

T.R.
GEBZE TECHNICAL UNIVERSITY
GRADUATE SCHOOL

**EFFECTS OF DIFFERENT TEST CONDITIONS ON
COMBUSTION CHAMBER INSTABILITY**

NADİR KÖKÇÜ

A THESIS OF MASTER OF SCIENCE
DEPARTMENT OF ENERGY TECHNOLOGIES
APPLIED PROPULSION SYSTEM DESIGN AND
ENGINEERING FOR AEROSPACE TECHNOLOGIES PROGRAM

ADVISOR: ASSOC. PROF. DR. RECEP ÖNLER

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T.C.
GEBZE TEKNİK ÜNİVERSİTESİ
LİSANSÜSTÜ EĞİTİM ENSTİTÜSÜ

FARKLI TEST KOŞULLARININ YANMA ODASININ
KARARSIZLIĞINA ETKİLERİ

NADİR KÖKÇÜ

YÜKSEK LİSANS TEZİ
ENERJİ TEKNOLOJİLERİ ANABİLİM DALI
HAVACILIK VE UZAY TEKNOLOJİLERİNDE
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ABSTRACT

This thesis delves the effects of changes in the combustion chamber design as well as changes in test conditions, especially on dynamic pressure data. It is aimed to evaluate the test data obtained in order to determine whether the test parts with different characteristics, which are manufactured in the study, have advantages over each other.

A central emphases of this research is to determine the dynamic pressure characterization in the test data. By analyzing the interaction between design variations and test conditions, the aim is to elucidate the complex dynamics affecting combustor stability. Together with the fabrication of the part and the associated physical testing, it increases the robustness of the research by providing a comprehensive understanding of the response of the combustor to design variations and different operating conditions. A comparison of the test conditions shows that each test condition has its own advantages over the other.

Key Words: Test, Combustion Instability, Dynamic Pressure , Coflow Swirler, Counterflow Swirler, Injector

ÖZET

Bu tez kapsamında, yanma odası tasarımı yapılan deęiřikliklerin yanı sıra test kořullarındaki deęiřikliklerin, özellikle dinamik basınç verileri üzerindeki etkilerinin incelenmesi hedeflenmektedir. Çalışmada imalatı gerçekleştirilen, farklı özelliklere sahip test parçalarının birbirilerine göre avantajlı yönlerinin olup olmadığının tespit edilmesi için elde edilen test verilerinin değerlendirilmesi hedeflenmektedir.

Bu araştırmanın temel vurgularından biri, test verilerindeki dinamik basınç karakterizasyonunun belirlenmesidir. Tasarım varyasyonları ve test kořulları arasındaki etkileşimi analiz ederek, yanma odası stabilitesini etkileyen karmařık dinamikleri aydınlatmak amaçlanmaktadır. Parça imalatı ve buna baęlı fiziksel testlerin gerçekleştirilmesi ile birlikte, yanma odasının tasarım deęiřikliklerine ve farklı çalışma kořullarına verdięi tepkinin kapsamlı bir şekilde anlařılmasını saęlayarak araştırmanın saęlamlığını artırmaktadır. Test kořulları göz önünde bulundurularak yapılan karřılařtırmalar sonucunda, her bir test kořulunun kendi içinde dięerine göre avantajlı taraflarının olduęu tespit edilmiřtir.

Anahtar Kelimeler: Test, Yanma Kararsızlıęı, Dinamik Basınç, Eřdönüřlü Döndürücü, Tersdönüřlü Döndürücü ,Enjektör

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LIST OF SYMBOLS AND ABBREVIATIONS

η_b	: Combustion Efficiency
ρ	: Density
μ	: Dynamic Viscosity
η	: Efficiency
Φ	: Equivalence Ratio
ν	: Kinematic Viscosity
$\dot{m}$	: Mass Flow Rate
$\dot{m}_{red}$	: Corrected Mass Flow Rate
∞	: Ambient
C_p	: Specific Heat
AFR	: Air to Fuel Ratio
CLP	: Combustion Loading Parameter
DAS	: Data Acquisition System
DDAS	: Dynamic Data Acquisition System
HMI	: Human Machine Interface
Hz	: Hertz
MPa	: Megapascal
P	: Pressure
Pa	: Pascal
PLC	: Programmable Logic Control
T	: Temperature
W	: Work

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1. INTRODUCTION

1.1. Gas Turbine Engine

Today, airplanes are preferred both as a means of transportation due to their speed, comfort, and reliability, and because of their critical importance in military operations. The most important component that affects the reliability and performance of an aircraft is its engine. In the combustion chambers within the engine, fuel reacts with air to convert the chemical energy in the fuel into kinetic energy [1]. During this conversion process, vibrations and noise occur due to the combustion phenomenon. From a combustion chamber, various expected features include high combustion efficiency, reliable and smooth ignition, induced stability in the combustion chamber, independence from pressure changes, low pressure loss, minimal smoke emission and complete combustion, low cost, ease of maintenance, simple design, durability, and compatibility with various fuels. To meet these expectations, there are three different types of combustion chambers designed: tubular (can-tubular), tubular-annular (can-annular), and annular (annular). Among these different types, the annular type combustion chamber is commonly used in modern gas turbine engines. Today, annular type combustion chambers are more widely used in both commercial and military fields. High levels of noise and vibrations occur in the combustion chamber for unknown reasons. This thesis will investigate the parameters causing instability within the combustion chamber.

Gas turbine engines are a type of internal combustion engine that works on the principle of converting chemical energy from fuel into mechanical energy through the combustion process. They are commonly used in vast applications, including aviation, power generation, and marine propulsion. Gas turbine engines generally follow the Brayton cycle, which consists of several stages: compression, combustion, and expansion. This passage offers a concise overview of the gas turbine's operational principles, with further in-depth information available in resources like Boyce's Gas Turbine Handbook [2].

1.2. Literature Review

Rohan M Gejii and friends are conducted an experiment [3] on self-excited combustion dynamics in a liquid-fueled lean direct injection combustor operating at (1 Mpa) high pressure. The variables investigated include combustor and plenum intake length, air inlet temperature, air to fuel ratio, axial fuel nozzle location, and fuel composition.

Donghyun Hwang and Kyubok Ahn are conducted an experiment [4] analyze the combustion instability characteristics of swirl-stabilized combustors employing a premixed gas blend of ethylene and air. The research involved modifying several flow and geometric factors, such as inlet average velocity, equivalence ratio, swirler vane angle, and combustor length. Instruments like dynamic pressure sensors, a hot-wire anemometer, and a photomultiplier tube were employed to observe pressure fluctuations, velocity perturbations, and variations in heat release within both the inlet and combustion chambers.

W. Konrad and friends conducted an experiment [5] during the BR710 jet engine development, audible combustor instabilities were encountered. A systematic approach was adopted to identify and address the issue. This involved two main strategies: one examining individual engine components for potential involvement, and the other analyzing pressure signals from various engine sections to locate the source of disturbance. The investigation revealed that the main reason for the combustor rumble was a self-induced aerodynamic instability caused by the design of the fuel injector head.

Michel C. Janus and friends conducted an experiment [6] about the influence of surrounding conditions and fuel makeup on the stability of combustion in LPM combustors. It examines how alterations in heat release can result in notable pressure oscillations, potentially interacting with acoustic modes within the combustion chamber. Tests are carried out on a reduced-scale combustion chamber burning various fuel combinations, encompassing natural gas, propane, and mixtures of hydrogen and hydrocarbons. The experiments employ a common swirl-stabilized fuel nozzle designed for premixed applications in industrial gas turbines. The findings, derived from both experimental and computational analyses, demonstrate the impact of shifts in inlet air temperature, moisture levels, and fuel composition on the stability characteristics of combustion.

Ayo Oyediran and friends conducted an experiment [7] about in combustion-acoustic instabilities occur when the rise in acoustic energy resulting from the fluctuating heat release of the flame exceeds the dissipation of acoustic energy within the system. To accurately forecast and measure combustion-acoustic instabilities, it is crucial to precisely ascertain the unsteady heat release rate and boundary conditions. This overview synthesizes research undertaken on various combustion apparatuses. These investigations comprise both theoretical and empirical inquiries into unsteady heat release rates, with certain studies examining disruptions in fuel delivery systems (particularly evident in rocket instabilities), while others explore hydrodynamic phenomena like those found in ramjet dump combustors.

M.Barrere and F.A.Williams conducted an experiment [8] combustion instabilities in motors and furnaces, categorizing them into three main types: system instabilities, combustion chamber instabilities, and intrinsic instabilities. Within combustion chamber instabilities, three subcategories are identified: acoustic instabilities, shock instabilities, and fluiddynamic instabilities. Experimental and theoretical aspects of each type are examined separately, with attention given to various combustion systems including solid-propellant rockets, hybrid rocket motors, liquid-propellant rocket engines, and industrial burners. The review aims to facilitate discussions among specialists studying combustion instabilities, emphasizing similarities and differences across different systems. Notably, examples of system instabilities and acoustic instabilities are found in various combustion systems.

Pierre Wolf and friends focus [9] on the occurrence of combustion fluctuations within annular combustion chambers, with specific attention given to azimuthal patterns. It underscores the recent advancements in computational techniques that enable the anticipation of such patterns, thanks to the progress in massively parallel computing. The investigation delves into how varying mesh resolutions impact Large Eddy Simulation (LES) of a practical helicopter combustion chamber, employing grids comprising different amount of elements. Findings are assessed based on average and fluctuating parameters, highlighting the efficacy of LES in scrutinizing combustion oscillations in annular gas turbine combustion chambers.

Kim Seung-III focus [10] on his analytical exploration of nonlinear pressure fluctuations, both longitudinally and transversely, occurring within combustion chambers. The analytical framework incorporates various nonlinear gas dynamics and combustion processes of second and third orders. It investigates how different parameters and initial conditions affect

limit cycles and the emergence of pressure fluctuations. Results indicate that nonlinear acoustic motion predominantly impacts the amplitude and stability of limit cycles, while nonlinear combustion response largely governs instability onset. The study also examines standing and spinning wave modes for transverse oscillations, their presence contingent upon the number of modes and initial conditions. To validate the analytical findings, comparisons are made with numerical approaches, demonstrating a favorable agreement and validating its utility in analyzing instability phenomena.

Miller et al. [11] concentrate on examining the combustion dynamics of a gas-centered, liquid-swirled coaxial injector element in a single injector liquid rocket combustion setup. The oxidizer comprises superheated water and oxygen, with kerosene employed as the fuel. Noticeable spontaneous instabilities are detected. As the chamber length increases, the predominant modes transition from the first to the third longitudinal mode. Resonant frequencies determined using a chamber acoustics model closely match the measured values.

2. THEORY

2.1. Components of a Gas Turbine Engine:

Compressor: The compressor is the first stage in the gas turbine cycle. It compresses incoming air, increasing its pressure before it enters the combustion chamber.

Combustion Chamber: This is where fuel is mixed with compressed air and ignited. The resulting high-temperature, high-pressure gases are the products of combustion.

Turbine: The turbine captures energy from the high-temperature, high-pressure gases and transforms it into mechanical energy. This energy powers the compressor and any external load, such as a generator or the fan in an aircraft engine.

Exhaust Nozzle: The exhaust nozzle allows the high-speed exhaust gases to exit the engine, producing thrust in aircraft engines or turning a power turbine in stationary applications.

Components of a Gas Turbine Engine is shown in Figure 2.1

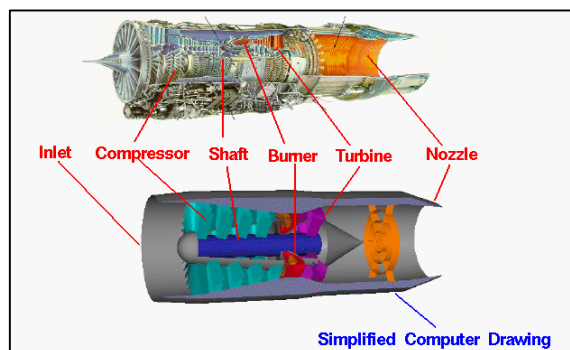


Figure 2.1: Component of Gas Turbine Engine [12]

2.2. Brayton Cycle:

Brayton cycle is a thermodynamic cycle which defines the operation of a gas turbine engine, consisting of four main steps: compression, combustion, expansion, and exhaust. Simple gas turbine drawing shown in Fig.2.2 Let's delve into the technical details of each stage [1-4]:

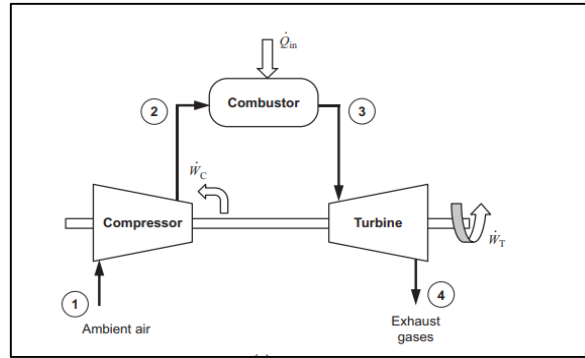


Figure 2.2: Simple Gas Turbine Drawing [13]

1. Compression (Process 1-2):

Air is drawn into the engine and compressed in the compressor. This is typically an isentropic (constant entropy) compression process. The compression increases the pressure and temperature of the air, leading to a higher energy state.

