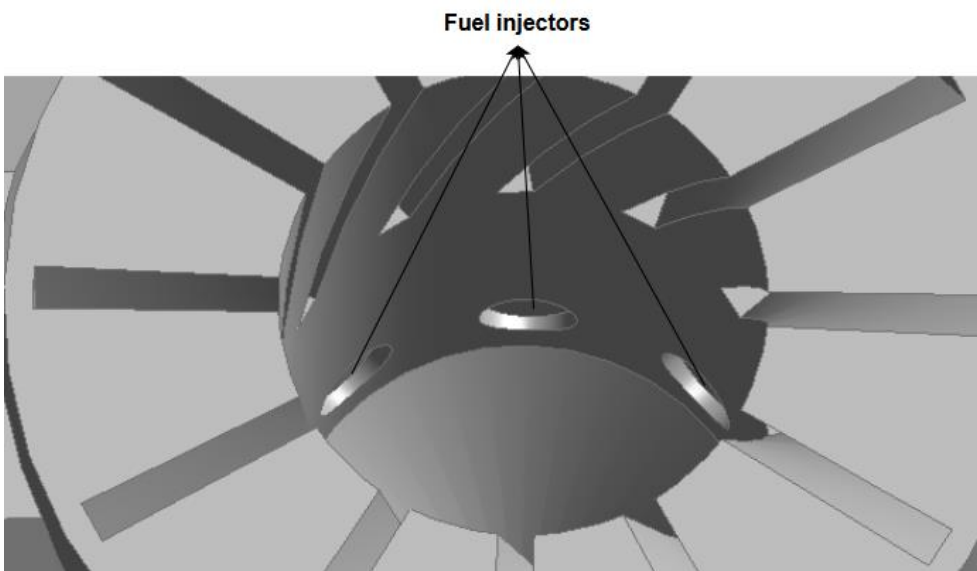


Figure 39 Eight fuel transverse injectors, all with a 2mm diameter.

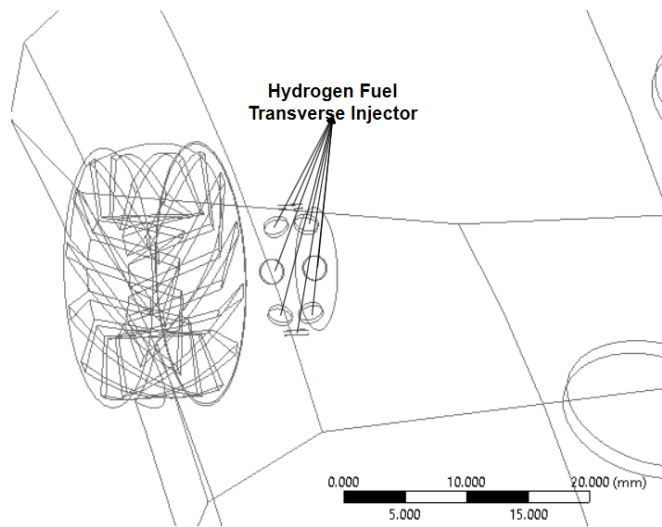


Figure 40 Transparent view eight transverse injectors.

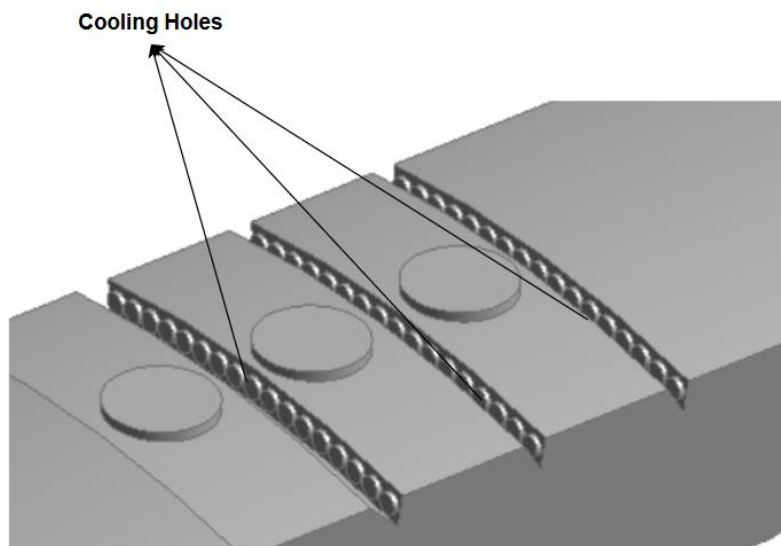


Figure 41 Upper rows cooling holes inlet.

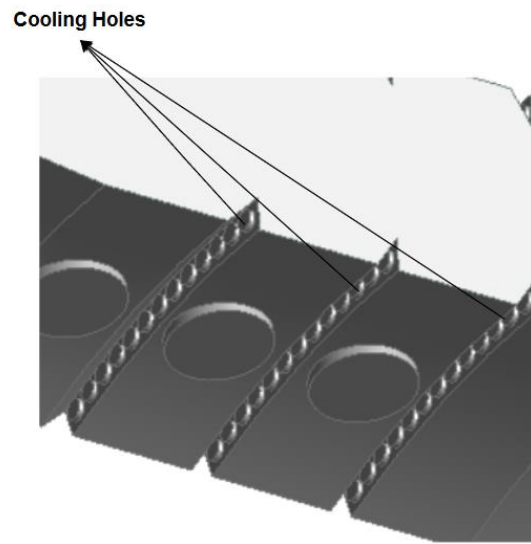


Figure 42 Lower rows of cooling holes inlet.

3.4.2. Boundary conditions

As shown in Table 06, the air distribution for the secondary jet is deemed too high. Hence, 30% of the total air is distributed to cooling air inlets. Moreover, this modification avoids high-velocity inlets from the secondary jets, which can lead to higher pressure drop. Then, the air distribution for the entire hydrogen annular combustor is shown in Table 11. It is assumed that the boundary conditions shown in Table 12, Table 13, and Table 14 are intended for the cruising stage, where the power setting is 65%. To comply with the ICAO's LTO cycle, boundary conditions for all flight stages and equivalence ratio parametric study are depicted in Table 15.

Table 11 Air distribution percentage for all parametric studies.

Component	Percentage distribution (%)
Swirler inlet	12
Cooling dome inlet	8
Primary jet inlet	20
Secondary jet inlet	20
Dilution jet inlet	10
First-row cooling inlet	10
Second-row cooling inlet	10
Third-row cooling inlet	10

Table 12 Boundary conditions for four hydrogen fuel injectors.

Description	Area each inlet (mm ²)	Number of inlets	The mass flow rate of each inlet (kg/s)
Fuel inlet	3.4636	72	0.0013
Swirler inlet	225.38	18	0.1914

Dome dilution inlet	242.51	18	0.0638
Primary jet inlet	173.43	36	0.1595
Secondary jet inlet	173.43	36	0.3987
Dilution jet inlet	179.08	36	0.0797
First-row cooling inlet	6.9965	540	0.0053
Second-row cooling inlet	6.9965	540	0.0053
Third-row cooling inlet	6.9965	540	0.0053

Table 13 Boundary conditions for eight hydrogen fuel injectors.

Description	Area each inlet (mm ²)	Number of inlets	The mass flow rate of each inlet (kg/s)
Fuel inlet	3.4636	144	0.00065
Swirler inlet	225.38	18	0.1914
Dome dilution inlet	242.51	18	0.0638
Primary jet inlet	173.43	36	0.1595
Secondary jet inlet	173.43	36	0.3987
Dilution jet inlet	179.08	36	0.0797
First-row cooling inlet	6.9965	540	0.0053
Second-row cooling inlet	6.9965	540	0.0053
Third-row cooling inlet	6.9965	540	0.0053

Table 14 FAR and equivalence ratio using hydrogen fuel.

Location	Fuel-to-air ratio (FAR)	Equivalence ratio (Φ)
Recirculation zone	0.0162	0.5558
Primary zone	0.0081	0.2779
Secondary zone	0.0040	0.1389
Dilution zone	0.0032	0.1111

Table 15 Boundary conditions for different hydrogen equivalence ratios.

Flight stage	Power settings (%)	Total fuel mass flow rate (kg/s)	Recirculation zone FAR	Recirculation zone Equivalence ratio
Taxi	12	0.0167	0.0029	0.1
Approach	30	0.0429	0.0074	0.27
Cruise	65	0.0930	0.0162	0.5558
Climb	85	0.1216	0.0211	0.73
Take-off	100	0.1431	0.0249	0.86

3.4.3. Solution method, controls, and monitors

Because of the case's complexity, it includes a turbulence model, pdf combustion, energy model, etc. It was mandatory to select optimal methods to obtain quick and accurate results. Fluent recommends running a cold flow first for a combustion case to ease the computational flow field. Therefore, cold flow can be accomplished by turning off the volumetric option in the species transport model. Once the “convergence” is met, the simulation is continued by implementing the pdf combustion method. Here, convergence criteria are defined by:

1. Scaled residuals are decreased to sufficient values, as shown in the Table 16.
2. Parameters do not change with more iterations. In this work, the monitored parameters are temperature outlet, mass flux at the outlet, and overall mass imbalance.
3. Mass imbalance is less than 0.5% [96]. Mass imbalance is the difference between the total mass inlet and the total mass outlet.

Table 16 Scaled residuals criteria.

Parameters	Absolute criteria
Continuity	10^{-3}
X-velocity	10^{-3}
Y-velocity	10^{-3}
Z-velocity	10^{-3}
Energy	10^{-6}
K	10^{-3}

epsilon	10^{-3}
Fmean	10^{-3}
fvar	10^{-3}
P1	10^{-6}

In this work, a *Pressure*-based scheme was selected to solve the fluid flow since flow is expected to be in a subsonic regime. Hence, *Pressure-Velocity Coupling* and *Spatial Discretization* schemes were chosen as recommended by Fluent. Then, the Pressure-Velocity Coupling is *Coupled* since it is appropriate for a complex flow and requires fewer iterations to converge than others. The Gradient is solved by *Least Squares Cell-based* because of its accuracy compared to cell-based gradient and is less expensive computationally than the node-based gradient. PRESTO! solves the pressure discretization scheme having good accuracy for flow in high swirl numbers, high-speed rotating flows, high-Rayleigh-number natural convection, flows in strongly curved domains, and flows involving porous media [96]. Default Fluent settings solve other parameters. The summary of solution methods is depicted in Table 17.

Table 17 Solver methods for the numerical setup of hydrogen annular combustor.

Parameters	Solver
Pressure-Velocity Coupling	Coupled
Flux Type	Rhie-Chow: distance-based
Gradient	Least Squares Cell-Based
Pressure	PRESTO!
Momentum	Second order Upwind
Turbulent Kinetic Energy	First order Upwind

Turbulent Dissipation Rate	First order Upwind
Reynolds Stresses	Second order Upwind
Energy	Second order Upwind
Mean Mixture Fraction	Second order Upwind
Mixture Fraction Variance	Second order Upwind

The default values of the relaxation factors generally work well, but in the present case, they are deemed too aggressive, leading to convergence problems. Hence, these values are greatly reduced to very low numbers, as shown in the Table 18.

Table 18 Relaxation factors for the numerical setup of hydrogen annular combustor.

Parameters	Relaxation Factors
Momentum	0.2
Pressure	0.2
Density	0.1
Body Forces	0.5
Turbulent Kinetic Energy	0.3
Turbulent Dissipation Rate	0.3
Turbulent Viscosity	0.5
Pollutant NO	0.3
Energy	0.4
Temperature	0.3
P1	0.3
Mean Mixture Fraction	0.3
Mixture Fraction Variance	0.75

CHAPTER 4

RESULT AND DISCUSSION

The present chapter discusses numerical results based on the parametric study. It begins with the influence of fuel injector configurations. Then, the swirl vane angle is varied, adjusting with the best fuel injector configuration based on NO_x emissions, outlet temperature, and flame structure. Finally, the equivalence ratio is then changed to accommodate ICAO's LTO stage, as shown in Figure 14. In total, eleven simulations were done with an independent mesh, which was validated in the section 3.3. The turbulence model, combustion model, and radiation model for the hydrogen annular combustor follow the methods explained in the section 3.2, which also has been validated. As stated in Section 1.5, this work aims to reduce NO_x emissions while maintaining optimal combustion performance and temperature by using different fuel injection methods and swirl vane angles.

4.1.Effect of Total Number and Orientation of Fuel Injectors

This subchapter compares kerosene and hydrogen fuel under different injector designs. The results highlight how the number and orientation of injectors affect the flow dynamics when switching to hydrogen, given several fuel properties such as low density, high diffusivity, and rapid flame speed.

4.1.1. Velocity profile

When switching to hydrogen fuel in annular combustor gas turbine, the velocity field undergoes significant changes due to hydrogen's unique combustion properties, as depicted in Figure 43.

