

T.R.
GEBZE TECHNICAL UNIVERSITY
INSTITUTE OF ENERGY TECHNOLOGIES

**INTEGRATION OF FUEL FLOW DIVIDER COMPONENT TO
THE TURBOSHAFT ENGINE AND INVESTIGATION OF
TRANSIENT PERFORMANCE**

AHMETCAN TENGİLİMOĞLU
A THESIS SUBMITTED FOR THE DEGREE OF
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THESIS SUPERVISOR
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YÜKSEK LİSANS JÜRİ ONAY FORMU

GTÜ Enerji Teknolojileri Enstitüsü Yönetim Kurulu'nun 13/06/2022 tarih ve 2022/08 sayılı kararıyla oluşturulan jüri tarafından 15/06/2022 tarihinde tez savunma sınavı yapılan AHMETCAN TENGİLİMOĞLU'nun tez çalışması ENERJİ TEKNOLOJİLERİ Anabilim Dalında YÜKSEK LİSANS tezi olarak kabul edilmiştir.

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SUMMARY

Gas turbine engines are one of the paramount in the mechanical engineering in terms of complexity. The engines are combination of different modules and subsystems. The harmony of the subsystems is vital since a failure can propagate to other modules and consequently cause catastrophic results. Therefore, integration of a component to a subsystem and a subsystem to the engine are comprehensive processes.

In this study, conceptualization of the flow diagram of the fuel system is made according to the engine requirements. Possible fuel flow divider architectures are evaluated and selection of the concept is made by taking into consideration of design requirements. Different alternatives are considered for the placement of the component according to the design aspects related to the component design. The component integration studies are made with different levels of tests such as component, system and engine levels. The test data comparisons are made and successful integration of the component is validated.

Key Words: Gas Turbine Engine, Fuel System, Engine Subsystems, Subsystem Validation.

ÖZET

Gaz türbin motorları, makine mühendisliğinde karmaşıklık konusunda en zorlayıcı alanlardan biridir. Motorlar birçok farklı parça ve alt sistemin bir araya gelmesinden oluşmaktadır. Bu alt sistemlerin uyum içinde çalışması hayati öneme sahiptir çünkü bir alt sistemde meydana gelebilecek bir hatanın diğer alt sistemleri de etkilemesi ve katastrofik sonuçların ortaya çıkması olasılığı bulunmaktadır. Bundan dolayı parçanın alt sisteme ve alt sistemin motora entegrasyonu kapsamlı bir süreçtir.

Bu çalışmada, yakıt akış bölücü parçasının kavramsal tasarımı yakıt sistemi gereksinimlerine göre yapılmıştır. Olası yakıt akış bölücü mimarileri değerlendirilmiştir ve seçim, tasarım gereksinimleri göz önünde bulundurularak yapılmıştır. Çeşitli parça konumu alternatifleri, farklı tasarım yönlerinden incelenmiştir. Parçanın entegrasyon çalışmaları farklı seviyelerde testlerle yapılmıştır. Bunlar parça, sistem ve motor seviyesi olarak sıralanabilir. Test verileri karşılaştırılmış ve parçanın başarılı entegrasyonu valide edilmiştir.

Anahtar Kelimeler: Gaz Türbin Motoru, Yakıt Sistemi, Motor Altsistemleri, Alt Sistem Validasyonu.

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LIST OF ABBREVIATIONS AND ACRONYMS

<u>Abbreviations</u>	<u>Explanations</u>
<u>and Acronyms</u>	
cc	: Cubic Centimeter
g	: Gram
kg	: Kilogram
Hz	: Hertz
s	: Seconds
C	: Celsius
D	: Inside Diameter of Tubing
ν	: Kinematic Viscosity
ε/D	: Relative Roughness
f	: Friction Factor
ρ	: Density
Re	: Reynold Number
V	: Velocity
ΔP	: Pressure Difference
FN	: Flow Number
$\dot{m}$	: Mass Flow
m	: Meter
L	: Length
K_L	: Minor Loss Coefficient
h_L	: Head Lose
AGB	: Accessories Gearbox
AIR	: Aerospace Information Report
ARP	: Aerospace Recommended Practice
CAN	: Controller Area Network
CS-E	: Certification Specification - Engines
DAS	: Data Acquisition System
EASA	: European Aviation Safety Agency
FADEC	: Full Authority Digital Engine Control