2. Combustion (Process 2-3):

In the combustion chamber, The compressed air is mixed with fuel and ignited, resulting in a high-temperature, high-pressure gas. This process is an isobaric (constant pressure) combustion, where chemical energy from the fuel is released, causing a major increase in temperature and pressure.

3. Expansion (Process 3-4):

The high-pressure, high-temperature gases produced in the combustion chamber expand through the turbine. This is an isentropic expansion process, where the gases do work on the turbine blades, converting thermal energy into mechanical energy.

4. Exhaust (Process 4-1):

The remaining exhaust gases exit through the exhaust nozzle. This process is typically isobaric or near-isobaric, as the exhaust gases are expelled at a relatively constant pressure.

Efficiency and Specifics:

The efficiency of the Brayton cycle is affected by the compression ratio (ratio of the maximum volume to minimum volumes while cycling). Higher compression ratios generally lead to increased efficiency.

The cycle efficiency is also affected by the specific heat ratios of the working fluid (usually air) at constant pressure and constant volume. T-S Diagram of Brayton Cycle is shown in Fig. 2.3 Efficiency formula of Brayton Cycle is defined in Eq.2.1

$$\eta_{th} = \frac{W_{net}}{Q_{in}} = \frac{W_t - W_c}{Q_{in}} \quad (2.1)$$

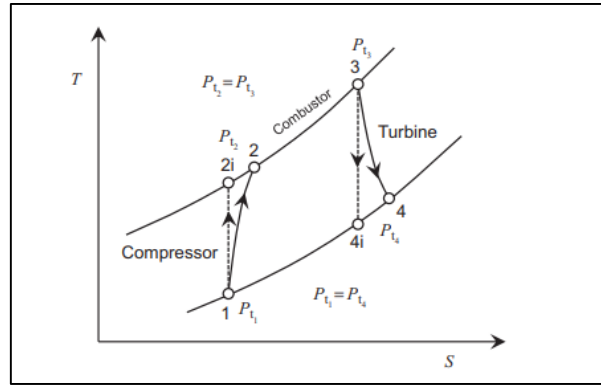


Figure 2.3: Brayton Cycle T-S Diagram [13]

2.3. Combustion Process

The combustion chamber faces the challenging task of efficiently burning substantial amounts of fuel, delivered via fuel spray nozzles, alongside large volumes of air provided via the compressor. Its objective is to release heat in a manner which provides the air to expand and accelerate, generating a consistent flow of uniformly heated gas meeting the turbine's varied operational conditions. This task demands achieving minimal pressure loss and maximizing heat release within the confined space available.

The quantity of fuel introduced to the air hinges on the required temperature increase. However, the upper temperature limit is restricted to a range of 850 to 1700 degrees Celsius due to the materials used in constructing turbine blades and nozzles. The incoming air is already heated to temperatures between 200 and 550 degrees Celsius through compression work, necessitating an additional temperature increases of 650 to 1150 degrees Celsius during the combustion process.

Given that the gas temperature required at the turbine fluctuates with engine thrust and, in the event of a turbo-propeller engine, the power needed, the combustion chamber must exhibit stability and efficiency across a broad spectrum of engine operating conditions. The importance of efficient combustion has surged in importance because of the rapid growth in

commercial aircraft traffic, resulting in heightened public concern over atmospheric pollution attributed to exhaust emissions.

Incoming air from the compressor reaches the combustion chamber at speeds of up to 500 feet per second (152.4 m/s). However, due to this high velocity, unsuitable for combustion, the initial task of the chamber is to diffuse the air—decelerate it and elevate its static pressure. Combustion of kerosene, at regular mixture ratios, occurs at just a few feet per second. Igniting fuel in the diffused air stream, which now moves at approximately 80 feet per second, would result in the flame being extinguished. To ensure sustained combustion across various engine operating conditions, a zone of low axial velocity is established in the chamber.

Under standard operating conditions, the total air to fuel ratio in a combustion chamber can fluctuate between 45:1 and 130:1. However, for efficient burning, kerosene ideally requires a ratio of 15:1. Consequently, fuel is burned with only a portion of the air entering the combustor, forming what is known as a primary combustion zone. This is facilitated by a flame tube (combustion liner) equipped with mechanisms for regulating the airflow distribution within the chamber.

Approximately 20 percentage of the airflow mass is brought in through the snout or entrance section. In close proximity to the snout, swirl vanes and flare facilitate the entrance of the primary combustion zone. The rotational motion of the air induces an upstream flow at the core of the flame tube, fostering the intended recirculation. The residual air not collected by the snout moves into the circular gap between the flame tube and the casing of the combustor. Secondary holes in the flame tube body, contiguous to the combustion zone, permit around 20% of the primary air flow to enter the combustion zone. Air distribution in combustion chamber is shown in Fig.2.4:

The interaction of air from the swirl vanes and the secondary air holes generates a zone of low-velocity recirculation, forming a toroidal vortex akin to a smoke ring. This stabilizes and anchors the flame, expediting the burning of freshly introduced gases.

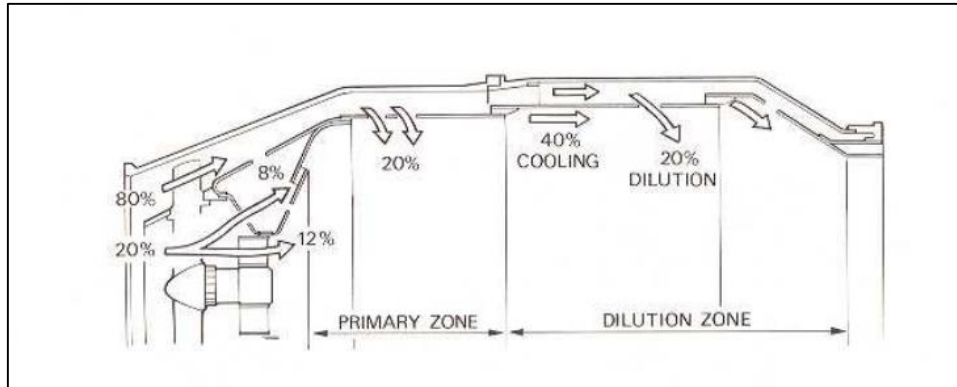


Figure 2.4: Distribution of Air [14]

Propelled fuel droplets rapidly reach ignition temperature through injection. It is structured so that the nozzle's conical fuel spray intersects the center of the recirculation vortex. This, combined with the overall turbulence in the primary zone, considerably aids in dispersing and blending the fuel with the incoming air. The temperature of the combustion-released gases reaches about 1,800 - 2,000 Celsius degrees, which is excessively high for the turbine's nozzle guide vanes inlet.

Of the total air flow not used in combustion, approximately 60% is gradually introduced into the flame tube. About 33% of this is employed to decrease gas temperature in the dilution zone (secondary zone) before reaching the turbine, while the rest is used to cool the flame tube walls. This is accomplished by directing a cooling air film along the inner surface of the flame tube wall, providing insulation from the hot combustion gases. In a recent breakthrough, cooling air can enter a system of channels within the wall of the flame tube, resulting in a decrease of up to 50% in the necessary airflow for wall cooling.

It is imperative to complete combustion before introducing dilution air into the flame tube; otherwise, incoming air may cool the flame, causes deficient combustion. An igniter plug's electric spark starts combustion, and the flame becomes self-sustained.

2.4. Components of Combustion Chamber

A combustion chamber consists of a combination of different components. These components are shown in Fig. 2.6.

Casing: The outer shell of the combustor is known as the casing, and it constitutes a relatively uncomplicated structure. Typically, minimal maintenance is needed for the casing.

The casing receives protection from thermal stresses through the airflow within it, resulting in limited thermal performance concerns. Nevertheless, the casing functions as a pressure vessel, necessitating the ability to endure the contrast between the elevated pressures within the combustor and the lower pressures externally. This mechanical load, more than thermal considerations, significantly influences the design of the casing.

Diffuser: The main function is to slow down the air, initially highly pressurized and accelerated by the compressor to optimized for entering the combustor. This reduction in velocity unavoidably leads to a loss in total pressure. Hence, a key design challenge is to minimize this pressure loss as much as feasible. Additionally, the diffuser must be meticulously designed to minimize flow distortion by steering clear of flow phenomena such as boundary layer separation. Similar to other components in gas turbine engines, the diffuser is engineered to be as compact and lightweight as possible.

Liner: The liner is responsible for enclosing the combustion process and facilitating the introduction of different airflows (including intermediate, dilution, and cooling, as described in the airflow paths section) into the combustion zone. Constructing the liner requires careful consideration, ensuring its ability to withstand prolonged cycles of high temperatures. As a result, liners are often crafted from superalloys such as Hastelloy X. Despite the use of high-performance alloys, effective air cooling is imperative. Some combustors incorporate TBC; but, air cooling remains a critical aspect. Generally, there are two primary methods of liner cooling: film cooling and transpiration cooling. Film cooling involves the injection (using various methods) of cool air from outside the liner to the inner side, creating a protective thin film of cool air. This film mitigates the liner temperature from approximately 1800 Kelvin (K) to about 830 K, for instance. Transpiration cooling, employs a porous material for the liner. The porous structure allows a small amount of cooling air to permeate, offering cooling benefits akin to film cooling. The main distinctions lie in the resulting temperature distribution of the liner and the volume of cooling air required. Transpiration cooling yields a more uniform temperature profile as the cooling air uniformly emerges through pores. In contrast, film cooling introduces air through slats or louvers, resulting in an uneven temperature profile with cooler regions at the slats and warmer regions between them. Crucially, transpiration cooling utilizes significantly less cooling air, approximately 10% of the total airflow, compared to 20-50% required for film cooling. The conservation of air for

cooling allows more to be allocated to the combustion process, a crucial consideration for high-performance, high-thrust engines.

Snout: The snout functions as an extension of the dome and serves as an air splitter. It effectively segregates the primary air from the secondary air flows, including intermediate, dilution, and cooling air.

Dome/Swirler: The dome and swirler constitute components of the combustor through which the primary air passes upon entering the combustion zone. Their primary function is to induce turbulence in the airflow, facilitating the rapid and thorough mixing of air with fuel. In earlier combustor designs, bluff body domes (rather than swirlers) were commonly employed, utilizing a straightforward plate to create wake turbulence for fuel and air mixing. However, contemporary designs predominantly use swirl-stabilized configurations (incorporating swirlers). The swirler establishes a localized area of low pressure, promoting the recirculation of some combustion products and generating heightened turbulence. Nevertheless, it's crucial to note that increased turbulence corresponds to higher pressure losses in the combustor. Therefore, the design of the dome and swirler must be meticulously executed to avoid excessive turbulence generation, ensuring that it remains within the necessary range for effective fuel and air mixing.

Igniter: The majority of igniters employed in gas turbine applications mirror electrical spark igniters, akin to those found in automotive spark plugs. For effective ignition, the igniter must be positioned within the combustion zone where fuel and air are already mixed. However, it should be located sufficiently upstream to prevent damage from the combustion process itself. Once the combustion is initiated by the igniter, it becomes self-sustaining, rendering the igniter inactive. In combustor configurations like can-annular and annular types, where the flame can propagate between combustion zones, the necessity for igniters at each zone is diminished. A few systems utilize ignition-assist techniques, with one such method being oxygen injection. In this approach, oxygen is introduced to the ignition area, facilitating the smooth combustion of fuel. This technique proves especially beneficial in certain aircraft applications where engine restarts at high altitudes may be required.

Fuel Injector: The fuel injector plays a crucial role in delivering fuel to the combustor and collaborates with the swirler (mentioned above) to ensure effective mixing of fuel and air. There exist four primary categories of fuel injectors: pressure-atomizing, air blast this type of injectors are used in industry frequently, vaporizing these types are used in older gas

turbine engines applications and premix/prevaporizing injectors generally used in low emission gas turbine engine applications. Pressure-atomizing fuel injectors operate by relying on elevated fuel pressures (reaching up to 3,400 kilopascals) to atomized the fuel. While this type of fuel injector offers simplicity, it comes with several drawbacks. The fuel system must possess robustness to endure such high pressures, and the fuel tends to undergo heterogeneous atomization, leading to incomplete or inconsistent combustion, resulting in increased pollutants and smoke. Fuel Injector Section is shown in Fig 2.5.