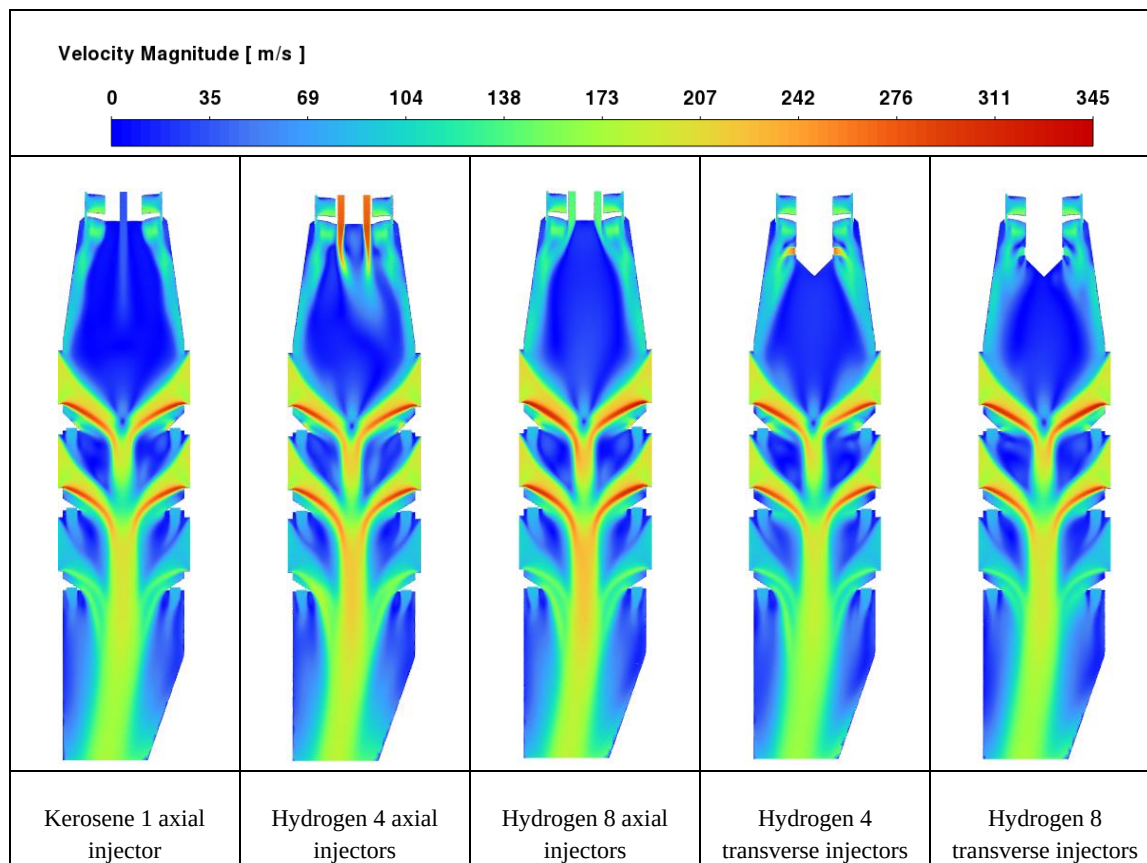


Figure 43 Velocity contour using different fuel and injectors configurations.

It is worth mentioning that the hydrogen one fuel injector configuration is excluded in Figure 43 due to its incredibly high velocity magnitude value, which renders other injector configurations unanalyzable. Kerosene combustion with a single fuel injector shows a considerably low momentum of around 80m/s near the fuel injection point, considering kerosene's higher density than hydrogen. While increasing the fuel injector for hydrogen reduces velocity near the injector, the hydrogen four axial injectors show a high velocity magnitude of approximately 250m/s. A more distributed flow field is demonstrated when the fuel injector is increased to eight axial injectors, which reduces the velocity gradients and may improve fuel-air mixing. The transverse injectors generate localized vortices or a recirculation zone, further improving fuel mixing. The annulus air causes high velocity near the air jet inlets due to impingement on the liner walls.

Changing the fuel injector configuration and fuel composition alters the output velocity and velocity profile throughout the combustor, which eventually affects the thrust produced, as depicted in Figure 44 and Figure 45.

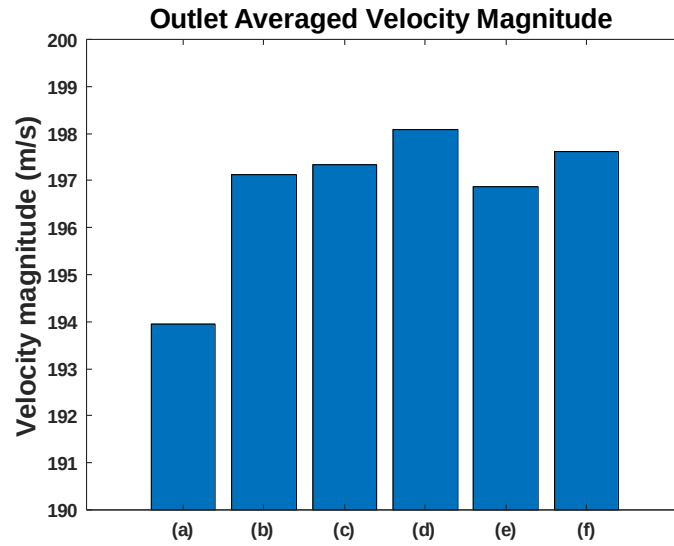


Figure 44 Outlet averaged velocity using: (a) Kerosene 1 fuel injector; (b) Hydrogen 1 fuel injector; (c) Hydrogen 4 fuel injectors; (d) Hydrogen 8 fuel injectors; (e) Hydrogen 4 fuel transverse injectors; (f) Hydrogen 8 fuel transverse injectors.

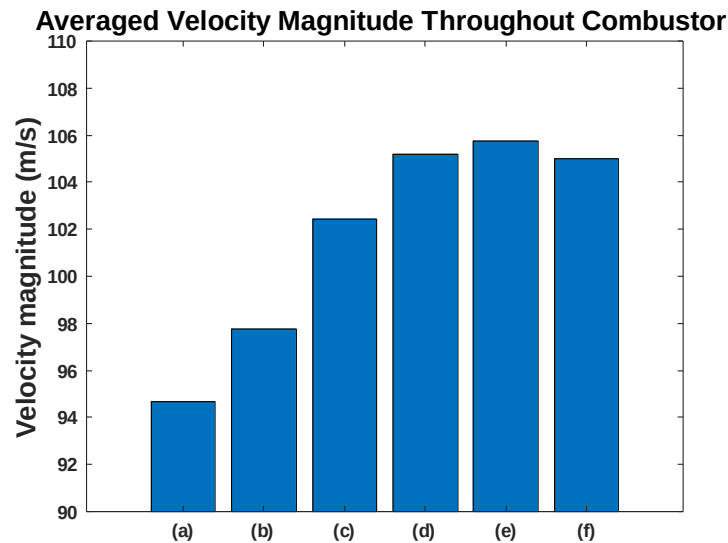


Figure 45 Averaged velocity magnitude throughout combustor using: (a) Kerosene 1 fuel injector; (b) Hydrogen 1 fuel injector; (c) Hydrogen 4 fuel injectors; (d) Hydrogen 8 fuel injectors; (e) Hydrogen 4 fuel transverse injectors; (f) Hydrogen 8 fuel transverse injectors.

Examining Figure 44 and Figure 45, the bar chart shows the kerosene-based combustor with the lowest output velocity compared to various hydrogen injector configurations. Kerosene's slower reaction rate and lower flame speed result in less intense combustion, which may lead to lower flow acceleration at the outlet. The highest averaged outlet

velocity magnitude is observed at eight hydrogen injectors, reaching up to $\sim 199\text{m/s}$. A larger number of injectors ensures enhanced mixing and uniform combustion, optimizing thermal energy conversion into kinetic energy. These charts indicate that a hydrogen burner can produce similar output thrust compared to the kerosene burner, compensating for the hydrogen's lower mass flow rate.

4.1.2. Temperature distribution

The influence of fuel composition and injector designs on flame temperature is depicted in Figure 46. This figure includes the hydrogen one fuel injector to give an equitable comparison to the kerosene one injector.

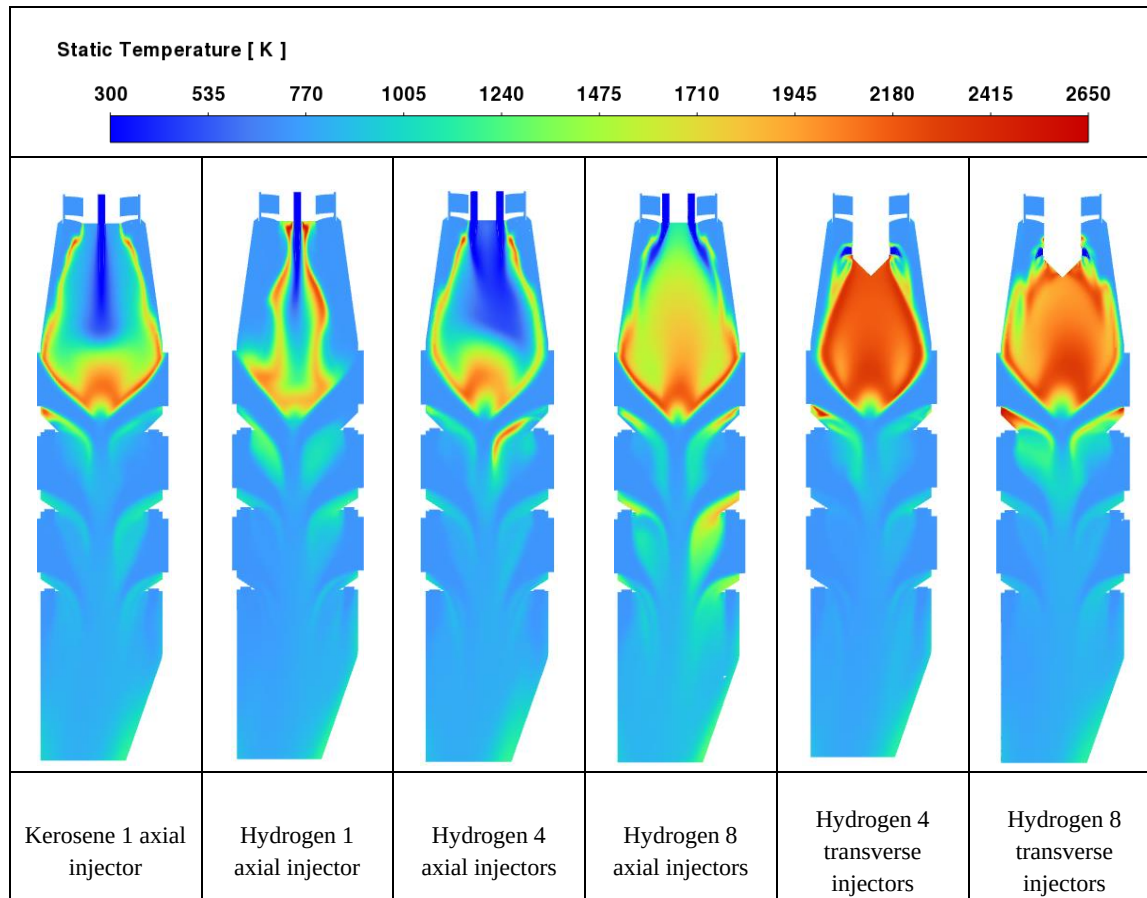


Figure 46 Temperature distribution using different fuel and injector configurations.

Judging from Figure 46, the flame temperature for kerosene is relatively moderate compared to hydrogen due to its lower adiabatic flame temperature and slower reaction kinetics. Moreover, the temperature distribution shows a distinct central flame zone, with a gradual increase in radial temperature, indicating the fuel begins to react with the oxidizer. The single hydrogen injector results in higher flame temperature, as hydrogen's AFT is much higher than kerosene. Furthermore, the flame zone appears narrower and

more intense, concentrated in the core region. The high velocities introduce strong turbulence, destabilizing the flame and creating non-uniform combustion zones. It also reduces the hydrogen fuel residence time in the recirculation zone, pushing the flame further downstream.

Increasing the number of fuel injectors distributes the hydrogen fuel more evenly, leading to a wider flame and slightly increased peak temperature than the single injector. The flame is more stable due to better fuel and air mixing, reducing the likelihood of localized hotspots. It is also noted that the transverse orientation of four and eight injectors produces a hotter flame temperature compared to axial injectors, reaching almost 2650K.

Indeed, the transverse injection increases mixing intensity, but with a cross-flow mixing in the recirculation zone, it also may reduce average outlet static temperature compared to axial injectors, as shown in Figure 47.

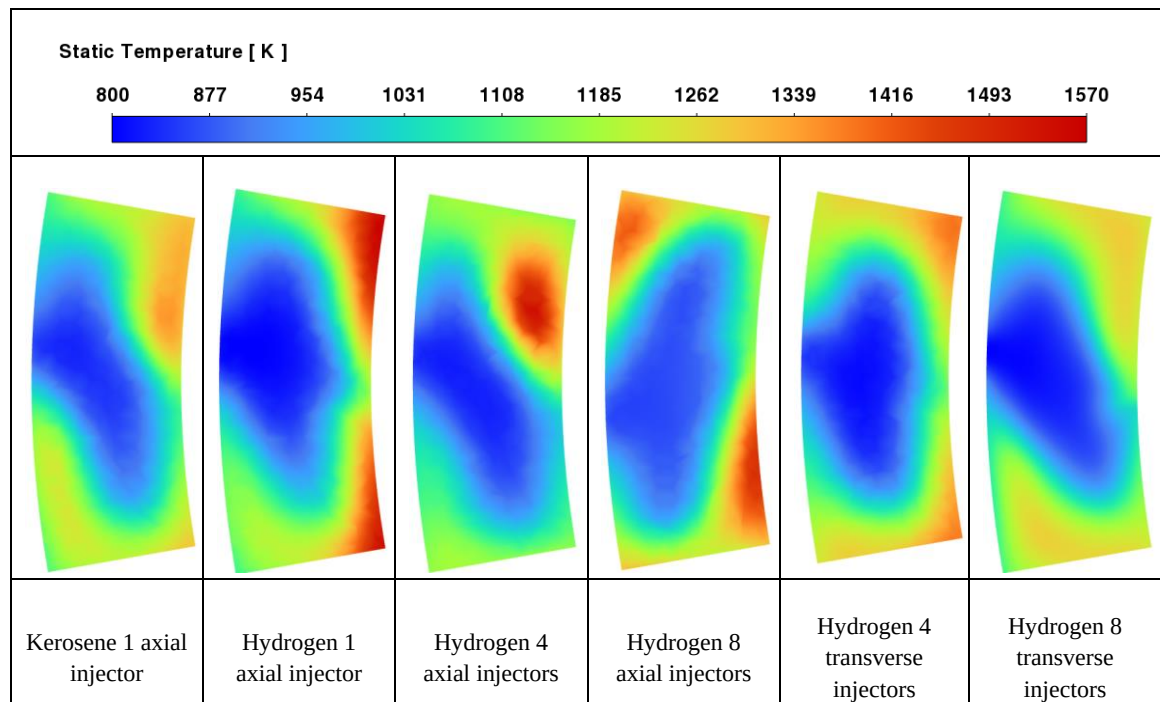


Figure 47 Outlet temperature using different fuel and injector configurations.