FFD	:	Fuel Flow Divider
FMU	:	Fuel Metering Unit
GTU	:	Gebze Technical University
MOC	:	Means of Compliance
SAE	:	Society of Automotive Engineers
TEI	:	Tusaş Engine Industries



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1. INTRODUCTION

The gas turbine engines are widely used from air transport to power generation. The primary power plant of the air transportation is by far gas turbine engines as they have advantage in weight to power ratio at comparison with other engine types. Reliability and performance goals for the gas turbine engines are high. Subsystem designs have crucial role to meet these targets. The process of design, implementation and test must be well orchestrated and performed.

The main gas turbine engine modules are compressor, combustion chamber, turbine and nozzle. Afterburner, low pressure turbine, fan or propeller can be integrated to the engine depending on configuration of the engine. The auxiliary systems are also needed for the operation of the engine. Some of the functions provided by these auxiliary systems are starting power, ignition, lubrication oil and fuel supply. [1]

The main purpose of the gas turbine fuel system is to guarantee supply of the required fuel to the engine [1]. The fuel is sprayed and burned in the combustion chamber. It is vital to uninterrupted supply of the fuel to the combustion. The gas turbines are working with continuous flame. They are started on the ground with starting procedures. After that, the flame should not be interrupted [2]. Any disruption at the fuel supply causes engine to flame out, in other words, stopping of the engine [3]. The flame out of the engine considered as a failure. The flame out must be avoided even the engine can be started in the air.

Gas turbine engines can produce tremendous amount of power but it is needed to supply high level of fuel flow. On the other hand, engines start with low level of fuel flow. One of the fuel system requirements is to supply required fuel schedule for engine starting. Special attention should be put on the engine starting because it is transient process. The procedure and fuel flow should be carefully adjusted. Providing the accurate fuel supply in wide range of flow rates is hard to achieve and the fuel supply range of gas turbine engines are generally wide.

The selected ignition configuration and flow requirement mandated by the configuration are studied. The fuel flow should be divided into two lines because of the selected configuration. The fuel flow divider is introduced to the fuel system to

cover all of the fuel flow requirements. The alternative design options can be followed in the design. Placement of the component and used valve types are major tradeoffs in the component design.

As the fuel system health can affect the engine operation and safety, the fuel system should be designed and tested for different operating conditions to validate the fuel supply requirements. The component, system and engine level tests are planned and executed. The data gathered from the tests are compared with each other.

1.1. Purpose of the Study

Engine design process has certain design and validation phases. The design starts with engine requirements and finishes with validation of these requirements. In this process, it is important to conceptualize the compliance methods and proof documentations to the requirements. The design assurance tests do not have certain procedures coming from standards. Therefore, the test procedures must be developed by the design owner.

Even system modeling, hand calculations and finite element analyses cannot guarantee that the component will meet performance and safety requirements. In order to guarantee the safe operation of the turbine engine the design assurance tests have paramount importance.

This study is based on the sub-system requirements, integration and validation process of the fuel system. Efforts to define the sub-system and interface requirements are discussed. Hand calculations are made to specify component requirements according to the sub-system requirements. Validation process is conceptualized to perform respectively, component, system and engine level tests. Differences in between these tests and the necessity to perform such high number of tests are discussed.

2. BACKGROUND

2.1. Gas Turbine Starting

As any fuel powered engines, the gas turbine engine need initial energy to reach its operating condition. An engine starter is used for cranking the engine to speed where the ignition can be achieved. Different kinds of starters can be used but the objective does not change which is to accelerate the engine to the ignition point. With the ignition, energy in the fuel helps the engine to speed up.

Ignition of the gas turbine engine means achieving continuous flame in the combustion chamber. Unlike internal combustion engines, ignition is not continuous after the starting procedure. After the engine is ignited successfully, the engine should be accelerated to the self-sustaining speed. The self-sustaining speed is important threshold for the engine starting. It is the point where engine generated power becomes sufficient to keep the engine speed steady. If the engine cannot be accelerated to self-sustaining speed, the starting procedure fails. The starting procedure finishes when the engine reaches ground idle condition.