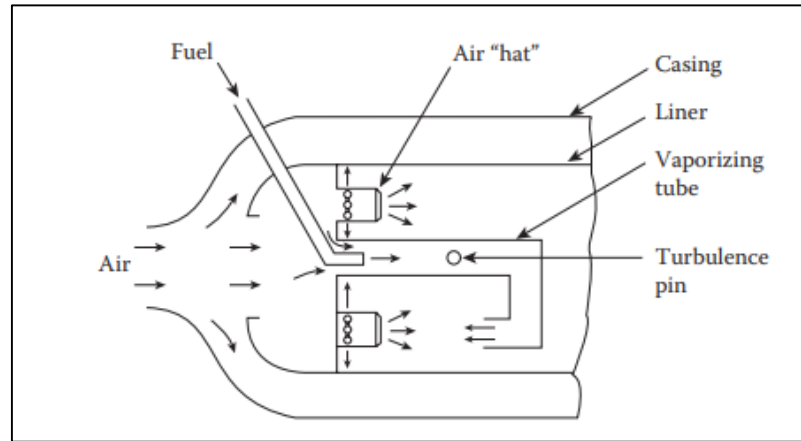


Figure 2.5: Fuel Injector Section [15]

Also atomization is one of the most important thing for injectors. Atomization refers to the process through which a specific volume of fluid undergoes dispersion into numerous small droplets, subsequently transforming into a gaseous and combustible state. Various factors, including properties of the fuel, oxidizer, and injector, govern the process of atomization. The diverse array of injector designs in use today introduces variations in injector properties. One crucial property is the flow number, denoted as FN and defined as

$$FN = \frac{\dot{m}}{\sqrt{\Delta P}} \quad (2.2)$$

The flow number holds significant importance as it signifies the effective area of the injector, serving as an indicator of the flow-path size. Although the flow number is often presented in non-dimensionally correct terms, the inclusion of a density term allows for its application to a specific injector with different fluids.

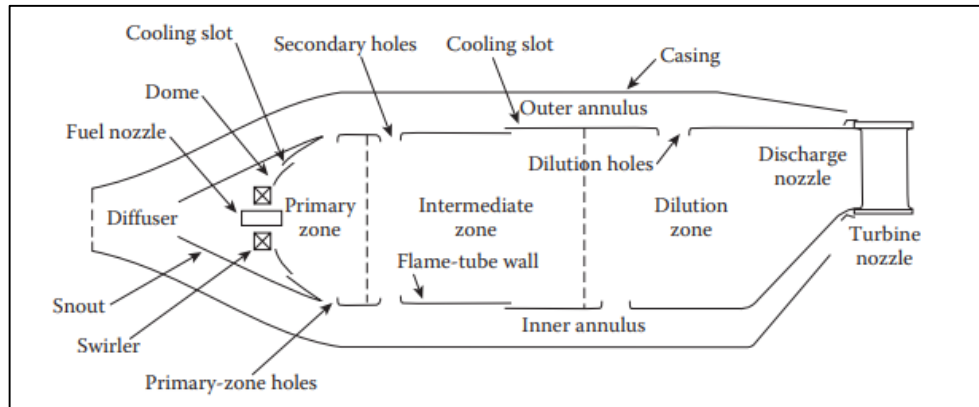


Figure 2.6: Main Component of Combustor [15]

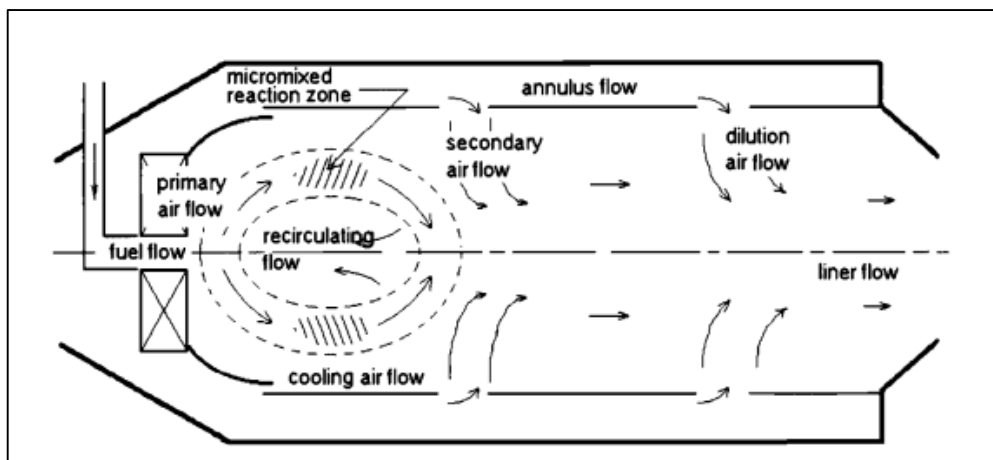


Figure 2.7: Flow Patterns in Combustor [16]

Parameters Affecting Combustion Chamber Design

1. Higher Combustion Efficiency
2. Smooth Ignition
3. Wide Stability
4. Pressure Loss Stability
5. Low Emissions
6. Maintainability and Durability
7. Size and Shape Compatible with Engine Envelop

2.5. Combustion Chamber Types

Can Type Combustion Chamber(Tubular)

Initial aircraft propulsion systems employed can (or tubular) configuration combustion chambers, wherein the airflow exiting the compressor is divided into several distinct streams.

A can type combustion chamber composed of a series of individual combustion cans arranged in a circular or annular pattern around the engine's axial flow. Each combustion can is a self-contained unit with its set of fuel injectors, flame holders, and combustion zones. Main air from the compressor is directed into each separate can, where it undergoes deceleration, blends with fuel, and subsequently undergoes ignition. Additional air, known as secondary air, is sourced from the compressor as well. This secondary air is routed external to the liner, within which the combustion process unfolds. Subsequently, the secondary air is typically introduced into the combustion zone through openings in the liner, facilitating the cooling of the liner via a method known as thin film cooling. Can Type Combustor is shown Fig.2.8. and Fig.2.9.

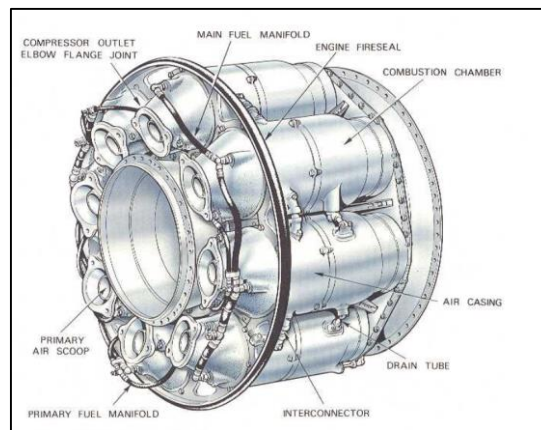


Figure 2.8: Can Type Combustion Chamber [14]

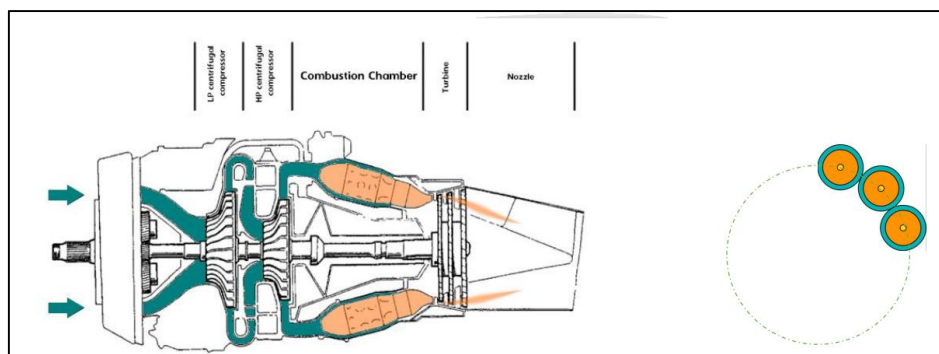


Figure 2.9: Single Shaft Turboprop Engine Section [14]

Tubo-Annular (Cannular) Combustion Chamber

Several separate flame tubes are installed at even intervals along a shared circular casing. This design serves as an intermediary between can-type and annular combustion chambers, resembling a can-annular configuration. Similar to the can-type combustor, can-annular

combustors have distinct combustion zones housed in individual liners, each equipped with its fuel injectors. However, in contrast to the can-type combustor, all the combustion zones collectively utilize a shared circular casing. Consequently, each zone is relieved from the duty of functioning as a pressure vessel. This type of combustion chambers have some advantages such as, reduced shaft length, simplified maintenance, also like can type combustor, easier development. But also have some disadvantages such as, increased volume, weight & frontal area, increased pressure difference between inlet and outlet. Turbo Annular Type Combustor section is shown Fig.2.10.

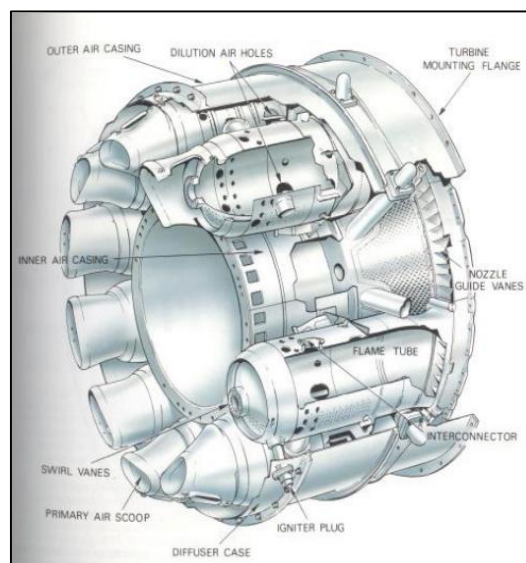


Figure 2.10: Turbo-Annular Type Combustion Chamber Section [14]

Annular Type Combustion Chamber

An annular type combustion chamber is a design commonly used in gas turbine engines, particularly in aircraft engines. The annular combustion chamber is characterized by its ring-shaped or annular design that surrounds the axial flow path of the engine. Air from the compressor is guided into the annular space, creating a continuous ring where combustion occurs. Fuel is injected into the annular space, typically through a series of fuel nozzles evenly distributed around the chamber. The incoming air is mixed with the injected fuel and combustion takes place in the annular space. The continuous shape allows for efficient mixing of fuel and air. Flame stabilization is achieved through design features or additional components to ensure that the combustion process remains stable and reliable. Annular combustion chambers are known for their efficiency and compact design. The continuous ring shape allows for a streamlined combustion process, often resulting in better thermal

efficiency. Annular combustion chambers are commonly used in aviation gas turbine engines, where the compact design and efficient combustion are advantageous for aircraft propulsion. Annular combustion chambers are often designed to provide access for maintenance. This may involve features such as removable panels or sections to facilitate inspection and repair. Annular Type Combustor is shown Fig.2.11.

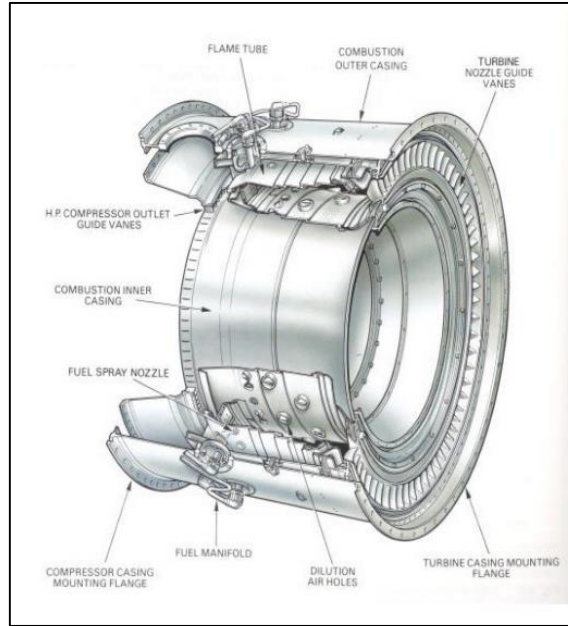


Figure 2.11: Annular Type Combustion Chamber Section [17]

2.6. Combustion Efficiency

Combustion efficiency indicates how effectively the combustion process transforms the chemical energy in fuel into thermal energy (heat). It is defined as the ratio of the actual heat produced during combustion to the maximum possible heat that could be released, considering the complete combustion of the fuel. Combustion Effectiveness is shown in Fig.2.12:

Combustion Efficiency Expressed in Eq.2.3

$$\eta_b = \frac{c_p[(m_a+m_f)T_{t4}-m_aT_{t3}]}{m_f h} \quad (2.3)$$

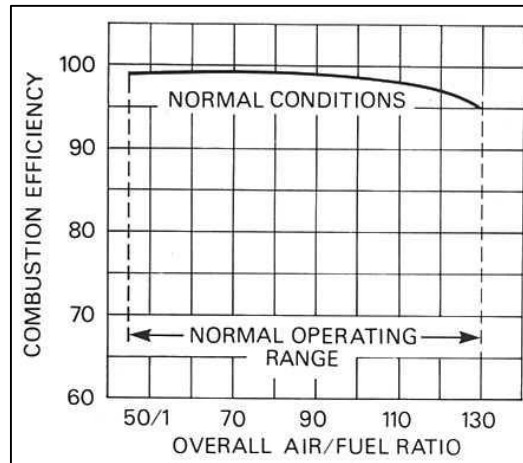


Figure 2.12: Average Combustion Effectiveness Of An Aviation Gas Turbine Throughout Operational Range [8]

General Observations:

- $\eta_b \downarrow$ as $p \downarrow$ and $T \downarrow$ (because of dependency of reaction rate)
- $\eta_b \downarrow$ as Mach number $\uparrow$ (decrease in residence time)
- $\eta_b \downarrow$ as fuel/air ratio $\downarrow$

2.7. Combustion Design Parameters

Total Pressure Loss:

The total pressure loss is known as the difference in average total pressure between the compressor and the turbine. This loss encompasses the total pressure reduction in the diffuser and is typically presented as a percentage of the total pressure at the compressor exit. Elevated pressure losses contribute to enhanced combustor performance, allowing for a reduction in combustor size and weight. However, it's essential to note that heightened pressure losses simultaneously diminish the overall engine cycle performance. The pressure loss is proportional to the square of the compressor exit Mach number.