This figure illustrates the static temperature distribution at the combustor outlet, which is critical for turbine performance, thermal efficiency, and durability. The kerosene case depicts a uniform temperature distribution across the combustor outlet, ranging from 800 K to ~ 1150 K. Lower peak outlet temperature implies moderate heat release, typical for kerosene combustion with a single injector. The lower outlet temperature may reduce thermal efficiency compared to hydrogen cases.

Hydrogen with a single injector exhibits higher peak outlet temperatures, reaching up to 1570 K, with a slightly non-uniform distribution, which may lead to high thermal fatigue to the turbine blades. As mentioned, high-velocity fuel inlets push the flame further downstream, reducing fuel residence time. Using four hydrogen injectors improves temperature uniformity compared to a single injector. However, peak outlet temperatures are moderately reduced, which helps reduce thermal stress on the turbine blade but slightly decreases thermal efficiency. Further improvements in outlet temperature are observed with eight hydrogen injectors, reaching up to ~ 1450 K, indicating effective mixing and more balanced combustion across the combustor. Using four and eight hydrogen transverse injectors provides better uniformity, which minimizes thermal stress and improves turbine performance.

Figure 48 provides the outlet-averaged static temperature for different fuel injector setups in an annular combustor gas turbine. It gives additional insight into the average temperature at the combustor exit, which is crucial for turbine efficiency and longevity.

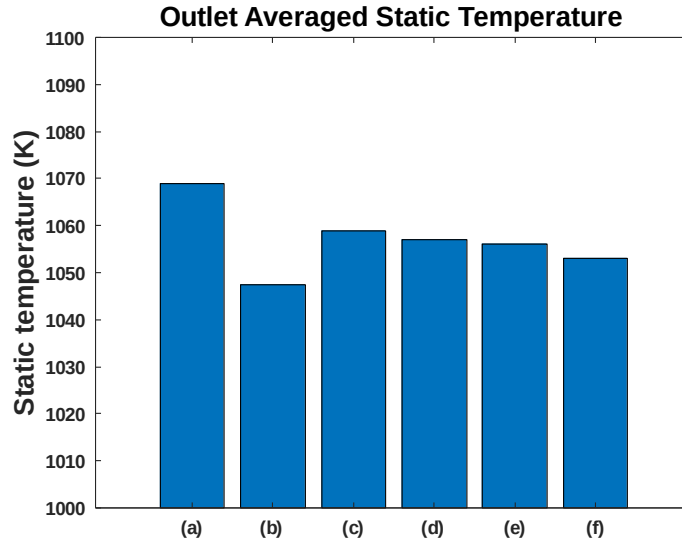


Figure 48 Outlet averaged static temperature using: (a) Kerosene 1 fuel injector; (b) Hydrogen 1 fuel injector; (c) Hydrogen 4 fuel injectors; (d) Hydrogen 8 fuel injectors; (e) Hydrogen 4 fuel transverse injectors; (f) Hydrogen 8 fuel transverse injectors.

Despite having a higher peak temperature outlet than kerosene, the hydrogen combustor demonstrates a lower average outlet temperature for all injection numbers. Reduced averaged static temperature might have been caused by the lower mass rate of hydrogen inlet than that of kerosene, minimizing the total mass of hot gases exiting the combustor. Furthermore, the excess water vapor, a byproduct of hydrogen combustion, might increase the cooling effect on the outlet temperature through its higher specific heat and latent heat of vaporization.

4.1.3. NOx emissions

Figure 49 displays the comparison of NOx emissions across six injector configurations, highlighting the influence of fuel type, the number of injectors, and injector orientation.

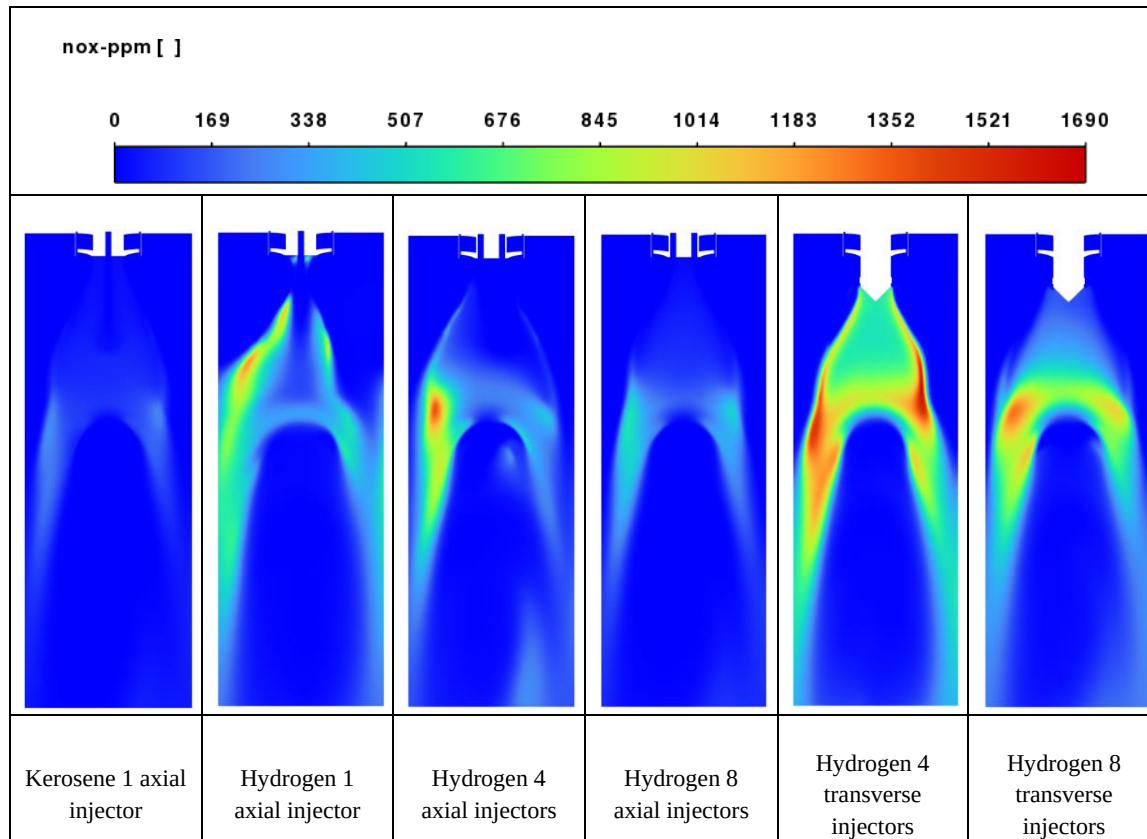


Figure 49 NOx emissions throughout the combustor using different fuel and injector configurations.

NOx emissions from kerosene with a single injector are minimal, with a maximum NOx of 298ppm. Kerosene combustion occurs at lower flame temperatures than hydrogen, thus reducing thermal NOx production. Higher NOx emissions are observed using a single hydrogen injector, with a maximum NOx of 1221ppm. Hydrogen's elevated flame temperature and rapid combustion promote higher thermal NOx formation. Furthermore, a single injector exacerbates uneven mixing, creating hotspots that may further increase NOx.

The NO_x emissions in four fuel injectors appear lower than those of a single injector, indicating improved fuel mixing and distribution, likely reducing localized maximum temperature. Further reduction in NO_x emissions is observed when eight injectors are implemented with a maximum NO_x of 565ppm. Increasing the number of fuel injectors promotes better mixing intensity, minimizing localized high-temperature zones, and mitigating thermal NO_x.

Regarding injector orientation, the transverse injectors demonstrate higher NO_x emissions than the axial injectors. The maximum NO_x emissions are observed in the four transverse injectors, reaching up to 1690 ppm. This indicates that transverse injection's rapid mixing may elevate NO_x emissions.

Since the equivalence ratio in the dilution zone is significantly low, the NO_x emissions are expected to be minimal since NO_x is directly related to the local static temperature in the combustion zone. Figure 50 shows the averaged outlet NO_x emissions using different fuel injector configurations.

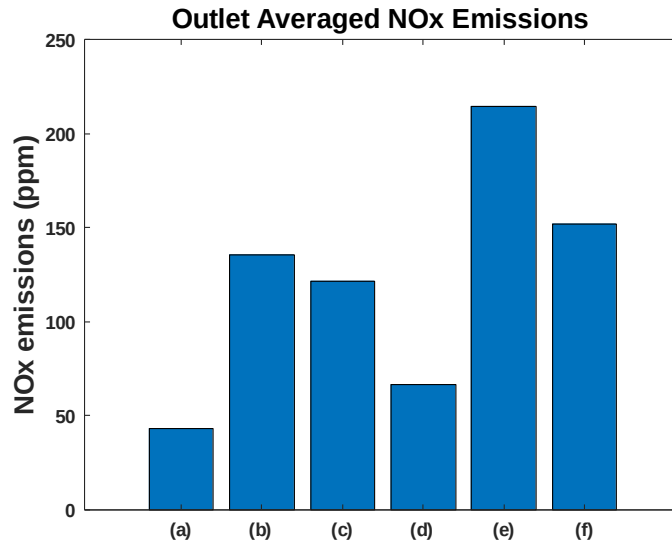


Figure 50 Outlet averaged NOx emissions using: (a) Kerosene 1 fuel injector; (b) Hydrogen 1 fuel injector; (c) Hydrogen 4 fuel injectors; (d) Hydrogen 8 fuel injectors; (e) Hydrogen 4 fuel transverse injectors; (f) Hydrogen 8 fuel transverse injectors.

As expected, kerosene fuel exhibits the lowest outlet NOx emissions (~44 ppm) due to slower combustion kinetics and reduced peak flame temperatures. Among different hydrogen injector configurations, the eight axial injectors demonstrate the lowest outlet NOx emissions (~67 ppm), while the maximum outlet NOx emissions are produced when using four transverse injectors (~214 ppm).

4.1.4. Fuel fraction

Figure 51 demonstrates hydrogen residues throughout the combustor with different fuel injector configurations. This figure shows the effectiveness of current injector designs, geometry, and boundary conditions regarding fuel mixing, influencing the flame temperature and stability in the recirculation zone.

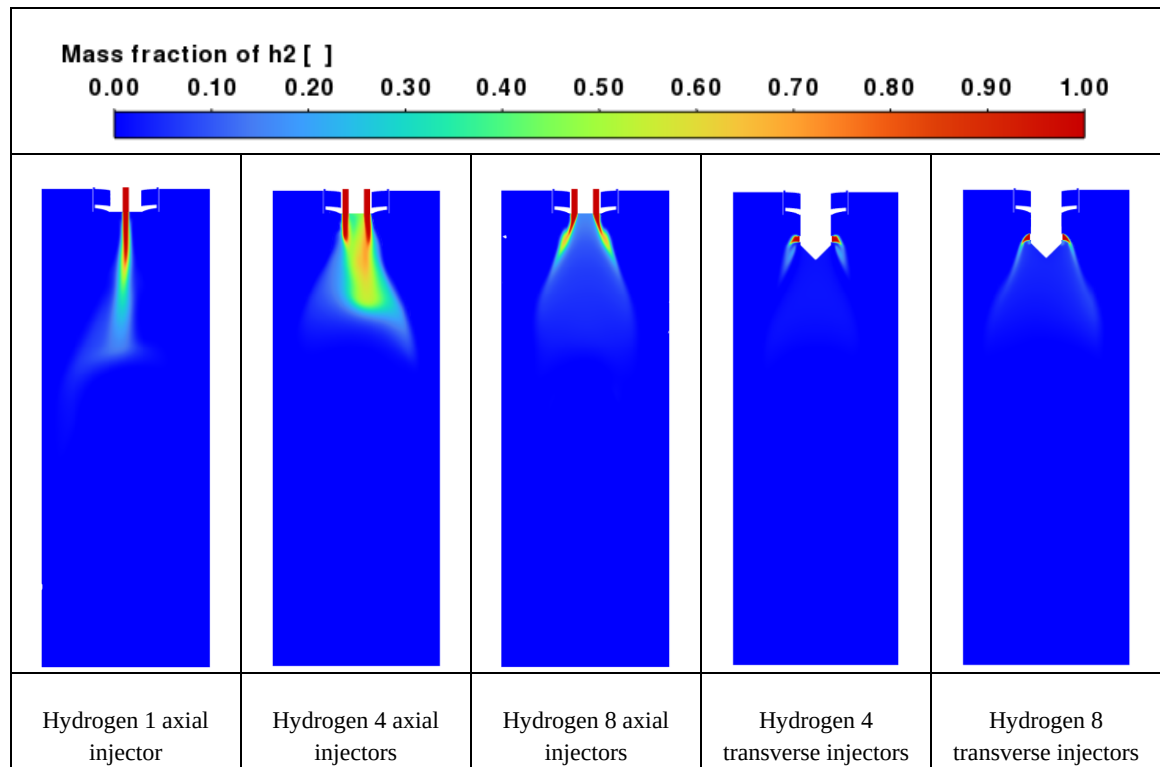


Figure 51 Hydrogen mass fraction throughout combustor using different fuel injector configurations.