The typical engine starting process are sorted as:

1. The starter cranks the engine to certain speed.
2. Fuel is supplied to the combustion chamber.
3. The engine ignition is performed.
4. Engine acceleration is supported with starter.
5. The starter is disengaged after self-sustaining speed.
6. The engine is accelerated to idle speed with increased fuel flow.

The gas turbine starting phases are indicated in Figure 2.1 [2] with respect to compressor speed, time and turbine inlet temperature.

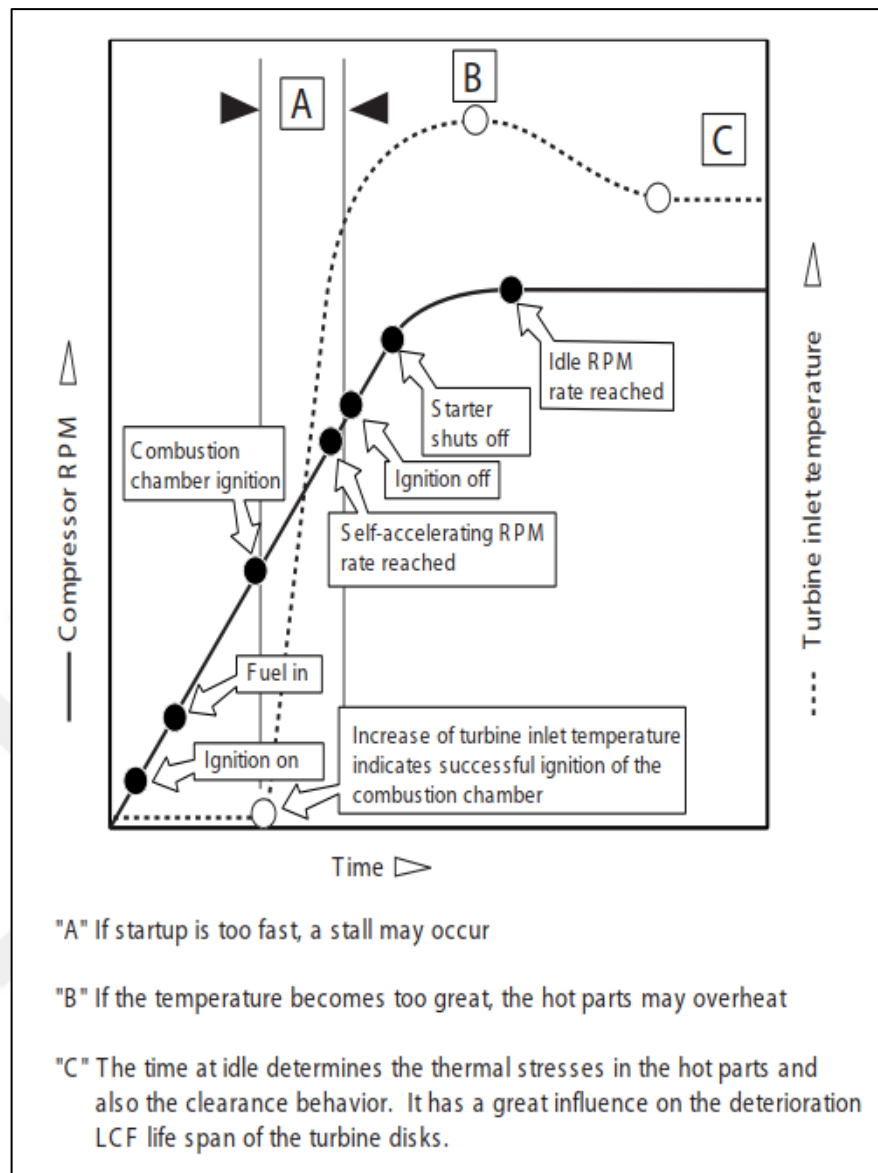


Figure 2.1: Gas Turbine Starting Phases

The procedure is simple on the paper but successful execution is more difficult. Ignition of fuel needs fine fuel droplets, fuel-air ratio in certain range and igniter positioned accordingly. The gas turbine engine speeds up after initial ignition of fuel. Parameters change along speed ranges. Therefore, it is not enough to ignite fuel but also, transient conditions should be tested and ensured.