Combustion Loading Parameter:

Combustion Loading Parameter relates the actual pressure drop through the combustor to the ideal pressure drop. It provides a measure of how well the combustor is performing with regard of pressure drop.

Understanding and optimizing these parameters are essential for designing and operating efficient and environmentally friendly gas turbine combustors. Engineers aim to achieve a

balance that ensures optimal combustion efficiency, low emissions, and reliable engine performance. Combustion Loading Parameter calculation is shown in Eq.2.4

$$CLP = \frac{\dot{m}}{P^n(\text{Volume})}; \quad n = 1.8 \quad (2.4)$$

Adiabatic Flame Temperature

The temperature of the flame holds paramount importance in combustion as it exerts control over the rate of chemical reactions. Definition of "flame temperature" can denote either a calculated or a measured value. In the case of the latter, it typically refers to the adiabatic flame temperature. This temperature defines the ideal temperature that the flame would reach when all of the energy released by the combustion of the fuel, which converts the fresh air/fuel mixture into combustion products, was used to heat these products. In reality, however, thermal losses occur in several different ways, through convection, conduction and radiation, where the flame temperature is lost, making it difficult to achieve adiabatic flame temperature. This is important in the calculation of combustion efficiency and heat transfer calculations.

In particular, where flame temperatures are higher than 1800K, the decomposition of combustion products becomes more important and absorbs most of the heat generated. At lower temperatures, the combustion of a stoichiometric or lean fuel-air mixture would typically produce only CO₂ and H₂O. However, at elevated temperatures, these products become unstable and partially revert to simpler molecular and atomic species and radicals, including CO, H₂, O, H, and OH. The energy absorbed during dissociation is considerable, leading to a substantial reduction in the maximum flame temperature is shown in Fig.2.13.

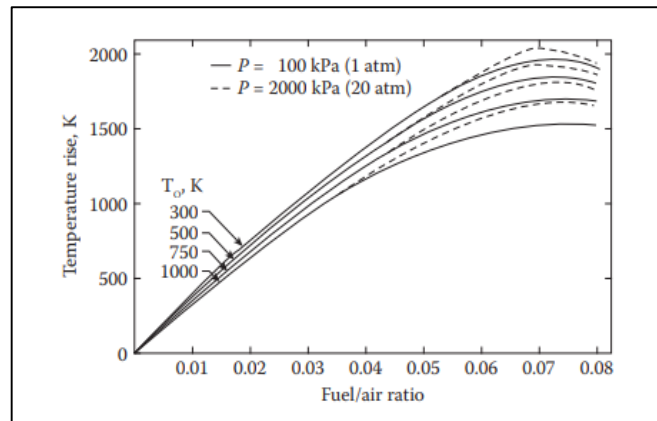


Figure 2.13: Adiabatic Temperature Rise Curves for Kerosine [15]

Residence Time

The duration that air and fuel spend in the combustion zone. Proper residence time is essential for achieving complete combustion and minimizing emissions. Residence time is calculated by the speed and trajectory of the reactants through the combustion chamber. A longer residence time allows more complete combustion.

Length to Diameter Ratio

Combustors should have not only sufficient length but also volume to create a low velocity flame stabilization area and a high velocity mixing area where combustion products are blended with excess dilution air. A length-to-diameter ratio of ~ 3 has emerged as necessary to:

- a. physically accommodate the primary and secondary zones
- b. achieve the combustion efficiency, stability and emission requirements

For values greater than 3, the liner cooling air flow rate rises and causes a significant increase in the model factor.

2.8. Combustion Instabilities

Combustion instabilities in gas turbine engines refer to undesired, self-sustained pressure fluctuations that occur during the combustion process. These pressure oscillations can manifest as vibrations, fluctuations in temperature, and acoustic waves within the combustion chamber. Combustion instabilities can have various negative effects on engine performance, efficiency, and reliability. Combustion instabilities in gas turbine engines are complex phenomena that arise from the interaction between combustion processes and fluid dynamics within the combustion chamber. These instabilities can occur under certain operating conditions and are influenced by various factors, including fuel properties, chamber geometry, and operational parameters. The combustion heat release process exhibit periodicity for any reason, the ensuing acoustic pressure waves originating from the combustion zone will also be periodic, sharing the same frequency. The existence of a combustion chamber introduces a time delay to these pressure fluctuations, contingent on the chamber's dimensions, geometry, and the average speed of sound within the combustor. Energy is added to the pressure fluctuations at frequencies where the peak of the amplitude of the pressure wave obtained at acoustic pressure coincides with the peak of the heat

oscillation. This coupling between the combustion process and the acoustic field results in the continuous addition of energy to the system during each cycle. Consequently, oscillations escalate in amplitude until dissipative viscous losses intervene, restraining further expansion. This scenario aligns with the well-established Rayleigh criterion for combustion oscillations. Similarly, energy is extracted from a pressure fluctuation at any frequency where the wave is 180° out of phase with the periodic heat release in the flame zone.

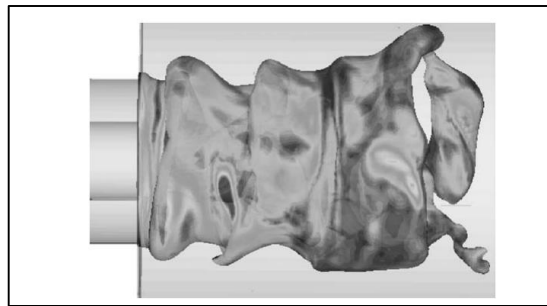


Figure 2.14: Simulated representation of a rotating flame altered by vortical structure [19]

Sources of Combustion Instabilities

Sources of instabilities in a combustion chamber of a gas turbine engine can stem from various factors, identifying and understanding these sources is crucial for designing combustion chambers that operate reliably and efficiently in gas turbine engine. These factors are listed below:

Acoustic Oscillations

Different definitions are employed to characterize the sound produced by a combustor whenever experiencing combustion instabilities. No universal guidelines exist; for instance, certain engine companies use the term "rumble" to encompass all audible acoustic oscillations, irrespective of their frequency. Conversely, in other contexts, the descriptors "rumble" or "growl" are specifically reserved for the noise occurring in the low-frequency range of 50 to 180 Hz, typically manifesting during sub-idle conditions. For higher frequencies especially frequency range between 200-500 associated with engine speeds at or above idle, the terms "howl" or "humming" are generally considered more appropriate.

Fuel Types

Changing fuel type or chemical structure can either increase or decrease combustion noise amplitudes, depending on how it affects chemical reaction time in relation to the

characteristic acoustic time. Research, such as that by Janus et al. [20], has shown that instability regimes in combustors are notably influenced by changes in fuel composition. In Janus research laboratory and tests have demonstrated that instability regimes can be influenced by environmental conditions. Janus focuses on understanding the impact of ambient conditions and fuel structure on combustion stability. Experiments include a subscale combustor burning natural gas, propane, and hydrogen/hydrocarbon mixtures, using a premixed, swirl-stabilized fuel nozzle typical of industrial gas turbines. Both experimental and numerical findings illustrate how stability regimes may shift with variations in inlet air temperature, humidity, and fuel structure. The results of Janus tests suggest that the observed shifts in instability regimes are primarily attributed to changes in reaction rates. Also another research is conducted by Keller [21], research was conducted to analyze how a valved pulse combustor responds to alterations in the synchronization between the resonant pressure wave and the instantaneous energy release rate. That alterations in both oscillation frequency and amplitude with changes in gaseous fuel composition is investigated.

Ambient Conditions

Inlet air temperature, humidity, inlet pressure of combustion chamber has effect on combustion process. Shortening the overall combustion time, whether through heightened fuel volatility decreasing evaporation time or elevated inlet air temperature diminishing reaction time, typically mitigates instabilities. It is essential to note that while this is often observed, it should not be considered a universal outcome, as numerous exceptions have been noted in both laboratory experiments and engine hardware tests. Considerable fluctuations in combustor stability performance may arise from shifts in geographical climate and seasonal weather conditions.

Aerodynamic Instabilities

Experiments and computational investigations into combustor aerodynamics have uncovered that the shear layers formed by opposing swirling airflows and the breakup regions of air jets exhibit the presence of well-defined large-scale structures. These features play a crucial role in facilitating high mixing rates, a fundamental requirement for achieving substantial volumetric heat release rates. However, they can also lead to periodic heat release, potentially triggering combustion instability. An integral aspect of this instability mechanism involves the time lapse between the formation of a coherent vortex structure and

the moment when combustion-induced energy release occurs within the vortex. This temporal gap may establish the appropriate phase relationship between the fluctuating pressure field and the intermittent heat release, driving the onset of instability. McManus [22] has been observed that in its research.

Fuel Injector

Fluctuations in the fuel flow rate significantly contribute to combustion oscillations in various combustion systems, particularly evident in rocket engines and gas turbines. Referred to as "chugging" or "rumble" depending on the frequency of the noise, it consistently denotes the interplay between the combustor's acoustics and the fuel-injection system.

Under conditions of low fuel supply pressure, pressure pulsations emerge, generating oscillations in the fuel flow rate. Subsequently, these fluctuations induce oscillations in the heat-release rate. If these heat-release oscillations are appropriately positioned and synchronized with the acoustic mode, they contribute energy to the mode, thereby sustaining the oscillatory state. Kenworthy is considered with this phenomena in its research.

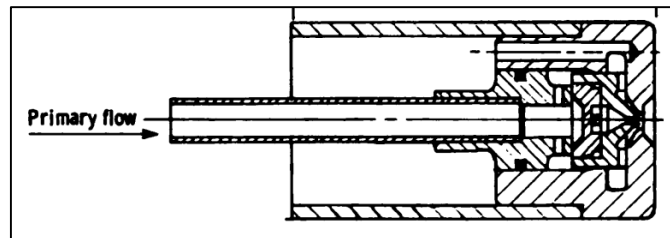


Figure 2.15: Simplex Injector Section [15]

Compressor-Induced Oscillations

Combustion noise could potentially stem from pressure fluctuations in the air supply originating from the compressor. Under normal conditions, particularly near the design point, the compressor efflux maintains a smooth and uninterrupted flow, occasionally disrupted by turbulence fluctuations that generally aid in preventing flow separations within the combustor diffuser. However, during specific "off-design" or transient conditions, the compressor may operate in proximity to its stall line. Consequently, the air supply to the combustor may carry amplified pressure fluctuations through the combustion process, leading to the generation of noise. Oscillations induced by the compressor under these circumstances can act as a catalyst for low-frequency noise.

Lean Premixed Combustor

Lean premixed (LPM) combustors exhibit heightened vulnerability to instabilities owing to reduced acoustic losses attributed to the absence of liner perforations and wall-cooling slots. Additionally, the rigid liner walls minimally absorb acoustic energy, contributing to this susceptibility.

3. TEST ARTICLE AND TEST CONDITIONS

In order to evaluate the differences in order to determine the combustion chamber instability mechanism, the production of coflow swirler and counterflow swirler and the production of injectors with different flow number values were carried out. In addition to the mechanical part changes, the test conditions were changed to enable more detailed interpretation of the test data obtained.

3.1. Test Rig

Atmospheric tests constitute a significant part of the combustion chamber testing process. The advantage of atmospheric tests over high-pressure tests in terms of time and cost, along with the adequacy of similarity in basic performance parameters, makes these tests crucial in such systems. Therefore, the initial tests of completed combustion chambers are conducted under atmospheric conditions, and improvement efforts are based on the data obtained from these tests. One important aspect to consider in these tests is combustion efficiency. A higher loading parameter in atmospheric tests results in a decrease in combustion efficiency. Additionally, there may be inefficiencies due to a decrease in fuel atomization quality in air-assisted fuel injectors. Hence, these factors should be taken into account when analyzing the results. Within the scope of this study, a design and setup for an atmospheric combustion chamber test rig were developed to conduct tests and characterize the performance of the designed combustion chamber.