Based on Figure 51, with a single hydrogen injector, the mass fraction distribution shows a narrower and longer hydrogen concentration near the injector. The fuel-air mixture is limited and localized due to high fuel inlet velocities, thus reducing fuel residence time. Using four injectors promotes hydrogen dispersion across the recirculation zone, thus reducing the likelihood of large unmixed zones. This contributes to a more efficient combustion and higher flame stabilization. The hydrogen mass fraction is further

homogenized in an eight fuel injectors configuration, which is likely optimal combustion performance. Transverse injection configuration promotes significant rapid mixing, creating a wider flame in the recirculation zone. Moreover, proper mixing with the air leads to a reduced hydrogen fraction at the combustor outlet, as depicted in Figure 52.

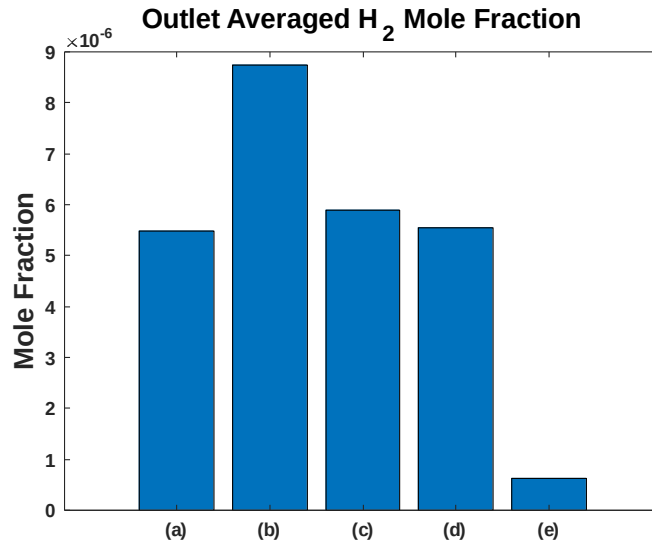


Figure 52 Outlet averaged Hydrogen residues using: (a) Hydrogen 1 fuel injector; (b) Hydrogen 4 fuel injectors; (c) Hydrogen 8 fuel injectors; (d) Hydrogen 4 fuel transverse injectors; (e) Hydrogen 8 fuel transverse injectors.

4.1.5. Concluding remark

Through subchapter 4.1.1-4.1.4, regarding the influence of fuel injector configurations and the comparison with kerosene fuel, it is possible to summarize that:

- Compared to kerosene, hydrogen has higher velocity magnitudes due to its low molecular weight in the same injection method. Hydrogen combustion produces higher flame temperatures due to its high reactivity, diffusivity, and adiabatic flame temperature. Moreover, all hydrogen different injector models exhibit higher averaged outlet velocity magnitude, suggesting similar thrust output to kerosene. All hydrogen injection setups produce higher outlet NO_x emissions; however, eight axial injectors demonstrate comparable outlet NO_x (67 ppm) to a kerosene single injector (44 ppm).
- Increasing the number of hydrogen injectors improves flow distribution and mixing, leading to wider, shorter, and hotter flames. This result indicates that fuel residence time and distribution are important to controlling flame stabilization. Transverse injectors enhance mixing than axial injectors, but they may introduce flame instability when combined with a combustor air swirler. Moreover, cross-flow injectors lead to higher exit NO_x emissions. For example, using the same swirl angle, four axial injectors yield NO_x of 121 ppm, while four transverse injectors produce 214 ppm. Similarly, eight axial injectors produce the lowest NO_x of 67 ppm, while eight transverse injectors generate 152 ppm.
- The eight axial hydrogen injectors depict somewhat comparable NO_x emissions to the kerosene single injector, offering a promising balance between high

performance and flame stability, minimizing risks associated with high flame temperature. However, these simulations were performed under the same swirl vane angle. Hence, each injector configuration is altered in the subsequent section using different swirl vane angles.

4.2.Effect of Swirl Vanes Angle

As stated, this subchapter examines the influence of swirl vane angles on each fuel injector configuration based on its temperature distribution, NO_x emissions, and the hydrogen residues throughout the combustor. Moreover, these simulation cases were done under the same equivalence ratio of 0.5558 in the recirculation zone, as depicted in Table 14.

4.2.1. Temperature distribution

The high swirling motion induced by increasing the swirl vane angles influences the flow field in terms of the size of the mixing region in the recirculation zone. The impacts of this swirling motion on flame temperature are demonstrated in Figure 53.

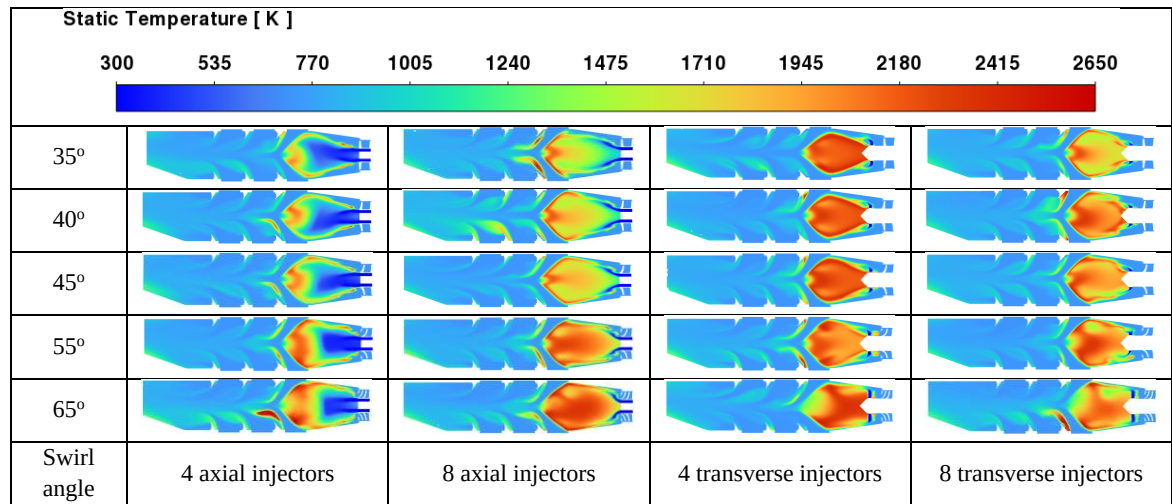


Figure 53 Temperature distribution using different hydrogen injector configurations and swirl angles.

Examining Figure 53, the influence of swirl vanes angle on temperature fields is contrasted for axial and transverse injectors. For the axial injectors, the flame is slightly elongated at low angles (35°-40°), with a relatively low temperature in the recirculation zone (RZ). Weak swirl intensity causes a limited mixing rate between the fuel and oxidizer, leading to a slower reaction rate and lower temperature in RZ. A significant change in flame structure

is observed at high swirl angles (55° - 65°). It is seen that more regions with intense red colors occur in RZ with high swirl intensity, which means that the flame temperatures have increased. The flame positions moved radially outward, colliding with the liner walls. This also means that high swirling strength may accelerate mixing and combustion rates.

The transverse injectors behave differently when the swirl angle is changed. For instance, in four transverse injectors, the flame is observed to be very intense, with red colors dominating the recirculation zone despite a low swirl angle (35° - 45°). The flame is slightly less intense when the swirl angle is increased to 55° or 65° . The four transverse injectors show a non-uniform flame structure in a high swirl intensity flow. This might have resulted from the cross-flow fuel-air mixture and high-turbulence intensity. Regarding eight transverse injectors, at a low swirl angle (35°), the flame is shown to be less intense. However, a hotter flame is observed at RZ once the swirl angle is increased. As the swirl angle increased, the transverse injectors showed inconsistent flame, where non-uniform flame temperature and shape occurred at a high turbulence flow. In other words, the transverse injectors are very sensitive to the influence of swirl angle.

Optimal swirl angles may improve the mixing and recirculation, raising the flame temperatures toward adiabatic limits, as in the case of the axial injectors. In addition, a higher swirl angle might create a shorter, wider, and more intense flame. The transition from elongated to shorter, intense flames directly correlates with the increased swirl number. However, the transverse injectors show that excessive angle could lead to flame instability or heat loss. One may argue that the transverse injectors may not need the swirl vanes since, in a crossflow setup, the fuel is injected into a perpendicular oxidizer flow,

creating shear layers and vortices that promote mixing. The addition of centrifugal flow may disrupt these turbulence vortices, thus causing combustion instability.

Combustion stability, temperature, and structure are critical factors determining gas turbine efficiency, emissions, and turbine blade life span. Figure 54 displays the combustor outlet temperature fields across various fuel injectors and swirl vanes angles.

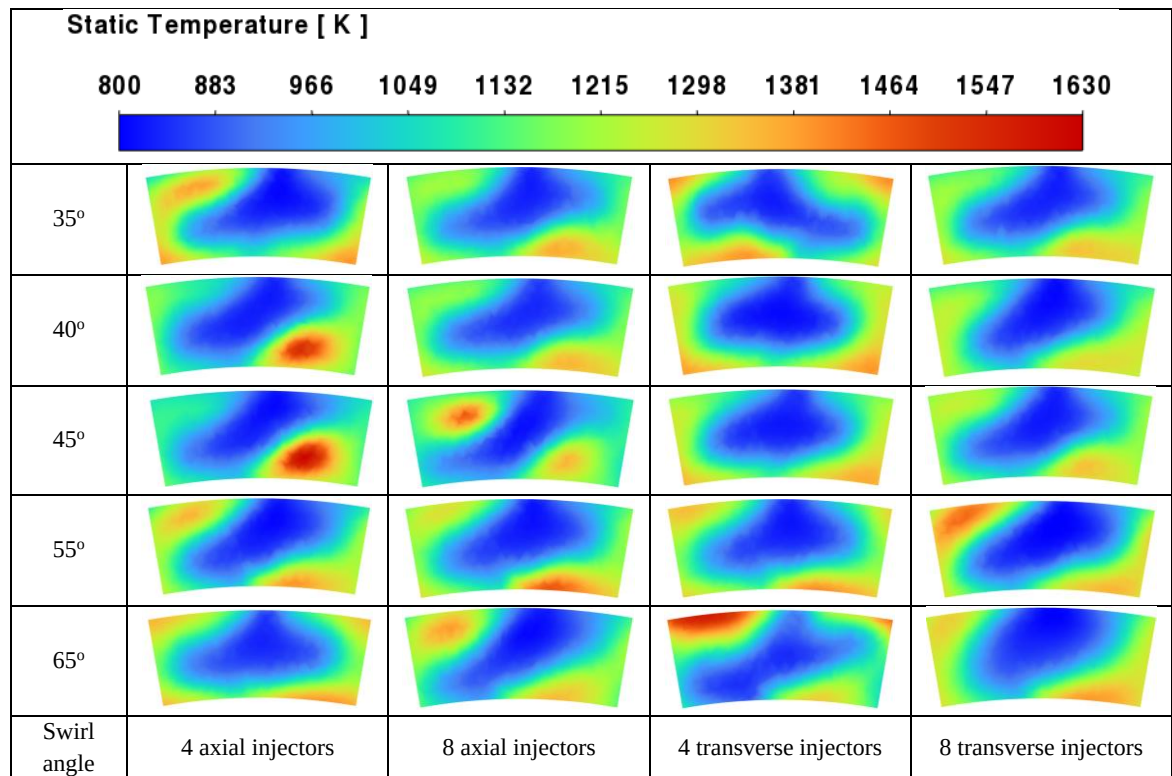


Figure 54 Temperature distribution at outlet plane of hydrogen injector configurations and swirl angles.

Generally, the cold region, in blue, seems to dominate the combustor outlet plane due to high velocities of cold flow stemming from the liner jet inlets. In axial injectors, high swirl angles (55°-65°) yield overall higher temperatures. However, localized hotspots are observed at four axial injectors with 40° and 45° swirl angles, which is detrimental to the turbine blade life span. Non-uniform distributions can lead to operation challenges, such

as uneven turbine blade wear, thermal stress, and increasing the instability of the lean combustion regime, especially for a hydrogen burner.

The transverse injectors demonstrate minimum hotspots across various swirl vane angles at the combustor outlet. Higher swirl intensity produces a hotter outlet flame temperature, symbolized by more intense red colors. However, the average outlet temperature (1050 K-1060 K) seems similar for any configurations, as shown in Figure 55. The dilution jets' inlet velocities are considered high, cooling the flame drastically in the dilution zone regardless of combustion flame temperature. In addition, the numerical error might cause the calculated outlet temperature between the simulated cases to be slightly different.