The gas turbine engines operate with continuous combustion. They do need ignition after first starting unless any flame out occur on the engine. Apart from the ground starting procedure, there are fault scenarios which lead to engine flame out at the air.

In some cases, engine ignition cannot be achieved during starting. These cases are named as false start. There are several reasons can lead to false start. One of the reasons is failed ignition of the combustion chamber.

2.2. Ignition Requirements

The engine should be successfully ignited in wide range of operating conditions. In ground engine tests at the test cell, there may not be faced with an ignition problem but operating envelope of the air vehicle cover many different conditions and the engine should also be ignited in this operating envelope. This includes different harsh conditions in terms of starting such as air start, hot and cold soakback starts.

Air start is the phenomenon which is making ignition in the air when flame in the combustion chamber is blown out. The engine should not be blown out in the air but if so, it can be still started and operated. There are two different ignition scenarios exist in these circumstances. These are re-starting or re-lighting.

Re-lighting is trying to recover the flame with activating igniters while engine speed is above the self-sustaining speed. On the other hand, re-starting is performing the start procedure with help of the engine starter. It is harder to achieve successful ignition with re-starting since the engine speed is lower and the air vehicle is in the high altitudes which means air density comparably lower from ground level.

Soakback starts are divided into two categories. They represents two extreme ends of the starting conditions which are hot and cold soak starts. In these tests, the engine is cooled down or heated up to the point where all metal and liquid temperatures are settled to steady state in a conditioned test cell. In the beginning of the test, the air sucked by the engine is also conditioned to extremes. These conditions simulate cold and hot climate environments. Ignition and engine starting should be successfully performed in these tests.

JSSG document [4] states the ignition requirement as: “The engine shall satisfactorily make ground and air starts, and shall restart under the conditions, limitations, and procedures, specified in this section. The engine shall start with inlet air at any temperature between and including the extreme hot and cold atmospheres”

2.3. Gas Turbine Fuel Systems

The gas turbine fuel systems comprise of different components and sub-components. Various functions should be performed to successfully supply needed fuel to the engine. Fuel filtering, pumping and regulation are some of these functions. The fuel system has fuel filter to protect the system components from contamination and damages caused by the contaminants. Pump elements provide needed fuel pressures to supply fuel to the fuel injectors. Pressurization is essential to fuel supply since there are three pressure loss sources in the fuel system. These are minor losses within the fuel system, the fuel injectors which generate high levels of pressure and air pressure inside the engine. After the fuel is filtered and pressurized, the fuel system should regulate fuel flow. The engine is controlled through fuel flow control. Therefore, fuel flow regulation directly affects the engine operation. The fuel system should be structured accordingly to provide required fuel with parallel to the engine control system fuel demand schedules.

General layout of fuel systems used in the gas turbine engines are indicated at Figure 2.2 [5]. Boost pumps are located at both airframe and engine side. It is a precaution to ensure minimum fuel pressure is above the limits in all operating conditions. If the fuel system pressure drops below the true vapor pressure, cavitation damage and fuel supply interruption can occur in the system. On the other hand, guaranteeing the fuel shut-off is crucial, too. Uncontrolled engine condition or engine fire are more risky than closed engine. Therefore, successfully shutting down the engine has importance. There are shut-off valves in both airframe and engine sides.

The fuel is atomized in the fuel injectors. They are basically small orifices. They create pressure on the fuel system. Additionally, the air pressure inside the engine pushes the fuel backwards on the fuel injectors. The fuel should be pressurized overcome both fuel injectors pressure losses and air pressure of the engine. There are also, system pressure losses inside hydraulic components and tubes. The high pressure pump performs this pressurization.

The metering components control total fuel flow supplied to the engine. Main control of the engine is done through the fuel control. The fuel pump supplies fuel more

than the engine need. Surplus fuel is bypassed at the metering components to inlet of the HP pump. This surplus fuel is used at the acceleration of the engine.