3.1.1. Test Rig Design and Capabilities

In atmospheric rig tests, comprehensive testing of combustion chamber parameters such as pressure drop, combustion efficiency, outlet temperature profile, and jacket temperature distribution is possible. The key focus in these tests is to maintain the corrected flow values specified at the design point under atmospheric conditions. The corrected flow, defined by the flow rate parameter NDF or m_{red} , is calculated using equations (3.1) and (3.2) [23]. In line with the fundamental principle of atmospheric testing, which involves testing the combustion chamber under atmospheric pressure conditions, the m_{red} value at the design point should also be the same for atmospheric rig testing. This allows tests to be conducted

at a lower flow rate in atmospheric conditions. While these tests could also be conducted under high-pressure conditions, it would require additional work to pressurize the air, leading to increased costs. Therefore, atmospheric condition tests were preferred considering the associated cost implications

In atmospheric tests, the inlet temperature of the combustion chamber can be maintained at the same value as the design point or lower temperatures can be used depending on the heating capacity. However, not using any heating can lead to stability issues in the combustion chamber and flameouts during the test. Therefore, it is important to heat the inlet air to a certain extent even if the design point cannot be reached. After determining the air flow rate to be supplied to the combustion chamber in atmospheric tests using equation (3.3), the fuel flow rate can be calculated considering the air-fuel ratio. The fundamental principle here is to ensure that the Air-Fuel Ratio (AFR) remains constant at both the design point and atmospheric test conditions

$$\dot{m}_{red} = \frac{\dot{m}_3 \sqrt{T_3}}{P_3} \quad (3.1)$$

$$\dot{m}_{red,atm} = \frac{\dot{m}_{3atm} \sqrt{T_{3,atm}}}{P_{3atm}} \quad (3.2)$$

Assuming that the $\dot{m}_{red}$ value should remain constant under real operating conditions and atmospheric operating conditions;

$$\dot{m}_{3,atm} = \frac{\dot{m}_3 P_{3,atm} \sqrt{T_3}}{P_3 \sqrt{T_{3atm}}} \quad (3.3)$$

$$\dot{m}_{fuel,atm} = \frac{\dot{m}_{3atm}}{AFR} \quad (3.4)$$

The test rig is designed to perform tests of combustion chambers of small size engines. The rig infrastructure is suitable for outlet temperatures, emission tests and other combustion-specific tests. Test rig working capabilities are defined in below Table.3.1

Table 3.1: Test Rig Capabilities

Max Inlet Pressure	< 2.0 bar
Air Inlet Temperature	$T_{amb} - 800$ K
Air Mass Flow	0.03 – 0.4 kg/s
Fuel Mass Flow	0.0005 – 0.026 kg/s
Thermocouple Type	Type K
Dynamic Pressure Sensor	Max 7 barg

3.1.2. Atmospheric Combustion Test System

The general layout of the test facility is depicted in Figure 3.1. As seen from the diagram, the test setup comprises two main sections: the control room and the test chamber. The separation of the test chamber from the control room and the ability to control the entire system from the control room have enhanced the security level of the system. Various test parameters such as air and fuel flow rates, preheating temperature, ignition, and others can be set by the operator from the control room. Additionally, all data collected during the test can be monitored in real-time through the data acquisition systems located in the control room.

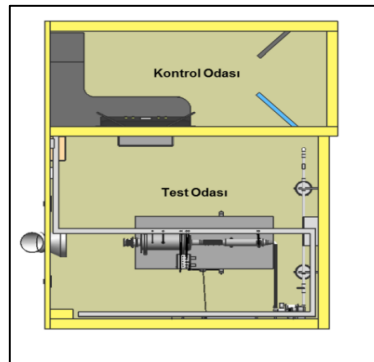


Figure 3.1: Test System

The test system consists of the following subsystems:

- Air Infrastructure
- Fuel Infrastructure
- Data Acquisition System
- Dynamic Data Acquisition System
- Control System
- Emission Measurement System
- Exhaust System

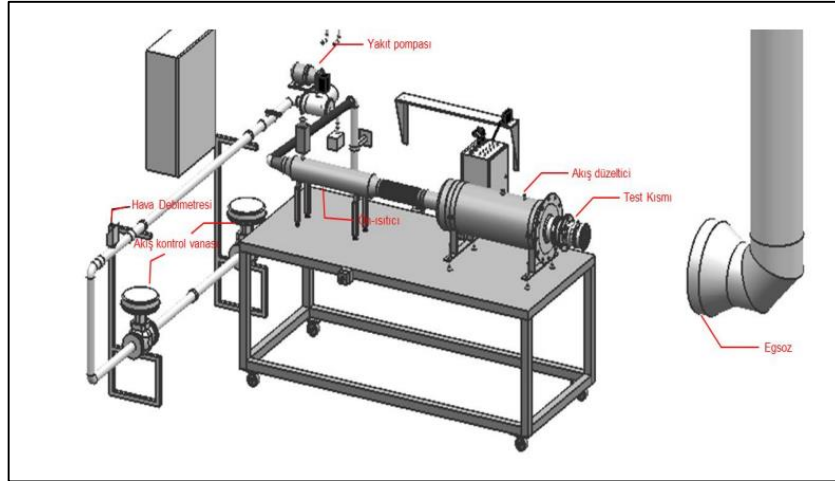


Figure 3.2: Test Room

The general structure of the test system is illustrated in Figure 3.2. The system comprises two main flow controls: one for air and the other for fuel. Control of the air flow is achieved using electro-pneumatic valves, while control of the fuel flow is managed by a fuel pump and a servo valve on a Coriolis-type flow meter. Air flow measurement is performed using a thermal flow meter. Prior to entering the test section, the air is heated to the required temperature using an electric heater. Before entering the test section, the airflow has been using an flow mixer to ensure uniform flow into the test section. The hot gases exiting the test section are expelled outside the test chamber via an open exhaust system. Data collected during the test is transferred to the data acquisition system located in the control room through the BOM arm.

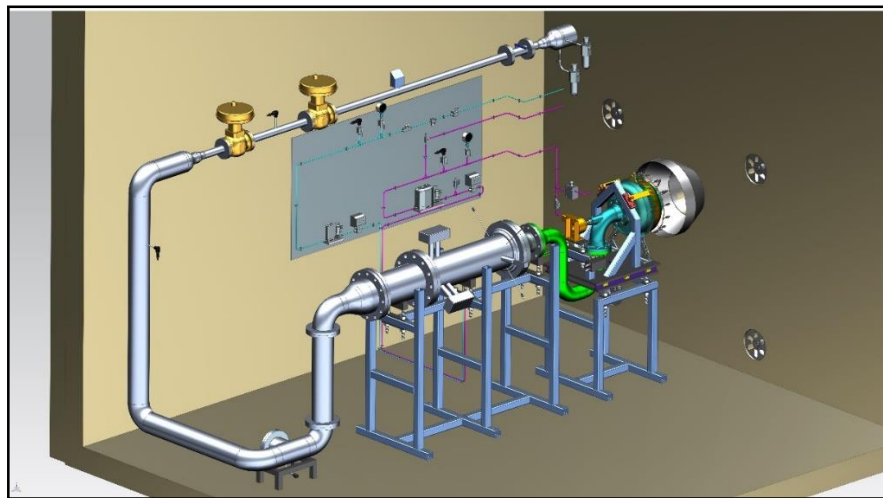


Figure 3.3: General Test System Infrastructure

3.1.3. Flow Mixer

The fundamental purpose of the flow mixer is to facilitate the attainment of a uniform distribution of air heated by the heater.



Figure 3.4: Flow Mixer

3.1.4. Exhaust

An open-system exhaust was selected to discharge the burned gases from the combustion chamber without any recirculation and to cool them with the addition of secondary air. The jet effect created by the hot burned gases at the outlet of the combustion chamber directs a secondary air flow towards the augmentor pipe, thereby facilitating the cooling of the exhaust gases. The primary parameters used to determine the dimensions of the exhaust include the distance between the test section and the augmentor, the ratio of the test section outlet to the augmentor diameter, the length of the augmentor, and the gas temperature. Additionally, to facilitate the discharge of the air inside, a fan was connected to the exhaust section to aid in expelling the burned gases outward.

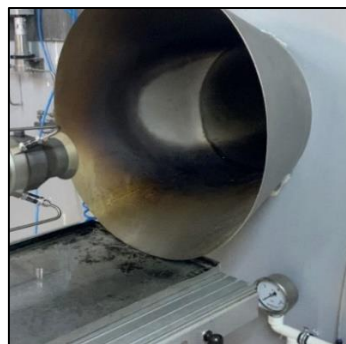


Figure 3.5: Exhaust System

3.2. Test Article

Within the scope of the study, a test article was designed and manufactured to simulate the operating conditions and flow path of both the co-flow and counter-flow premixed combustion chambers (Figure 3.6.) To enable instrumentation at the inlet of the combustion chamber, a dedicated inlet section was designed. Additionally, dynamic pressure measurements will be taken from the fuel line and on the casing. The transition between the test section and the flow conditioner was designed to facilitate the integration of different combustion chambers into the system as seamlessly as possible.

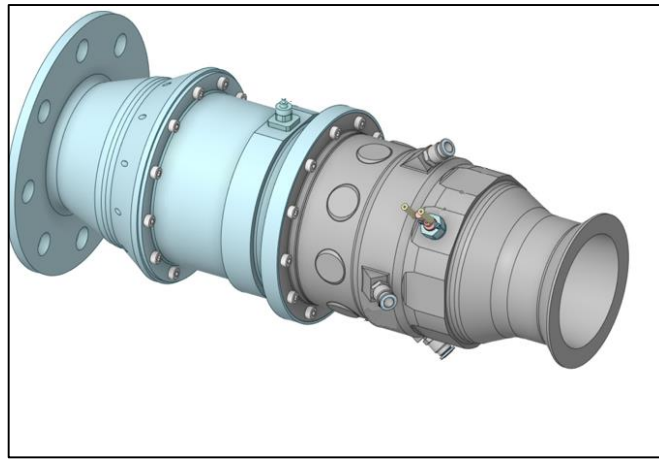


Figure 3.6: 3D Model of Test Article

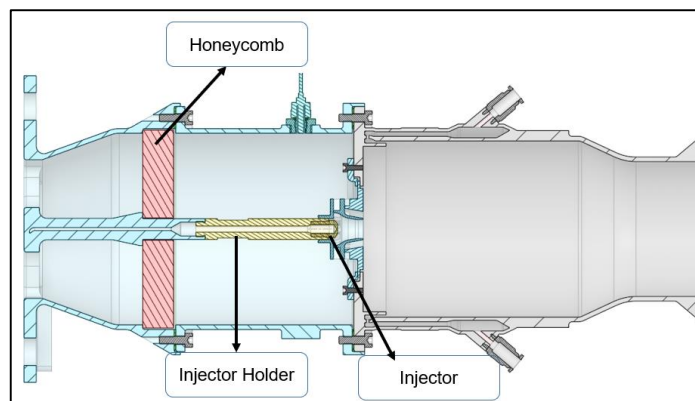


Figure 3.7: Section of Test Article

3.2.1. Instrumentation

The complex geometry of the combustion chamber poses limitations for instrumentation [24]. Therefore, as shown in Figure 3.8. measurement points are only designated at the inlet and outlet. At the inlet, total pressure, static pressure, and static temperature values are taken at different positions. The primary reason for these measurements is to ensure controlled heating of the test piece and to protect the facility. These values represent the inlet conditions of the combustion chamber. The outlet of the combustion chamber is a more accessible area for instrumentation. As per the atmospheric test rig concept, the outlet of the combustion chamber is directly open to the atmosphere. In this case, measurements can be taken using pressure and temperature sensors designed for the outlet, and emission measurements can also be easily obtained using an emission probe. However, for the evaluation of this test, only data from the dynamic pressure sensor will be considered.

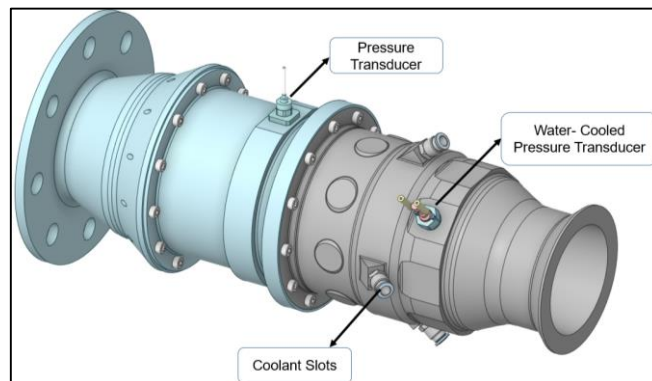


Figure 3.8: Instrummentation Locations of Test Article

The commonly used definitions of static and dynamic pressure in the literature related to fluid flow are as follows: Static pressure is the pressure at a point in a flow field where the flow velocity is zero. Dynamic pressure, on the other hand, is the pressure resulting from the motion of fluid particles. Total pressure is the sum of static and dynamic pressure. Measurement methods for dynamic pressure are generally more precise.