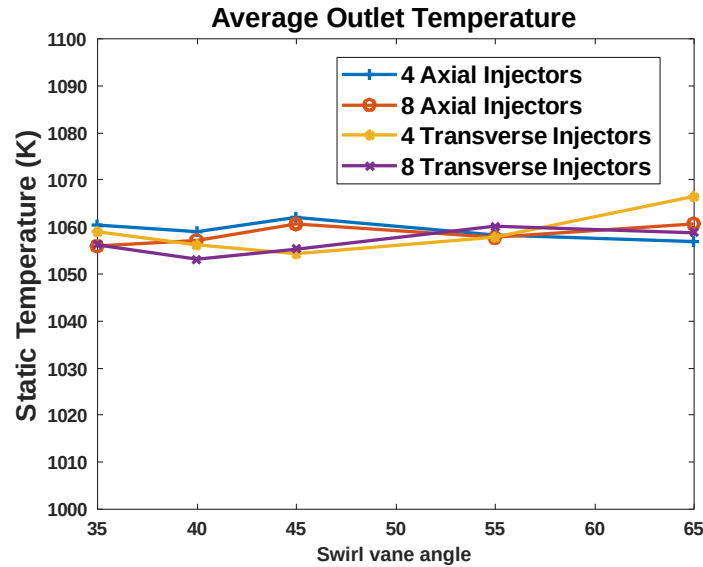


Figure 55 Outlet averaged static temperature on different hydrogen injector configurations and swirl angles.

4.2.2. NOx emissions

The setup of hydrogen fuel injectors and swirl vanes influences the behavior of the flow field and flame temperature, especially in the recirculation zone. In axial injectors, wider and hotter flame temperatures are observed in high-swirling flows, indicating that the fuel is properly mixed with the oxidizer. In contrast, unstable flame shapes and temperatures are observed for transverse injectors in a high-swirl stream.

The thermal NOx mechanism primarily influences NOx emissions in hydrogen combustion, which depends on local flame temperatures. Stronger swirls increase temperatures and, consequently, NOx production, as shown in Figure 56.

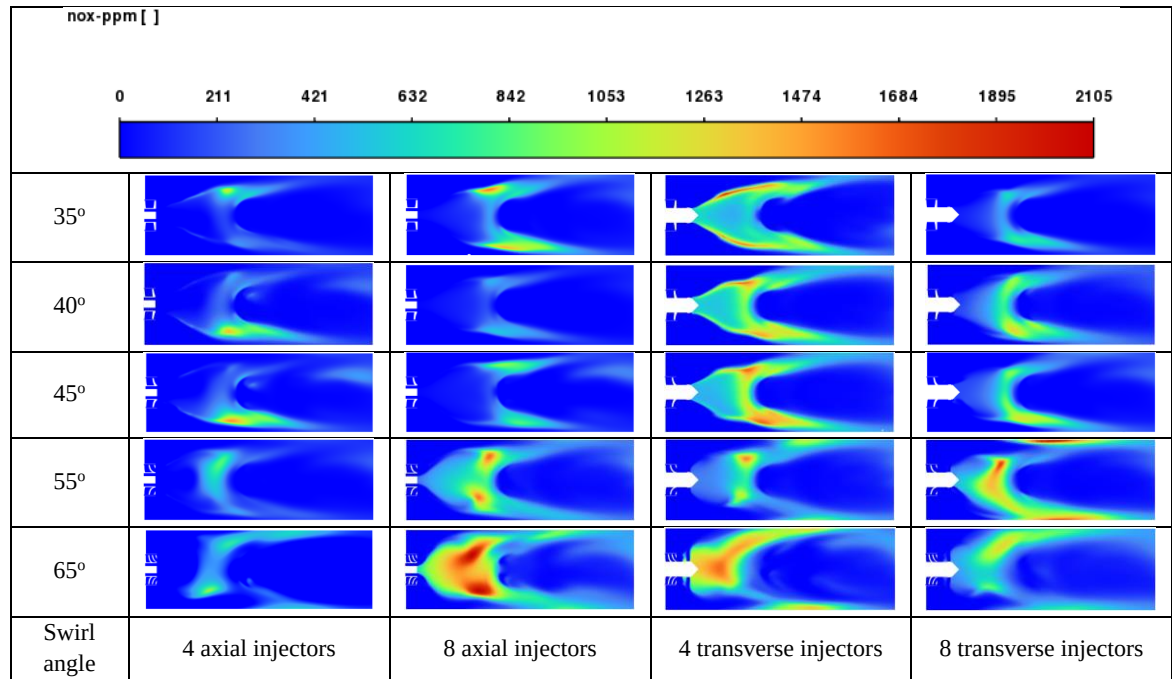


Figure 56 Horizontal plane NOx emissions using different hydrogen injector configurations and swirl angles.

Generally, lower swirl vane angles (35° and 40°) produce lower NOx emissions due to reduced mixing efficiency and lower combustion temperatures for axial and transverse injectors. A high swirl vane angle increases mixing and higher flame temperatures,

resulting in higher NO_x emissions. The highest NO_x emissions (~2,105 ppm) are released using eight axial injectors with a swirl vane angle of 65°. However, minimum NO_x emissions are produced at 40° in the same injector setup, showing a faint greenish color in the primary zone. One can observe that the eight transverse injectors at 35° exhibit a similar NO_x contour. These similarities in NO_x production can be observed in Figure 53, where both flames exhibit identical shapes and temperature distributions. As a result, these two configurations produce similar outlet NO_x emissions, as depicted in Figure 57.

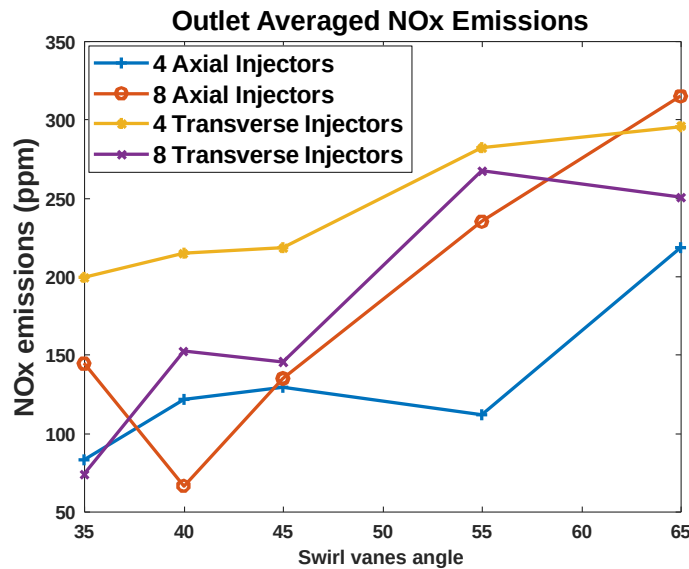


Figure 57 Outlet averaged NO_x emissions using different swirl vanes angles.

Looking at Figure 57, higher swirl angles tend to produce higher outlet NO_x pollutants for axial and transverse injectors. However, using the eight axial injectors with a 40° swirl angle, the minimum outlet NO_x emissions (~66 ppm) are observed, and the maximum outlet NO_x emissions (~314 ppm) are generated when the swirl vanes are increased to 65°. Interestingly, in the same configuration, a lower swirl angle (35°) causes higher outlet NO_x emissions, indicating the sensitivity of fuel injectors and swirl vane setup to NO_x

emissions. In contrast, other hydrogen injectors demonstrate the lowest outlet NO_x emissions at 35°.

4.2.3. Fuel fraction

The fuel injectors and swirl vane angle are crucial in determining the extent of fuel distribution, mixing, and combustion efficiency in the hydrogen-fueled annular combustor, as shown in Figure 58. Ensuring uniform and rapid mixing of hydrogen and air is essential for achieving high efficiency and low emissions.

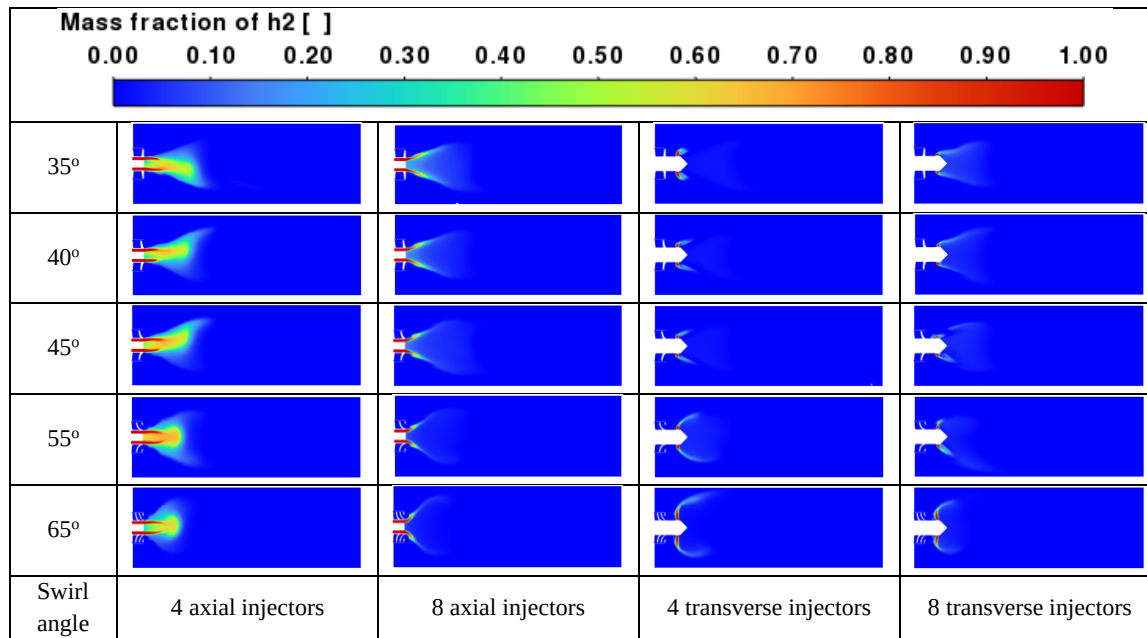


Figure 58 H₂ mass fraction on different hydrogen injector configurations using different swirl vanes angles.

As seen from Figure 58, in low swirl vane angles (30°-40°), the H₂ distribution is extended axially, with a high concentration of hydrogen (red and green zones) extending further downstream. As expected, the weaker swirling motion causes a limited hydrogen and air mixing rate, creating a longer hydrogen plume. Furthermore, it reduces combustion efficiency due to incomplete fuel utilization and an increased risk of unburned hydrogen escaping downstream. At a moderate angle (45°), the hydrogen distribution shows improved radial spread and a shortened hydrogen plume. The stronger swirl enhances turbulence and recirculation, decreasing hydrogen mass fraction quickly downstream. At

the highest swirl vane angle (65°), the broadest and shortest hydrogen plume promotes near-complete combustion in the recirculation zone. However, this configuration may require careful control to avoid mechanical stress on the combustor.

To ensure of how much unburned hydrogen exits the combustor due to the influence of swirl vanes angle, Figure 59 illustrates the outlet-averaged H_2 volume fraction.

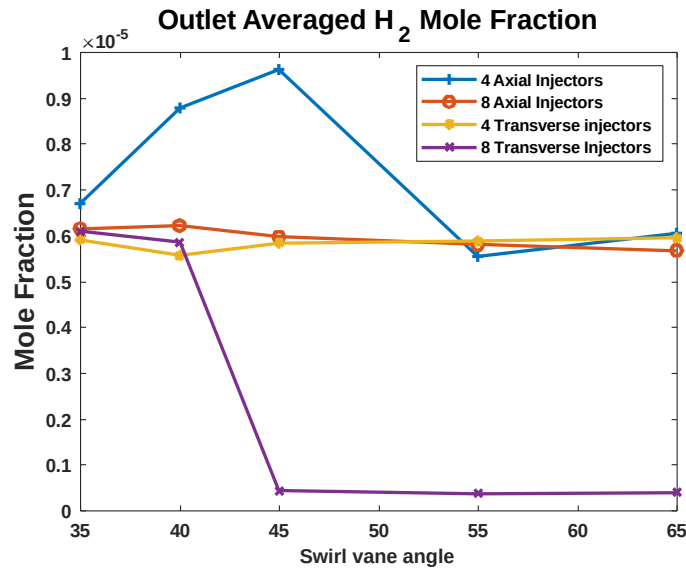


Figure 59 Outlet averaged hydrogen fraction using different swirl vanes angles.

The graph demonstrates minimal variation in the outlet hydrogen volume fraction across the range of swirl vanes angle. The outlet H_2 volume fraction lies under 10^{-6} for all angles, indicating a relatively low unburned hydrogen fuel exiting the combustor.

4.2.4. Concluding remark

Through subchapter 4.2.1-4.2.3, regarding the influence of swirl vanes angle on the flame temperature and emissions, it is possible to summarize that:

- Increasing the swirl vane angles expands the flow field in the recirculation zone radially outward due to stronger swirling motion. This also indicates the low-velocity region in the recirculation is increasing, which improves fuel residence time. In the case of axial injectors, higher swirling motion promotes wider, shorter, and hotter flames. In contrast, transverse injectors exhibit a disturbed flame shape and temperature at high swirl angles (55° and 65°), indicating that transverse injectors effectively minimize localized hotspots at low swirl angles. It is also possible that transverse injectors work well without swirl vanes due to their cross-flow regime between fuel and oxidizer, which promotes better mixing in the RZ.
- Across all fuel injector methods and swirl angles, eight axial injectors with a 40° swirl vane produce the lowest output NOx emissions of 66 ppm. At the same time, at 65° swirl, its maximum outlet NOx pollutants are elevated to 314 ppm. The second lowest outlet NOx emissions (~ 73 ppm) are demonstrated by eight transverse injectors with a 35-swirl angle. These two injectors show similar flame shape and temperature distributions; hence, their outlet NOx emissions are somewhat identical.
- Selecting appropriate fuel injectors and swirl vane angles is essential because they govern temperature uniformity and combustion stability, the two most critical factors controlling NOx in hydrogen flames. For gas turbines targeting near-zero

emissions, optimizing these parameters is non-negotiable. However, these simulated cases were performed under the same equivalent ratio. Therefore, the equivalence ratio will be varied based on ICAO's LTO cycle.