Figure 3.9: Dynamic Pressure Sensor

During the tests dynamic pressure data has been collected from casing with dynamic pressure sensor . Flame effects and pressure oscillations are determined. Kulite dynamic pressure sensors (Fig.3.9.) have been selected and used for data collection.

3.2.2. Control and Data Acquisition System

The test system is controlled electronically and manually via PLC(Programmable Logic Control). The PLC system controls the air control valve, fuel control valve, heater and some parameters in the adjacent systems. Communication between the PLC system and the operator is provided by HMI (Human Machine Interface). The test rig is managed by the test engineer via HMI. Test conditions (air flow rate, fuel flow rate, heater temperature, etc.) are controlled from this interface. Measurement parameters such as air flow rate, fuel flow rate, temperature and pressure are recorded with DAS (Data Acquisition System) and transferred to PLC system via server. A commercial data acquisition software was preferred for DAS. Security measures, which are one of the most important issues in test systems, also apply to this system. In order to ensure maximum safety, emergency stop operations have been created in the PLC system and the operation of this system has been checked before commissioning.



Figure 3.10: DAS/HMI System



Figure 3.11: DDAS System

3.3 Test Concepts

Tests with different concepts were carried out to determine the combustion chamber instabilities. While comparing the data obtained in the tests, it was decided to examine the dynamic pressure characterization as a result of literature reviews. The dynamic pressure sensor used was selected to be 7 barg in order to detect the instabilities occurring in the combustion chamber internal pressure. In this way, the fluctuations occurring could be evaluated precisely. The data obtained from these tests will be interpreted graphically. The following test concepts were performed to determine the combustion chamber instabilities.

- Coflow-Counterflow swirler effects
- Impact of fuel nozzle axial position
- Impact of spray characteristics of FN
- Impact of air inlet temperature(heater)
- Impact of cooling air pressure

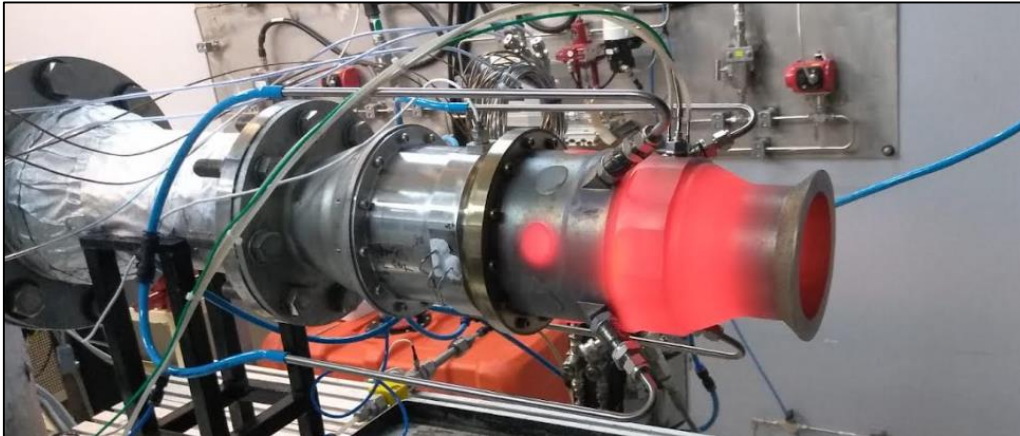


Figure 3.12: Test Article

In order to evaluate the data obtained in the test in a meaningful way and to evaluate the instability mechanism, the following concepts were used.

Minimum Pressure: The lowest value reached by the dynamic pressure data.

Maximum Pressure: The highest value reached by the dynamic pressure data.

Average Pressure: The average value of the dynamic pressure data.

P/P'(%): The ratio of the difference between the maximum pressure value and the minimum pressure value to the average pressure value.

Equivalence Ratio (Φ): The ratio of the stoichiometric AFR to the AFR during the test

Test Conditions: During the tests which parameters are used is defined in here. Air and fuel flow units are described as g/s

Dynamic pressure values are collected from DDAS panel, minimum pressure, maximum pressure and average pressure datas are getting from here. Interface visual of DDS pannel is shown below:

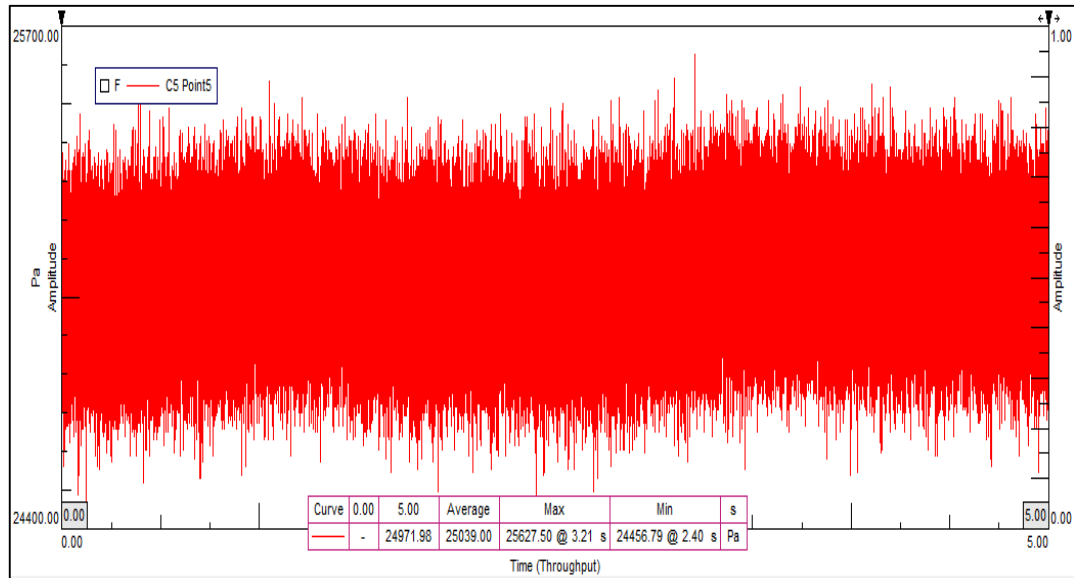


Figure 3.13: DDAS Interface Panel

a. Coflow-Counterflow swirler effects

Different type of swirlers are used to compare dynamic pressure value of swirler is used. Air and fuel mass flow rates(units are g/s) are changed and oscillations are observed. Same test conditions are conducted and repeated with different swirler. Details are listed below.

Table 3.2: Swirler Effects Dynamic Pressure Values (Fuel Flow Const.)

CASING					
Max(Pa)	Min(Pa)	Avg(Pa)	P/P' (%)	Eq.Ratio (Φ)	Test Conditions
118858	117644	118250	1.027	0.750	Air20-Fuel1 FN2.7 Counterflow Swirler
117901	116815	117371	0.925	0.833	Air18 -Fuel1 FN2.7 Counterflow Swirler
117414	116328	116892	0.929	0.937	Air16 -Fuel1 FN2.7 Counterflow Swirler
115927	114841	115380	0.941	0.750	Air20 -Fuel1 FN2.7 Coflow Swirler
112842	111808	112292	0.921	0.833	Air18 -Fuel1 FN2.7 Coflow Swirler
111457	110423	110946	0.932	0.937	Air16 -Fuel1 FN2.7 Coflow Swirler

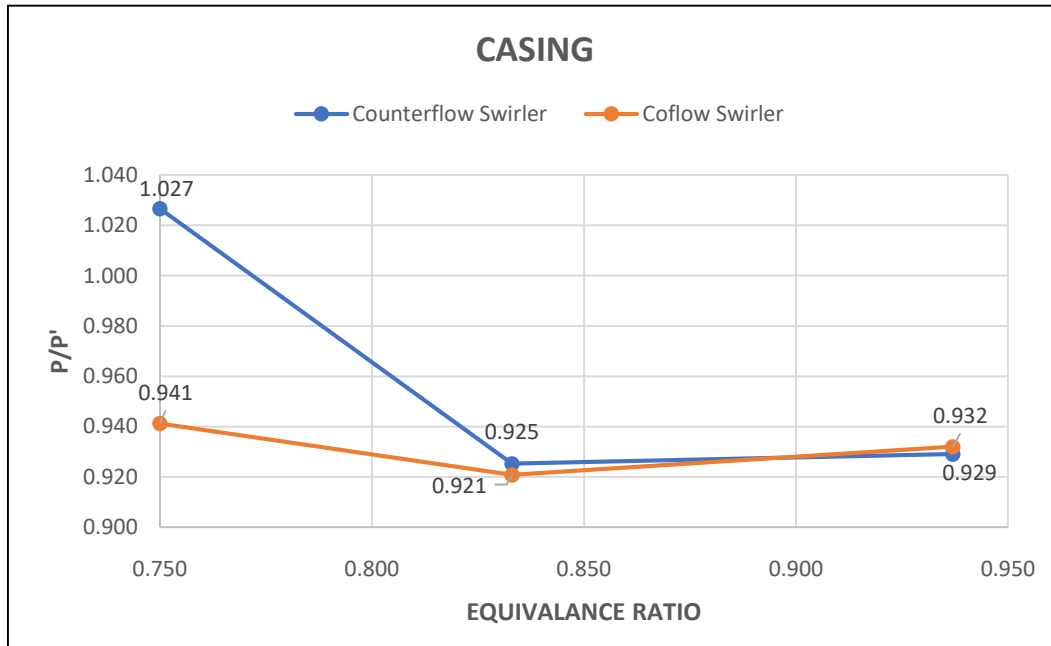


Figure 3.14: Swirler Effect Values Dynamic Pressure Graph

According to this table it was observed that for coflow and counterflow swirler both, when the air flow rate decreased, maximum, minimum and average pressure values are getting decrease. Also if we compare P/P' values, when air flow rates are decreased, it was determined that no definite conclusion could be reached. For the case where the change in P/P' value is evaluated by keeping one of the air or fuel values constant where the fuel flow rate is changed while keeping the air flow rate constant in order to increase data diversity

Table 3.3: Swirler Effects Dynamic Pressure Values -2 (Mass Air Flow Const.)

CASING					
Max(Pa)	Min(Pa)	Avg(Pa)	P/P' (%)	Eq.Ratio (Φ)	Test Conditions
117901	116815	117371	0.925	0.833	Air18-Fuel1 FN2.7 Counterflow Swirler
119328	118242	118779	0.914	0.750	Air18-Fuel0.9 FN2.7 Counterflow Swirler
120046	119020	119525	0.858	0.666	Air18-Fuel0.8 FN2.7 Counterflow Swirler

Tablonun devamı					
112842	111808	112292	0.921	0.833	Air18-Fuel1 FN2.7 Coflow Swirler
106834	105783	106279	0.989	0.750	Air18-Fuel0.9 FN2.7 Coflow Swirler
105732	104655	105194	1.024	0.666	Air18-Fuel0.8 FN2.7 Coflow Swirler