4.3.Effect of Equivalence Ratio

In this subchapter, simulations of the impact equivalence ratio were done to accommodate ICAO's LTO cycle, assuming the default case was implemented for the cruising phase, which uses roughly 65% of power settings. The fuel mass flow rates were adjusted for each flight phase based on cruising stage power settings, as depicted in Table 15. Furthermore, air distribution is set to be the same for all cases. The simulated cases are selected based on minimum NOx emissions at the outlet for each injector configuration and their respective swirl angle, as shown in Table 19.

Table 19 Simulated cases under the influence of different equivalence ratios.

Case #	Injector Config.	Swirl Angle	Outlet NOx (ppm)
Case 1	Four axial injectors	35°	82.702
Case 2	Eight axial injectors	40°	66.352
Case 3	Four transverse injectors	35°	199.195
Case 4	Eight transverse injectors	35°	73.818

4.3.1. Velocity profile

Considering the influence of equivalence ratios is established on altering fuel contents in the combustor, the velocities near the fuel injector point are changed, as shown in Figure 60.

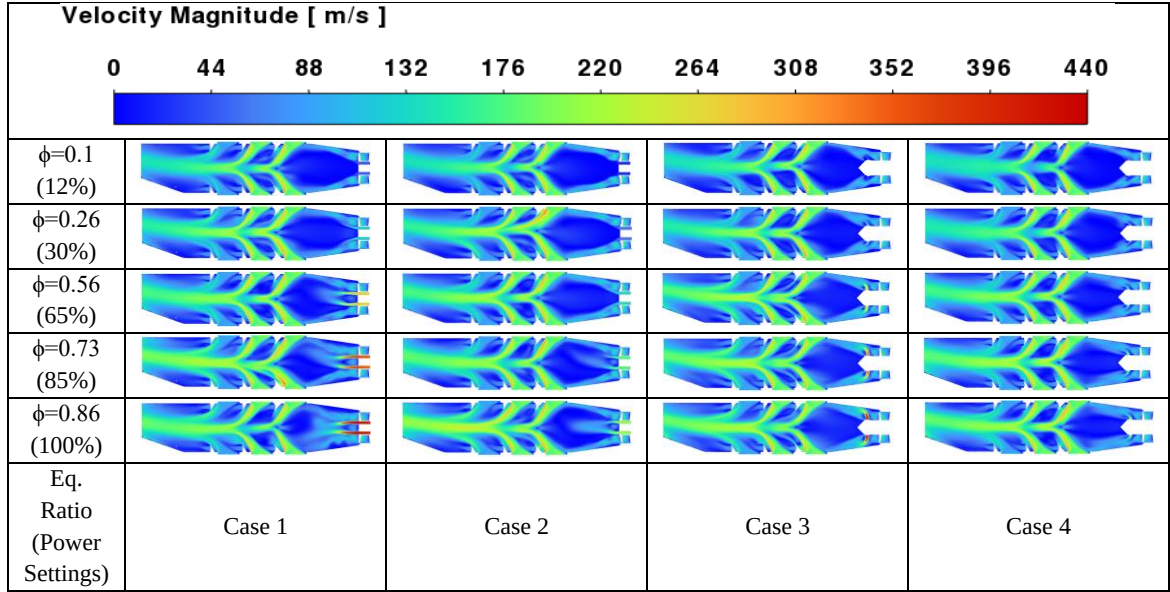


Figure 60 Velocity magnitude on different cases with various equivalence ratios.

The velocity magnitude near the injection point is relatively low at a low equivalence ratio ($\phi = 0.1$). In this work, a low equivalence ratio indicates a low fuel mass flow rate, which carries less fluid momentum in the combustor. As the equivalence ratios increased, the stream had more momentum, corresponding to the aircraft's higher thrust requirement. At near-stoichiometric conditions ($\phi = 0.86$), the velocity magnitude for Case 1 and Case 3 are significantly high (~ 440 m/s) owing to their four injectors. Meanwhile, eight injectors show lesser values under the same total fuel rate, as depicted in Case 2 and Case 4. Despite that, fuel injector configurations and swirl vane angles demonstrate identical outlet averaged velocities trend lines under the same equivalence ratio, as shown in Figure 61.

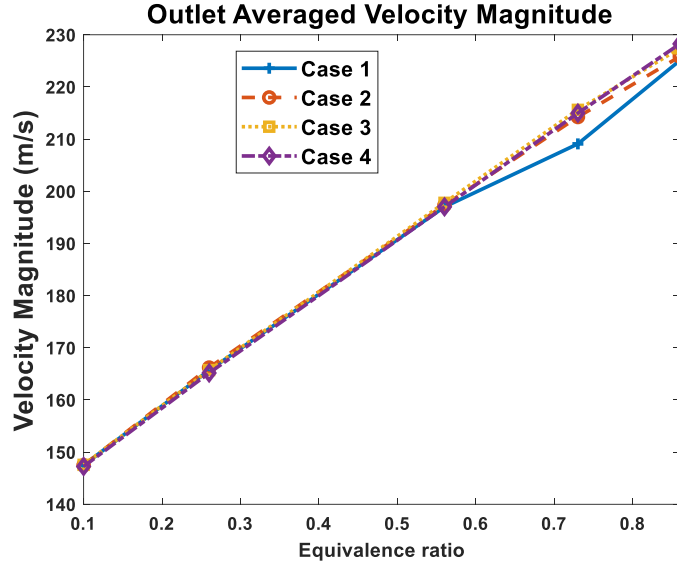


Figure 61 Outlet averaged velocity magnitude of simulated cases under different equivalence ratios.

Figure 61 shows all simulated cases produce similar outlet velocities under the same equivalence ratios. A low equivalence ratio's ($\phi = 0.1$) average output velocity magnitude is approximately 147 m/s. Conversely, the outlet velocities are raised considerably (~226 m/s) near the stoichiometric ratio ($\phi = 0.86$). Understandably, a higher equivalence ratio implies an increased fuel mass flux, promoting significant gas expansion and higher acceleration flow momentum downstream, which maximizes engine thrust. It can also be inferred that neither the injector nor the swirl angle greatly affects the outlet velocities. In addition, the jets from the primary, secondary, and dilution zones might dominate the outlet average velocities. It is worth noting that at ($\phi = 0.73$), Case-1 deviates slightly from the other cases due to slight inaccuracy in the numerical iteration.

4.3.2. Temperature distribution

In a hydrogen diffusion flame, the equivalence ratio, or the actual fuel-to-oxidizer mass flow ratio relative to the stoichiometric, directly influences combustion temperatures through its influence on local mixing efficiency, dilution effects, and heat release distribution. Figure 62 displays the temperature fields of the simulated cases under various equivalence ratios.

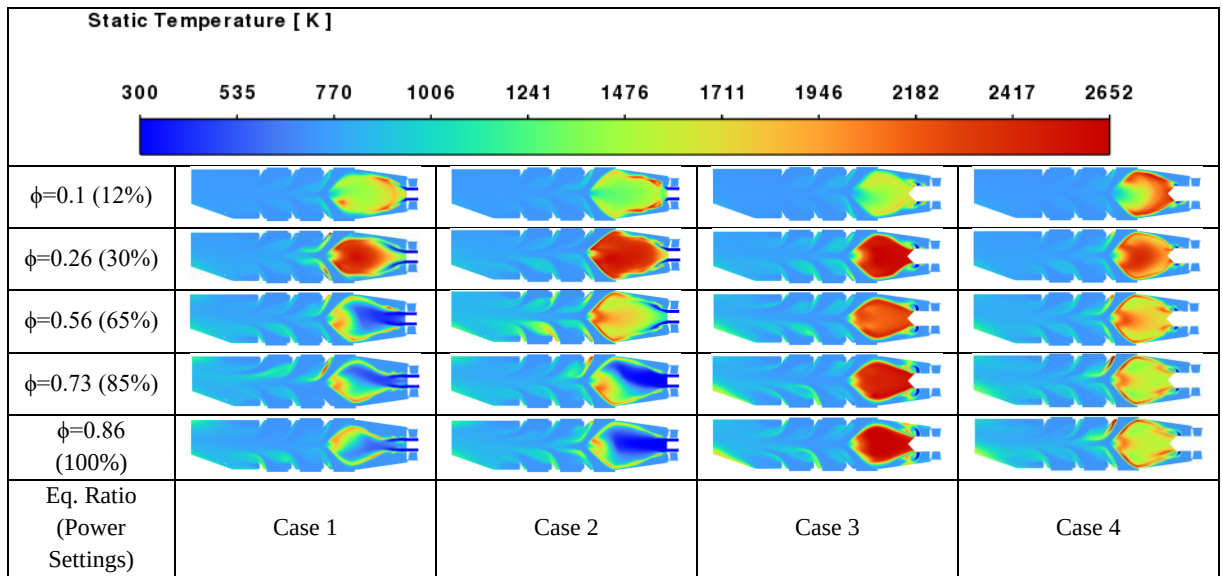


Figure 62 Temperature fields on different cases with various equivalence ratios.

In Cases 1 and 2, at a low equivalence ratio ($\phi = 0.1$), the static temperature remains relatively low at RZ due to minimal heat release, resulting in weak flame propagation. Indeed, such a scenario corresponds to idle or low-power operation, where little fuel is burned to sustain engine operation. However, as the equivalence ratio increased to 0.26 or 30% power, a large rise in flame temperature occurred in RZ. Optimal fuel mixing and sufficient hydrogen fuel may produce this sudden temperature rise. This behavior is also observed near the specified equivalence ratio ($\phi = 0.26$), as shown in Figure 63.

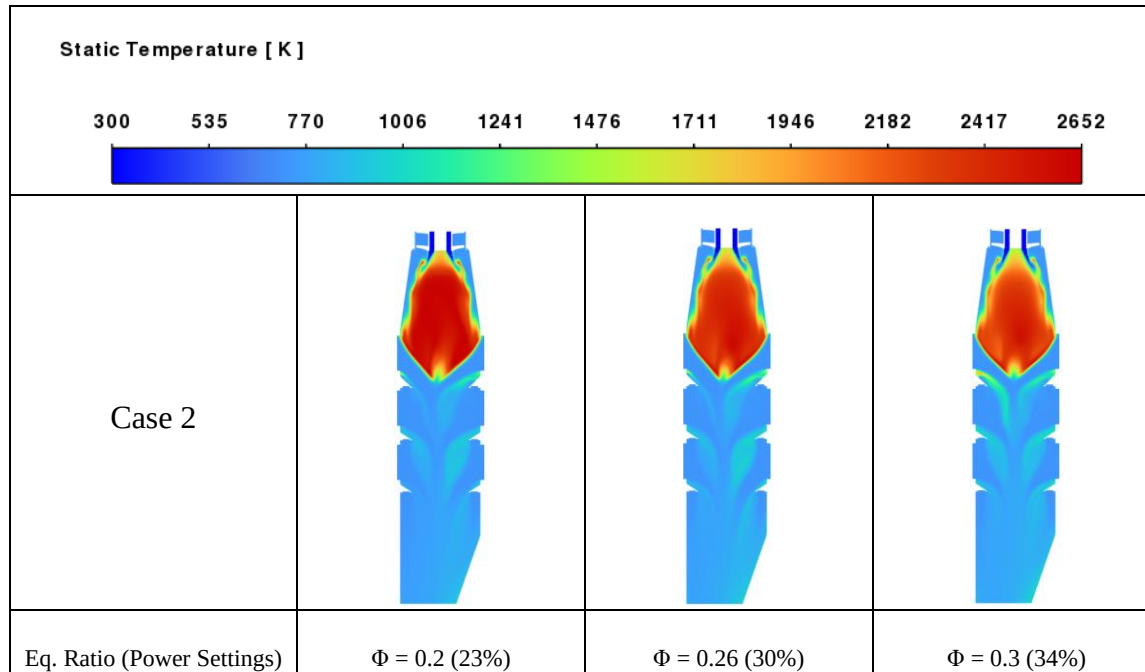


Figure 63 Static temperature distribution for Case 2 for various ultra-lean equivalence ratios.

Examining Figure 63, at an equivalence ratio ($\phi = 0.2$), Case-2 shows an intense red color at RZ, indicating a very high flame temperature. However, as the equivalence ratio increases, the combustion temperature slightly reduces as the temperature fields show lighter red. Returning to Figure 60, it can be concluded that for hydrogen axial injectors, fuel velocity in the range of 50 m/s to 150 m/s and low swirl angles might exert the optimum fuel mixing, producing a high combustion temperature. A well-developed high-temperature zone is visible when the equivalence ratio increases to 0.56 for Cases 1 and 2, where a small portion of the flame extends further downstream. This flame shape and temperature are appropriate for cruise conditions where efficiency and steady performance are crucial. However, at higher equivalence ratios ($\phi = 0.73$ -0.86), the flame structures are seen as unstable owing to their high fuel speed, which minimizes fuel burn time. The flame core should be extended downstream at an increased fuel mass inlet. However, the temperature reduces rapidly downstream due to cooling and dilution effects.

The transverse injectors behave differently, as depicted in Cases 3 and 4. Under the same equivalence ratio, Case-3 demonstrates significantly higher flame temperature, implying that four transverse injectors and a low swirl angle yield high mixing efficiency. On the other hand, Case-4 shows a high combustion temperature at low equivalence ratios, ranging from 0.1 to 0.26. However, this also could imply that the flame core occurs at RZ for Case 3, while the flames for other cases are extended downstream.

It is imperative that as the equivalence increases, the flow becomes more complex, with compact and elongated flames. In theory, higher equivalence ratios produce higher flame temperature flame. However, the flame temperature demonstrates the opposite due to geometry complexity and boundary conditions. Although, an increase in terms of peak outlet static temperature can be observed in Figure 64.

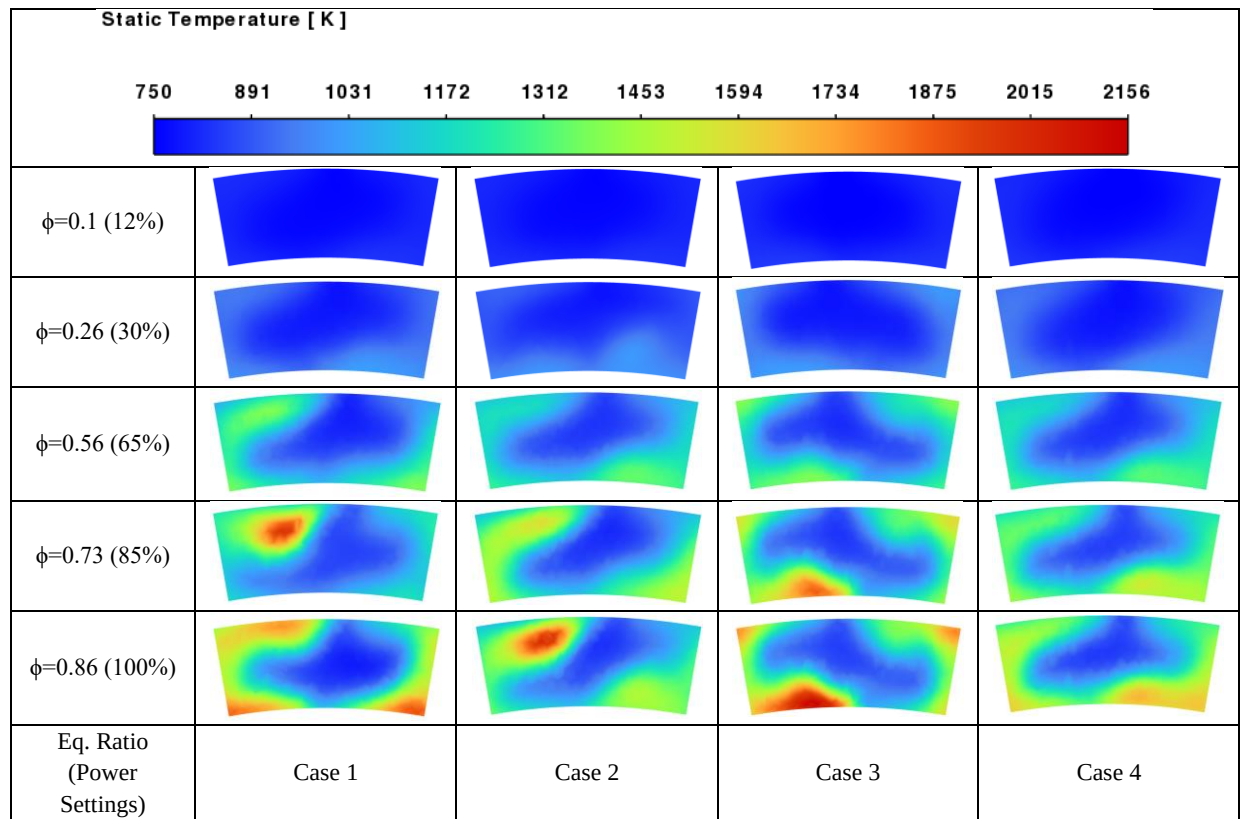


Figure 64 Outlet temperature on different cases with various equivalence ratios.

The figure shows the relationship between outlet static temperature distribution and cases (Case-1 to Case-4) across equivalence ratios (ϕ). The temperature progression (750 K to 2,156K) suggests that higher ϕ values systematically increase outlet static temperatures in all cases. ($\phi=0.1$) value corresponds to ultra-lean mixtures with excess air, releasing less thermal energy. Hence, the outlet flame temperature should be minimal. This aligns with low-power settings (idle), where outlet temperatures remain relatively low (closer to 750-850 K). As ϕ increases (e.g., $\phi = 0.56$), the combustion process releases more energy, increasing the outlet temperature to $\sim 1,500$ K. This value is associated with the longest flight stage (cruise phase), where the outlet temperatures are optimized to minimize thermal degradation while generating sufficient combustion efficiency. Near stoichiometric value ($\phi = 0.56$), combustion becomes more fuel-rich, releasing greater thermal energy and elevating static temperatures significantly (up to $\sim 2,156$ K), necessitating advanced turbine cooling strategies and materials to avoid thermal stress. However, this is typical of high-power operations like take-off, where an aircraft requires 100% thrust power for a short period.

The relationship between equivalence ratios and outlet temperature should be direct, where a higher equivalence ratio tends to increase outlet temperature. This correlation can be deduced in Figure 65. This data suggests a linear correlation between ϕ and average temperature across all cases. All cases demonstrate identical average outlet temperatures at the same ϕ , indicating fuel quantity might directly dictate outlet temperature by modulating the equivalence ratio. More fuel increases temperature through intensified combustion but requires robust thermal management. In contrast, less fuel reduces thermal stress at the cost of combustion efficiency.

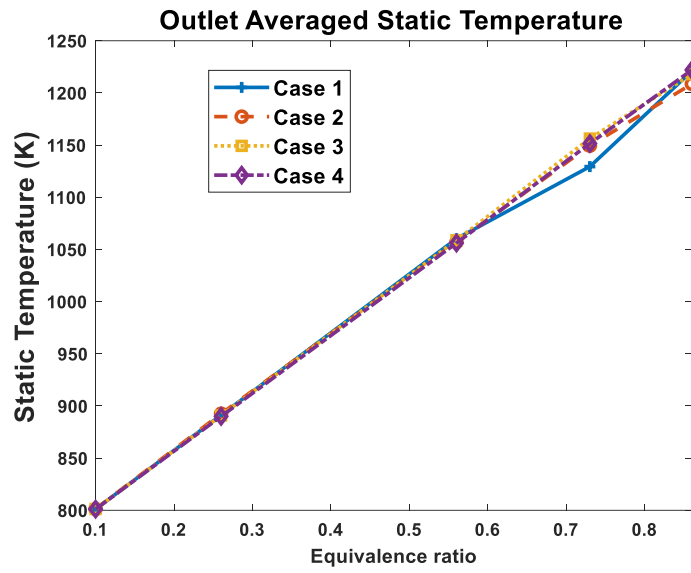


Figure 65 Outlet average static temperature on different cases with various equivalence ratios.

4.3.3. NOx emission

The equivalence ratio significantly impacts NOx emissions, with higher ϕ values tending to increase NOx due to elevated flame temperatures and oxygen availabilities. However, key design factors, including the number of injectors, orientation, and swirl angle, modulate this relationship by influencing fuel-air mixing efficiency and combustion dynamics, as depicted in Figure 66.

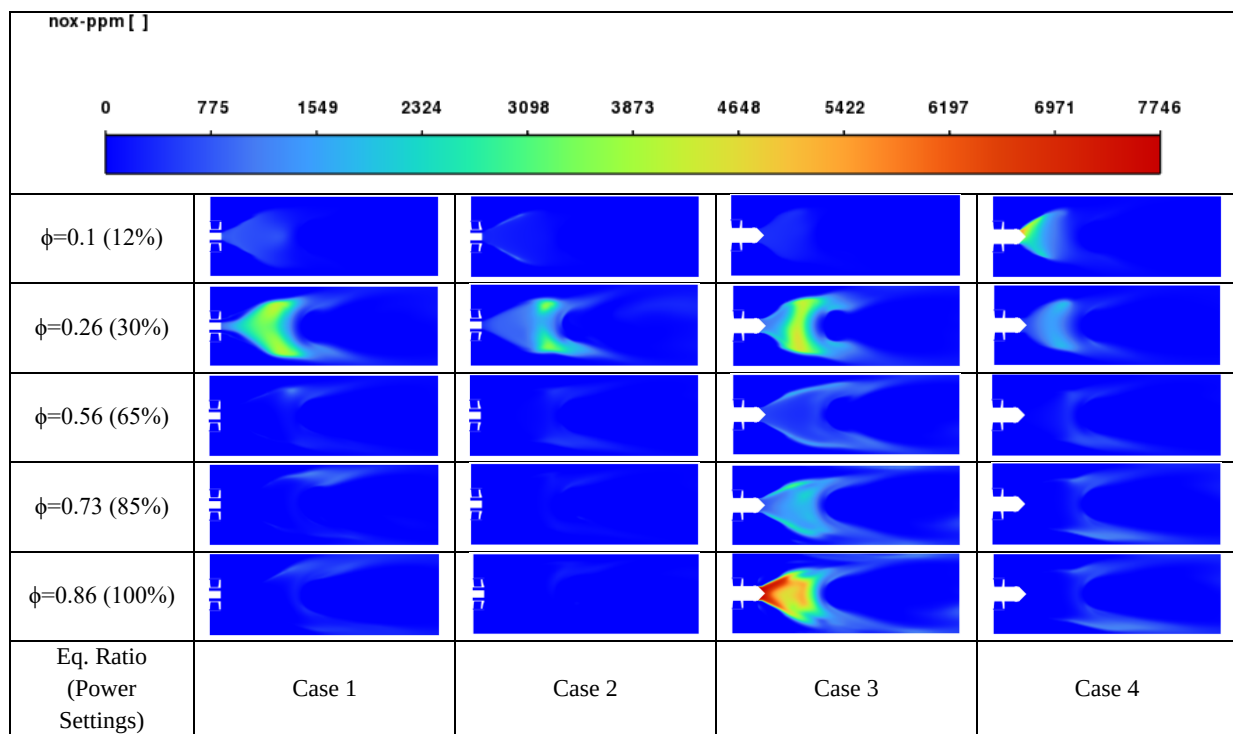


Figure 66 Horizontal plane NOx emissions on different cases with various equivalence ratios.

The relationship between flame temperature and NOx emissions is apparent in the provided figure. Excess air generally suppresses thermal NOx formation at low ϕ (0.1, ultra-lean mixture). However, enhanced mixing in configurations like Case-4 (4 transverse injectors, 35 ° swirl) creates localized hot spots, which elevate emissions (2500-3500 ppm). As the ϕ is increased to 0.26, cases 1, 2, and 3 demonstrate a spike in NOx emissions. In contrast, Case 4 reduces localized hot spots, thereby lowering NOx levels to 1500 ppm. At high ϕ

(0.86), near-stoichiometric combustion systematically elevates temperatures, pushing NO_x to peak levels (~7747 ppm) in Case 3 (4 transverse injectors, 35 ° swirl).

As in Cases 3 and 4, the transverse injectors introduce radial fuel penetration, which improves fuel mixing but exacerbates NO_x emissions, even at low ϕ , due to localized hot spots. On the other hand, axial injectors (Cases 1 and 2) demonstrate moderate NO_x levels, except at $\phi = 0.26$. Optimal fuel residence time and sufficient fuel flow may result in a high flame temperature, leading to an increase in NO_x. Ensuring that the amount of NO_x emissions has been reduced at the combustor outlet due to the cooling and dilution effects, Figure 67 shows the outlet-averaged NO_x emissions under different power settings and equivalence ratios.

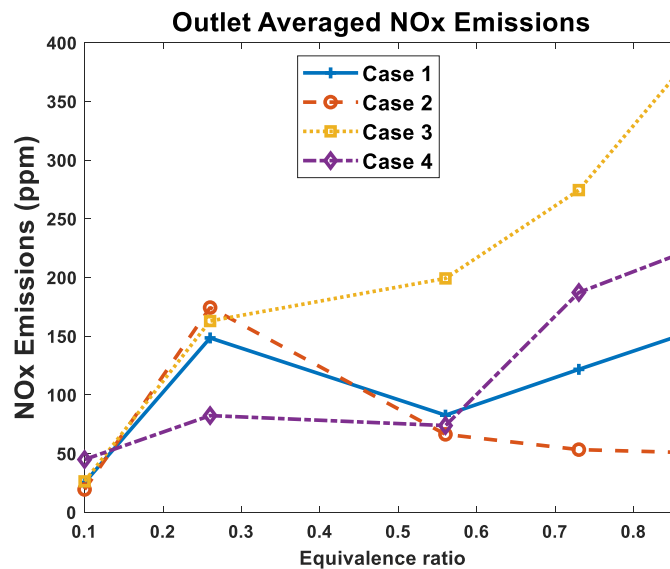


Figure 67 Outlet averaged NO_x emissions on different cases with various equivalence ratios.

At a low equivalence ratio ($\phi = 0.1$), lean combustion suppresses thermal NO_x formation due to lower flame temperatures. Case 4 exhibits lower NO_x emissions (~82 ppm) at $\phi = 0.26$, while other cases doubled that amount at the same equivalence ratio. Case 2 (8 injectors, 40° swirl) produces the lowest NO_x (66 ppm) among other cases during the cruise

conditions. This trend continues at higher equivalence ratios ($\phi = 0.73-0.86$, 85%-100% power), where Case 2 produces the lowest NO_x pollutants, reducing to ~51 ppm.

4.3.4. Fuel fraction

The equivalence ratio, ϕ , has a profound impact on the outlet hydrogen (H₂) mass fraction, reflecting the degree of combustion completeness and mixing efficiency. Injector design and swirl vanes further alter this fraction. Figure 68 represents the relationship between equivalence ratios and H₂ mass fraction for four distinct injector configurations, highlighting how combustion dynamics and design parameters interact to influence fuel mixing.