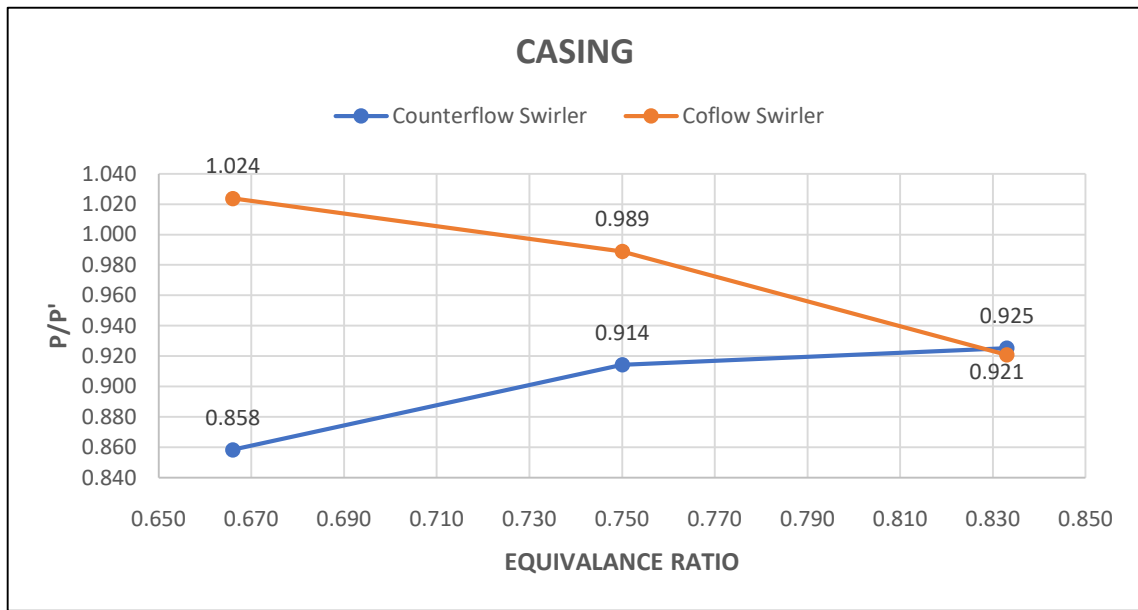


Figure 3.15: Swirler Effect Dynamic Pressure Values-2 Graph

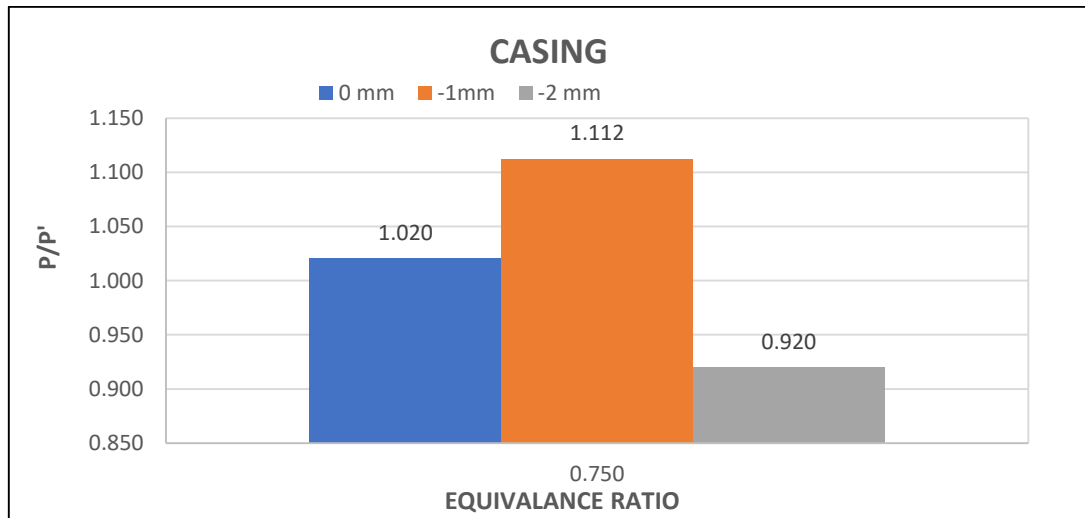
It was observed that for coflow swirler when fuel flow decreased P/P' values getting decreased. But it was observed that for coflow swirler when fuel flow decreased P/P' values decreasing trend. For counterflow swirler that is the opposite. When fuel flow is decreased P/P' values increasing trend. According to these results, there is no definitive conclusion has been reached.

b. Impact of Fuel Nozzle Axial Position

In order to determine the effects of injector axial position on combustion instability, the following data were obtained by increasing and decreasing the distance of the injector to the combustion chamber.

Table 3.4: Fuel Nozzle Axial Position Dynamic Pressure Values

CASING					
Max(Pa)	Min(Pa)	Avg(Pa)	P/P' (%)	Eq.Ratio (Φ)	Test Conditions
25738	24533	25098	4.801	0.750	Air20-Fuel1 FN2.7 (Nominal Pos.)
25097	23790	24490	5.337	0.750	Air20-Fuel1 FN2.7 (-1mm Pos.)
24567	23491	24015	4.481	0.750	Air20-Fuel1 FN2.7 (-2mm Pos.)

**Figure 3.16:** Fuel Nozzle Axial Position Dynamic Pressure Values Graph

It was observed that when the distance of the injector from the swirler increases P/P' values getting decreased. In order to be sure of the trend of the data obtained, the table obtained for the data taken at more than one point is as follows.

Table 3.5: Fuel Nozzle Axial Position Dynamic Pressure Values-2

CASING					
Max(Pa)	Min(Pa)	Avg(Pa)	P/P' (%)	Eq.Ratio (Φ)	Test Conditions
118738	117533	118098	1.020	0.750	Air 20-Fuel 1 FN2.7 (Nominal Pos.)
120986	119875	120417	0.923	0.675	Air20-Fuel 0.9 FN2.7 (Nominal Pos.)

Tablonun devamı					
121233	120131	120699	0.913	0.600	Air20-Fuel 0.8 FN2.7 (Nominal Pos.)
118097	116790	117490	1.112	0.750	Air20-Fuel 1 FN2.7 (-1mm Pos.)
119687	118533	119118	0.969	0.675	Air 20-Fuel 0.9 FN2.7 (-1mm Pos.)
120285	119046	119663	1.035	0.600	Air20-Fuel0.8 FN2.7 (-1mm Pos.)
117567	116491	117015	0.920	0.750	Air20-Fuel 1 FN2.7 (-2mm Pos.)
120120	119046	119637	0.898	0.675	Air20-Fuel 0.9 FN2.7 (-2mm Pos.)
120242	119191	119719	0.878	0.600	Air20-Fuel 0.8 FN2.7 (-2mm Pos.)

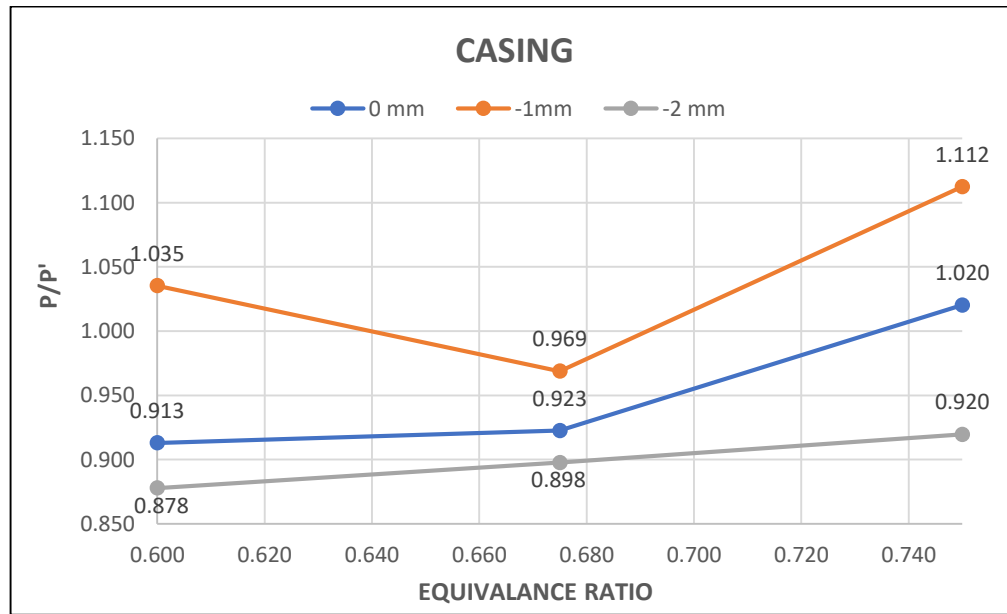


Figure 3.17: Fuel Nozzle Axial Position Dynamic Pressure Values-2 Graph

It was observed that no definite conclusion could be reached. There is no relation between injector distance and P/P' value. When the all test results observed, similar trend has been observed for different cases. According to this trend -2mm position is the optimum axial position is better for combustion instabilities.

c. Impact of spray characteristics of FN

In order to determine the effects of FN of injector on combustion instability, the following data were obtained by different FN number injectors are used for to the combustion chamber.

Table 3.6: Different FN Injector Dynamic Pressure Values

CASING					
Max(Pa)	Min(Pa)	Avg(Pa)	P/P' (%)	Eq.Ratio (Φ)	Test Conditions
118371	117337	117850	0.877	0.937	Air16-Fuel1 FN2.7
115704	114568	115135	0.987	0.937	Air16-Fuel1 FN3.6
117755	116553	117198	1.026	0.937	Air16-Fuel1 FN4.7

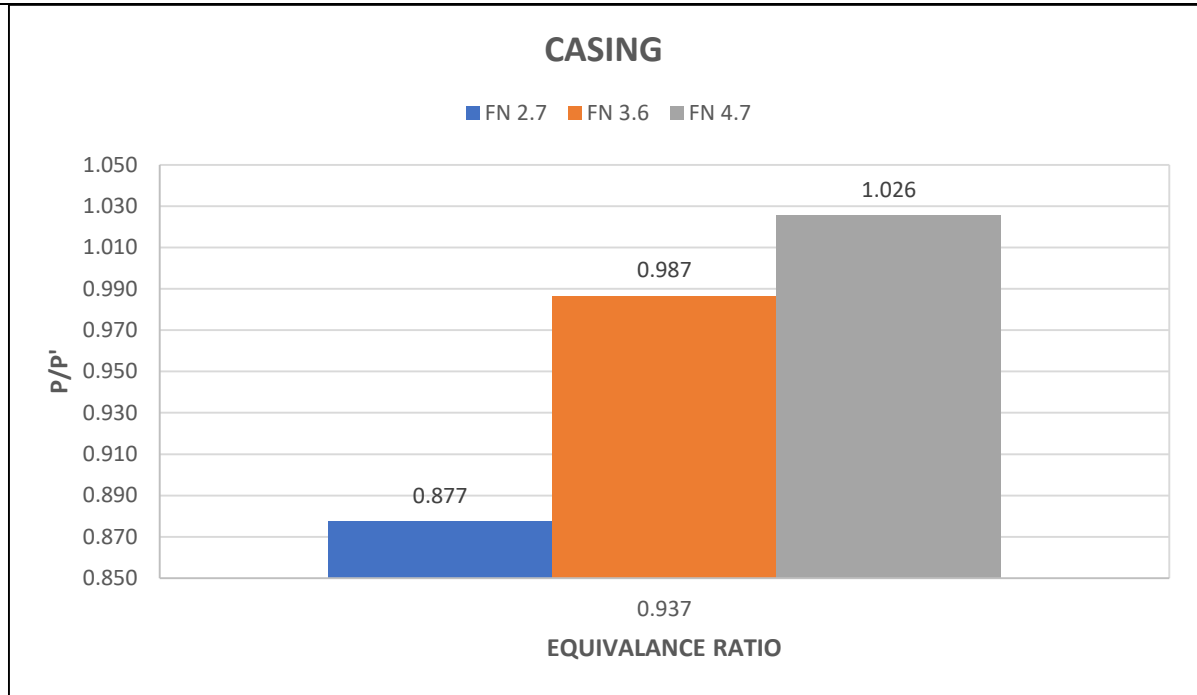
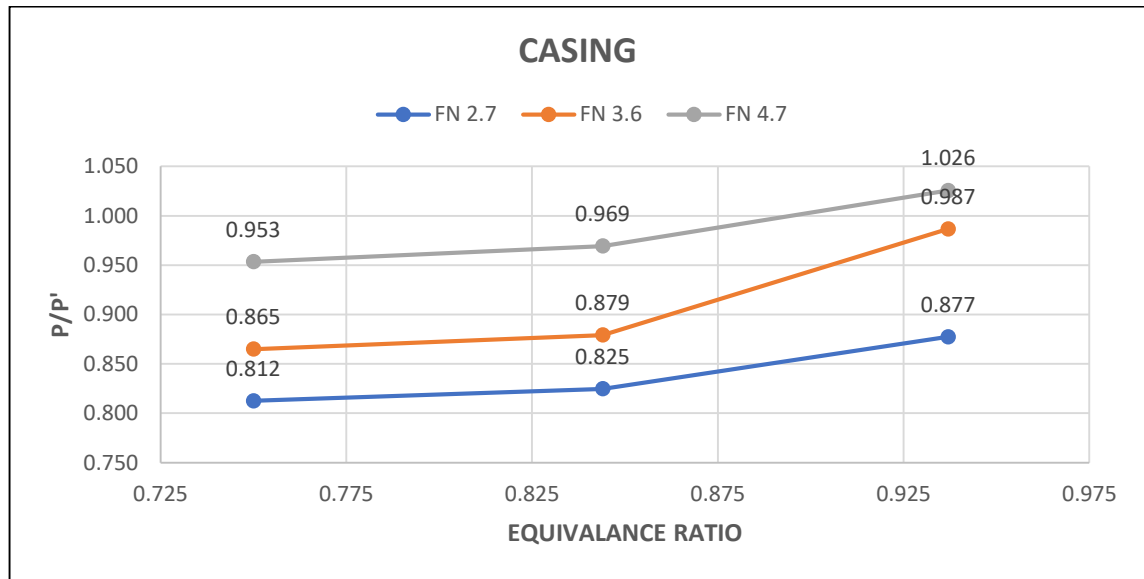


Figure 3.18: Different FN Injector Dynamic Pressure Values Graph

It was observed that FN of injector is increased, P/P' values are also increased too. In order to be sure of the trend of the data obtained, the table obtained for the data taken at more than one point is as follows.