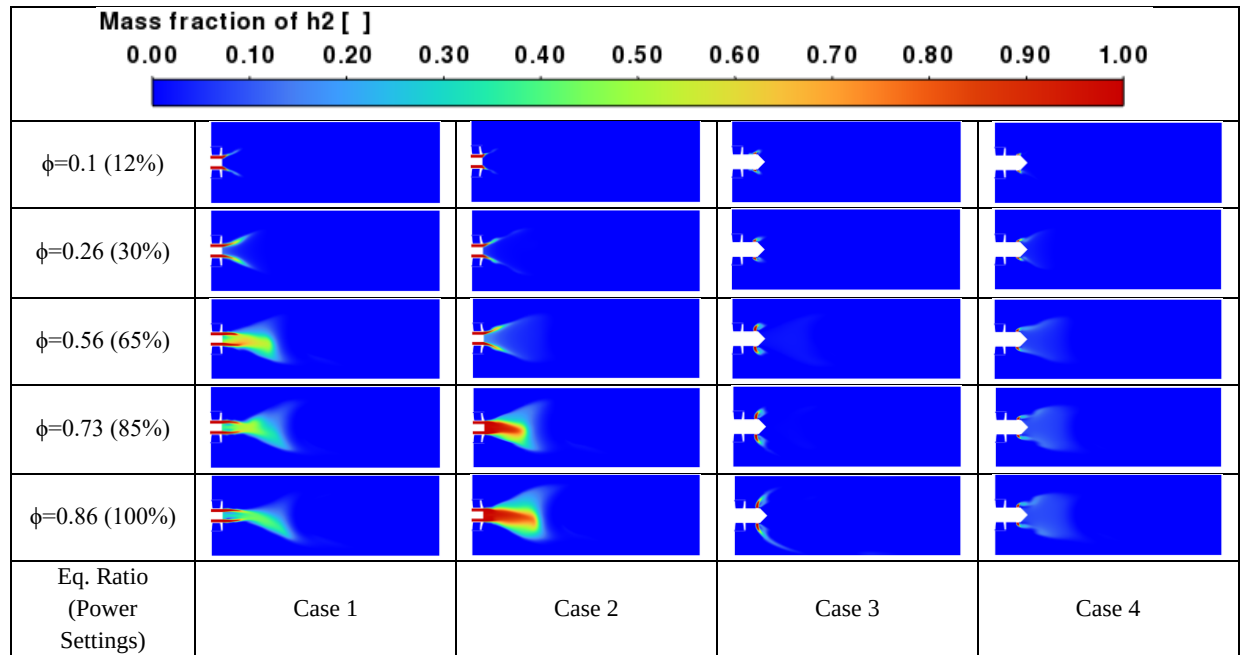


Figure 68 H₂ mass fraction on different cases with various equivalence ratios.

The equivalence ratio is adjusted by varying fuel flow at a constant air flow, significantly impacting the unburned H₂ mass fractions. With higher ϕ (richer mixtures), the H₂ plume in RZ is stretched due to the extension of fuel residence and incomplete combustion. Injector design critically modifies this plume shape: transverse injectors (Case 3 and 4) exhibit superior mixing, minimizing H₂ residuals at high ϕ (0.73-0.86) by enhancing turbulence and combustion efficiency. In contrast, axial injectors (Case 1 and 2)

demonstrate poor fuel mixing, leading to prolonged fuel residence and elevated unburned H_2 near the injector points. These trends can also be observed at the outlet, where transverse injectors exhibit better combustion efficiency, as depicted in Figure 69. Hence, the key trade-offs are that transverse injectors may have superior combustion efficiency and higher flame temperature at the cost of higher NO_x than axial injectors. Furthermore, increasing the number of injectors may reduce the NO_x emissions due to evenly distributed fuel flow in RZ, eliminating the possibility of localized hotspots.

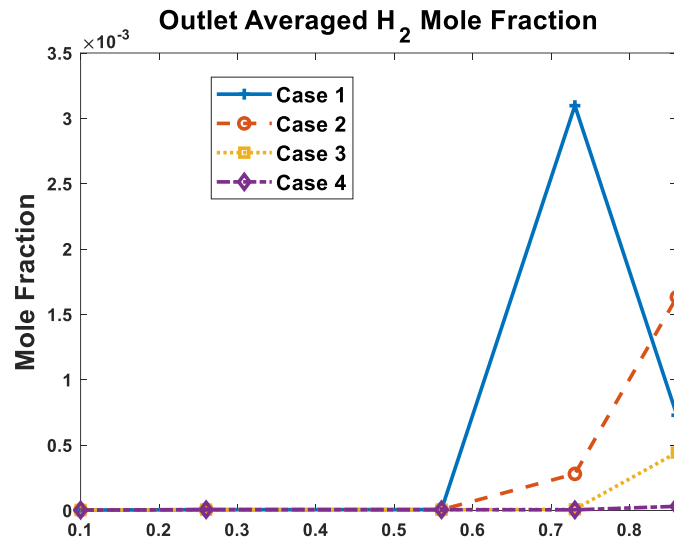


Figure 69 Outlet averaged hydrogen volume fraction on different cases with various equivalence ratios.

4.3.5. Concluding remark

Through subchapter 4.3.1-4.3.4, regarding the influence of equivalence ratios on the flow field, flame temperature, and emissions, it is possible to summarize that:

- Higher equivalence ratios, ϕ , result in increased velocity output downstream in the combustor due to stronger combustion and gas expansion, aligning with the thrust demands of aircraft engines. The total number of fuel injectors and their orientation might have little effect on the output velocities. However, the fuel mass greatly impacts the fluid momentum throughout the combustor. During the idle stage ($\phi = 0.1$, 12% power), the outlet averaged velocities are approximately 147 m/s. The outlet velocities during cruising ($\phi = 0.56$, 65% power) and take-off ($\phi = 0.86$, 100% power) stages are 197 and 226 m/s, respectively.
- At ultra-lean mixture, $\phi = 0.1$, flame temperatures are minimal in all injector modifications due to the lowest limit of hydrogen combustion, resulting in lower output temperature, which is appropriate for the idle stage. However, peak temperatures occur approximately at $\phi = 0.26$ for axial and transverse injectors. This phenomenon may have been caused by an optimum fuel residence and flow mixture, where sufficient hydrogen fuel remains long enough to properly mix with an oxidizer, yielding a high temperature and thus producing a spike in NO_x. As the ϕ increases, transverse injectors demonstrate considerable flame temperature, especially in four transverse and 35° swirl configurations. This results in high levels of NO_x at the outlet, almost tripling the amount of other injector setups in a cruising stage ($\phi = 0.56$, 65% power). Case 2 (8 axial injectors with a 40° swirl) generates

the lowest NO_x emissions (66 ppm) during this condition. In addition, as the equivalence ratio approached near-stoichiometric ($\phi = 0.86$, 100% power, takeoff), Case 2 even generated less NO_x (52 ppm). It is worth mentioning that H₂ stoichiometric combustion generally provides the highest adiabatic flame, thus producing significant amounts of NO_x. However, in this work, jets throughout the combustor tend to dilute an elongated flame, as in the case of a higher ϕ (higher fuel flow). This might explain why a much lower ϕ (0.26) generates the highest flame temperature.

- Transverse injectors outperform axial designs in fuel efficiency primarily through superior mixing and flame stabilization, enabling leaner and more complete combustion. While they present issues such as NO_x penalties, their ability to reduce waste fuel and stabilize flames makes them an excellent choice for high-efficiency combustors.
- Judging by the results, flame control is daunting for hydrogen flame, considering how sensitive the flame structure is to the injector setups, swirl angle, and equivalence ratios. The high temperatures at the outlet can lead to thermal fatigue and durability concerns in combustors with a high-power setting. Therefore, controlling flame behavior at high power requirements is mandatory. In the current geometry, eight axial injectors with a 40° swirl vane seem promising to combat NO_x emissions.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

5.1. Conclusion

This thesis work presents the development of a hydrogen-based burner in the aviation industry, along with the components of gas turbine engines, the modifications required to retrofit hydrogen fuel in an existing gas turbine engine (GTE), and the integration of the reaction mechanism into the simulation of a hydrogen diffusion flame. The primary objective of this work was to investigate the feasibility of incorporating hydrogen fuel into an aero-gas turbine engine, aiming to minimize NO_x emissions while maintaining optimal thermal energy and flame structure. Three parametric studies were conducted to achieve the thesis objectives. First, kerosene combustion will be compared against several hydrogen injection methods: four axial injectors, eight axial injectors, four transverse injectors, and eight transverse injectors. Second, the swirl angles are varied (35°, 40°, 45°, 55°, and 65°). Lastly, equivalence ratios are diverse based on ICAO's LTO cycle.

The simulation results indicate the significant impact of these parameters on the flow field, combustion efficiency, flame stability, NO_x formations, and unburned fuel emissions.

1. Hydrogen vs kerosene:

Switching from kerosene to hydrogen fuel introduces notable changes in combustion parameters. Hydrogen, with its higher flame speed and diffusivity, promotes rapid and efficient combustion; however, it also increases NO_x emissions. In contrast, a kerosene flame, while relatively stable due to its slower flame speed and higher volumetric

density, produces a lower peak adiabatic flame temperature and a lower outlet velocity. For instance, kerosene combustion yields a maximum flame temperature of ~ 2200 K and an average outlet velocity of 194 m/s. On the other hand, hydrogen combustion generates a maximum temperature of 2650 K and an average outlet velocity of ~ 198 m/s for all tested injector configurations. Hydrogen combustion produces minimum NO_x emissions of 67 ppm using eight axial injectors and maximum NO_x emissions of 214 ppm using four transverse injectors. In contrast, using a single injector, kerosene yields NO_x emissions of only 44 ppm.

2. Fuel injection configuration:

Under the same total fuel mass flow rate and swirl angle, increasing the number of fuel injectors from one to eight significantly enhances fuel distribution and mixing with air, leading to a more uniform combustion process. While a single injector resulted in poor hydrogen-air mixing and localized unburned fuel zones, eight axial injectors reduced these regions, enabling efficient combustion and lowering unburned hydrogen emissions. Transverse injectors greatly improve the mixing intensity between hydrogen and air, which may enhance flame stability. However, both four- and eight-transverse injectors demonstrate high flame temperatures in RZ, roughly 2650K, a major concern for the liner walls and NO_x emissions. In the same swirl angle (40°) and equivalence ratio (0.556), four transverse injectors manage to produce 214 ppm of NO_x, while four axial injectors release roughly 120 ppm. In similar manner, eight transverse injectors generate 150 ppm of NO_x, while eight axial injectors produce 67 ppm, indicating transverse injectors may produce double the amount of NO_x than axial injectors.

3. Swirl vane angle:

Varying the swirl vane angle from 35° to 65° demonstrated its critical role in turbulent mixing and flame anchoring. Generally, high swirl angles (55° and 65°) tend to produce hotter and wider flames in RZ. However, low swirl angles (35° and 40°) generate lower NO_x. For instance, eight axial injectors can produce NO_x as low as 66 ppm when the swirl angle is 40°, while the eight transverse injectors work best at 35°, producing NO_x of 73 ppm. It is worth noting that the combustion process behaves differently when the swirl angle increases for axial and transverse injectors. Transverse injectors exhibit instability as the swirl angle changes to a high angle, resulting in non-uniform flames in RZ. It is also imperative that transverse injectors work well without swirl vanes due to their inherent perpendicular fuel-air mixture.

4. Equivalence ratio:

A higher equivalence ratio produces an increased outlet velocity, resulting in higher output thrust under the same air distribution, which aligns with the thrust required for each power setting. The peak flame temperature and outlet NO_x emissions are generally observed at near-stoichiometric settings ($\phi = 0.86$, 100% power) for all cases except for eight axial injectors with a 40° swirl. This configuration achieves a somewhat acceptable NO_x level under different equivalence ratios. For example, at the cruise flight phase ($\phi = 0.56$, 65% power), this configuration achieves NO_x emissions of 66 ppm, which is desirable for the longest duration stage of any aircraft. Furthermore, the same configuration achieves lower NO_x emissions (51 ppm) at near-stoichiometric conditions ($\phi = 0.86$, 100% power). However, in the range of $\phi = 0.2$ to $\phi = 0.3$, the NO_x levels were high due to the optimum fuel mixing efficiency and fuel residence in the RZ, which elevated the flame temperature. The eight transverse

injectors with a 35 ° swirl angle also exhibit a similar low NO_x level from $\phi = 0.1$ to $\phi = 0.56$. However, as the equivalence ratio increased to high values ($\phi = 0.73$ and $\phi = 0.86$), the NO_x emissions increased to 200 ppm. It is worth noting that at higher fuel flow or higher ϕ , transverse injectors possibly demonstrate better flame stability than axial injectors, making it favorable for flame control.

5.2.Future Works

The numerical study of hydrogen flames is a highly complex process involving models for turbulence, reaction, and radiation. It is also worth mentioning that convergence is very difficult to obtain since each geometry, mesh, and boundary condition affects the convergence criteria. Thus, in the future, a few parameters that were not considered in this work may be improved and complemented, involving:

- Utilization of the transient case as the solver.
- Utilization of higher fidelity turbulence models, including URANS, RSM, and LES.
- Utilization of automatic mesh adaptation.
- Experimental works for highly pressurized air in a hydrogen diffusion flame.
- Study of different numbers of jet inlets.
- Study of double counter-rotating swirler.
- Study of different fuel injection angles with or without an air swirler.

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Vitae

Name :Hafidz Azhar Jakaria |

Nationality :Indonesia |

Date of Birth :5/9/1998|

Email :G202113470@kfupm.edu.sa|

Address :Jl. Kemangi, Blok D, No. 19, Perumahan Alam Sinar Sari, Cibeureum,
Dramaga, Kab. Bogor, Jawa Barat, Indonesia |

Academic Background :B. Eng Aerospace Engineering, |