Table 3.7: Different FN Injector Dynamic Pressure Values-2

CASING					
Max(Pa)	Min(Pa)	Avg(Pa)	P/P' (%)	Eq.Ratio (Φ)	Test Conditions
118371	117337	117850	0.877	0.937	Air16-Fuel1 FN2.7
118920	117943	118469	0.825	0.844	Air16-Fuel0.9 FN2.7
119379	118413	118894	0.812	0.750	Air16-Fuel0.8 FN2.7
115704	114568	115135	0.987	0.937	Air16-Fuel1 FN3.6
116200	115183	115673	0.879	0.844	Air16-Fuel0.9 FN3.6
119054	118029	118505	0.865	0.750	Air16-Fuel0.8 FN3.6
117755	116553	117198	1.026	0.937	Air16-Fuel1 FN4.7
119302	118151	118745	0.969	0.844	Air16-Fuel0.9 FN4.7
121661	120507	121045	0.953	0.750	Air16-Fuel0.8 FN4.7

**Figure 3.19:** Different Injector Dynamic Pressure Values-2 Graph

Similar characteristic has been observed for different test points too. According to this trend FN2.7 injector is the optimum injector for combustion instabilities.

d. Impact of Air Inlet Temperature(Heater)

In order to determine the effects of air inlet temperature on combustion instability, via heater inlet temperature of air is increased to 400 K and following datas were obtained from combustion chamber.

Table 3.8: Different Air Inlet Temperature Dynamic Pressure Values

CASING					
Max(Pa)	Min(Pa)	Avg(Pa)	P/P' (%)	Eq.Ratio (Φ)	Test Conditions
121333	116704	118968	3.891	0.750	Air20-Fuel1 FN2.7 Air Inlet 400K
121665	117224	119310	3.722	0.675	Air20-Fuel 0.9 FN2.7 Air Inlet 400K
122083	117199	119285	4.094	0.600	Air20-Fuel 0.8 FN2.7 Air Inlet 400K
118080	116952	117521	0.960	0.750	Air20-Fuel 1 FN2.7 Air Inlet 300K
120849	119746	120311	0.917	0.675	Air20-Fuel 0.9 FN2.7 Air Inlet 300K
121122	119952	120540	0.971	0.600	Air20-Fuel 0.8 FN2.7 Air Inlet 300K

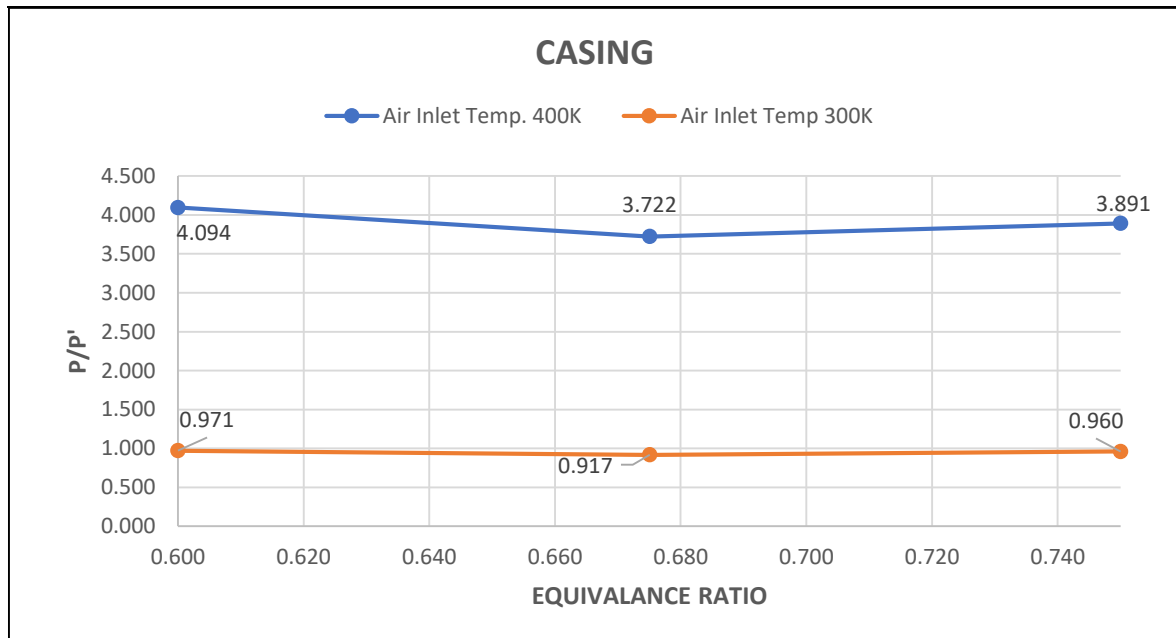


Figure 3.20: Different Air Inlet Temperature Dynamic Pressure Values

It was observed that when air inlet temperature is increased, P/P' values are increased. According to this test values, lower air inlet temperatures is better for combustion instabilities.

e. Impact of Cooling Air

In order to determine the effects of cooling air pressure on combustion instability, pressure of cooling air has been changed which is used for cooling to casing, following datas were obtained from combustion chamber.

Table 3.9: Different Cooling Air Pressure Dynamic Pressure Values

CASING					
Max(Pa)	Min(Pa)	Avg(Pa)	P/P' (%)	Eq.Ratio (Φ)	Test Conditions
118665	114292	116455	3.755	0.750	Air20-Fuel1 FN2.7 Cooling Air 1bar
118818	114309	116444	3.872	0.750	Air20-Fuel1 FN2.7 Cooling Air 2bar
118367	113960	116102	3.796	0.750	Air20-Fuel1 FN2.7 Cooling Air 3bar

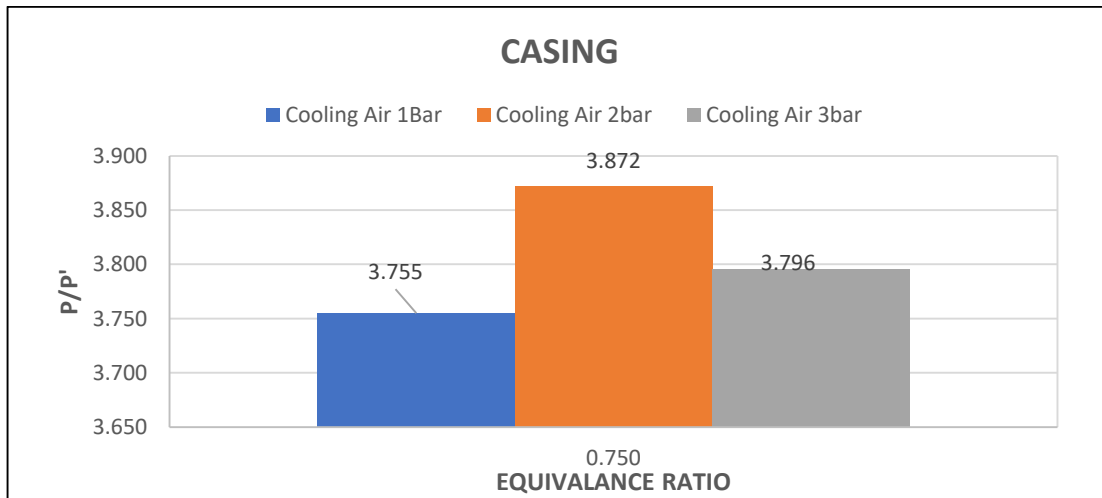
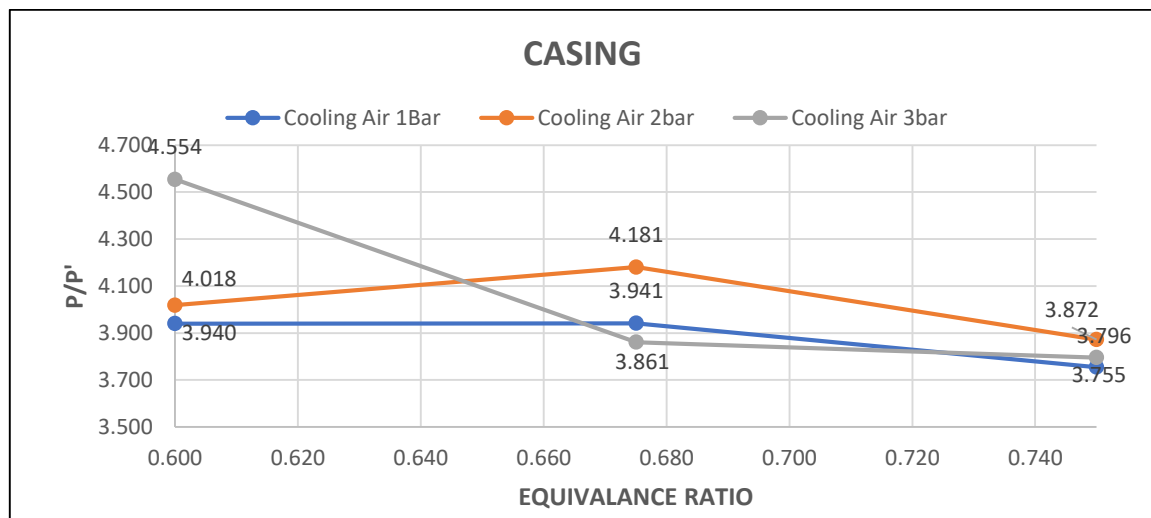


Figure 3.21: Different Cooling Air Pressure Dynamic Pressure Values Graph

It was observed that when cooling air pressure increased, according to P/P' value 1 bar is better for combustion instability. In order to be sure of the trend of the data obtained, mass air flow kept constant, fuel flow is decreased and the table obtained for the data taken at is as follows:

Table 3.10: Different Cooling Air Pressure Dynamic Pressure Values-2

CASING					
Max(Pa)	Min(Pa)	Avg(Pa)	P/P' (%)	Eq.Ratio (Φ)	Test Conditions
118665	114292	116455	3.755	0.750	Air20-Fuel1 FN2.7 Cooling Air 1bar
118622	114045	116128	3.941	0.675	Air20-Fuel0.9 FN2.7 Cooling Air 1bar
118503	113926	116160	3.940	0.600	Air20-Fuel0.8 FN2.7 Cooling Air 1bar
118818	114309	116444	3.872	0.750	Air20-Fuel1 FN2.7 Cooling Air 2bar
118665	113806	116230	4.181	0.675	Air20-Fuel0.9 FN2.7 Cooling Air 2bar
118315	113670	115592	4.018	0.600	Air20-Fuel0.8 FN2.7 Cooling Air 2bar
118367	113960	116102	3.796	0.750	Air20-Fuel1 FN2.7 Cooling Air 3bar
118256	113781	115901	3.861	0.675	Air20-Fuel0.9 FN2.7 Cooling Air 3bar
118827	113534	116222	4.554	0.600	Air20-Fuel0.8 FN2.7 Cooling Air 3bar

**Figure 3.22:** Different Cooling Air Pressure Dynamic Pressure Values-2

According to this table it was observed that when cooling air pressure increased, according to P/P' value there is no clear conclusion could be reached.

4. RESULTS

4.1. Conclusions

When designing the combustion chamber, it is desired that the flame burns in the desired region of the combustion chamber and is realized in a stable manner. In order to have a stable combustion, the combustion chamber instability mechanism and parameters are expected to be determined and input to the design. It has been determined in previous studies that the combustor instability mechanism varies depending on the differences in design and test parameters.

The results determined for the parameters of the combustion chamber instability mechanisms examined within the scope of this thesis, which vary depending on the mechanical part change and test concept, are as follows:

- As a result of the test data obtained from the coflow and counter flow swirler to examine the effect of mechanical parts on combustion instability, it was determined that there was no definite effect on the combustion chamber instability mechanism and therefore no clear conclusion could be reached.
- In order to determine the effects of injector axial position on combustion instability, the axial distance inside the combustion chamber was varied and according to the data obtained, it was determined that the optimum distance depending on the combustion chamber design was -2mm. This may vary depending on the combustion chamber length.
- In tests to determine the effects of injector FN on combustion instability, it was found that as the FN of the injector decreased, combustion instability decreased. For this test campaign, the injector with an FN of 2.7 was found to have the least effect on combustion instability.
- In order to determine the effects of air inlet temperature on combustion instability, the air inlet temperature was brought to 400 K through the heater. As a result of the test data obtained, it was determined that the combustion chamber instability increased as the temperature of the air entering the combustion chamber increased. For this reason, 300 K ambient temperature is considered to be the ideal temperature.

- In order to determine the effects of cooling air pressure on combustion instability, the pressure of the cooling air used for cooling the casing was varied. According to the results of the test data obtained, changing the pressure of the cooling air did not provide a definitive conclusion on the test data.

4.2. Future Works

All of the parameters examined in this thesis were carried out within the scope of the capabilities of a test rig with atmospheric inlet air conditions. In future studies, it is thought that it is more difficult to carry out studies in this field since high-pressure test rigs are not widespread worldwide. By repeating the same studies in a high-pressure test center and comparing the data obtained with the results of the atmospheric test center studied in this thesis, the potential effects of pressure change on combustion chamber instability mechanisms can be evaluated.

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BIOGRAPHY

The author Nadir KÖKÇÜ had graduated from Eskisehir Osmangazi University (ESOGU) Department of Mechanical Engineering in 2019. He started his career in Tusas Engine Industries Inc. (TEI) as a Quality System and Qualification Engineer and has been working in the field of gas turbine engine components test for nearly 5 years. His technical interest comprise thermo-fluids systems, compressible flow turbomachinery, heat transfer mechanisms and tests components of engine. The author currently working in TEI and testing combustion chambers in engines.