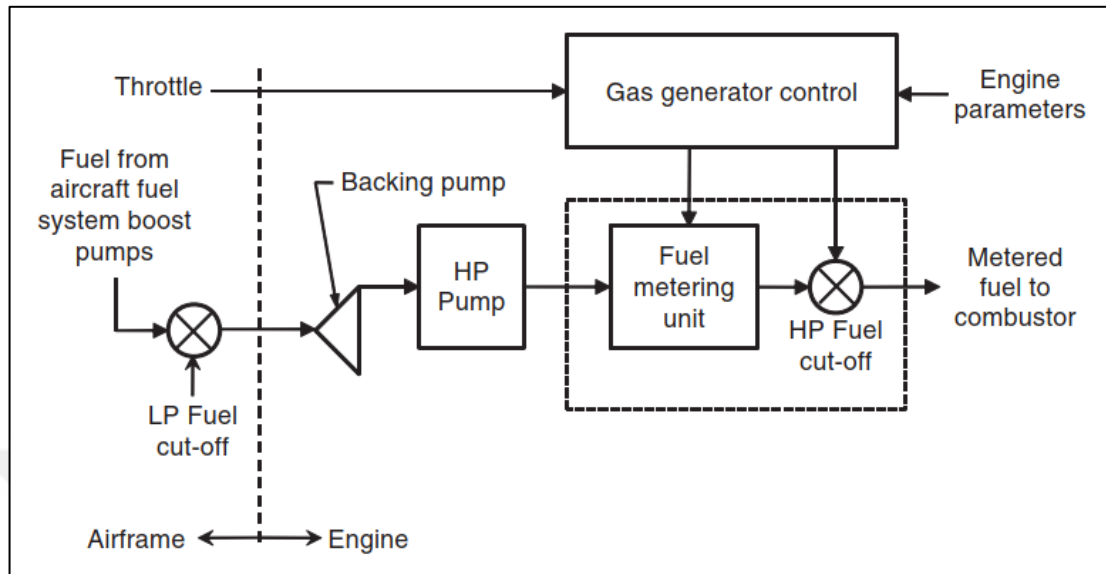


Figure 2.2: General Fuel System Layout of Gas Turbine Engine

The control system and components have evolved over the time [6]. As shown in Figure 2.3 [5], it is tried to integrate electrical control to fuel systems. In first examples, electrical control has limited function on systems and they used with mechanical back-ups. Over the time mechanical control parts are decreased and authority of electrical controls over the engine is increased [7]. In modern engines, Full Authority Digital Engine Control systems (FADEC) are used.

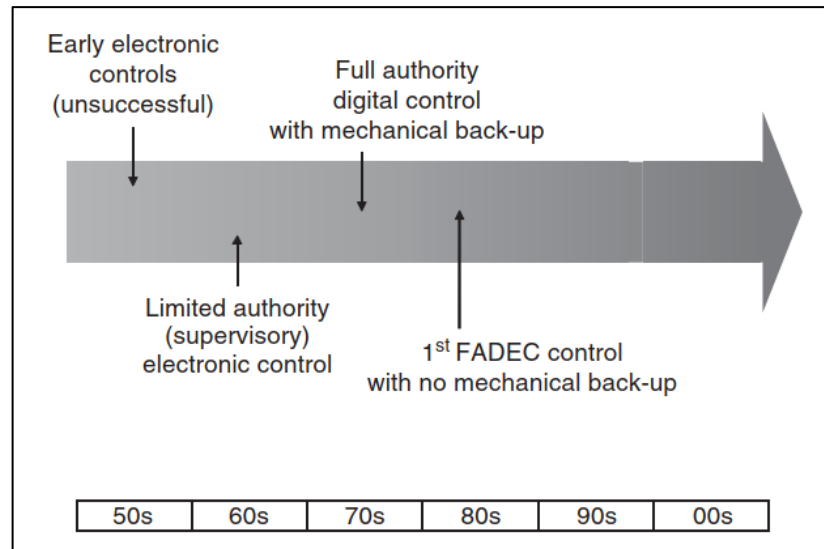


Figure 2.3: Evolution of the Fuel Control Systems

Besides the main functions of the fuel system, there are several other functions and systems can be introduced to the fuel systems such as flow division, oil cooling and variable stator vane control. As a highly pressurized system, the fuel system can be used as a pressure source for other systems. Also, the fuel is supplied from the airframe tank which means that the fuel is comparatively at low temperatures. The fuel can be used as a heat sink in gas turbine engine designs. Through the engine design process these needs are defined. The integrated approach with other engine modules should be performed.

2.4. Means of Compliance Methods

In the design process, validation methods should be assigned for the requirements. The design is step by step process so is validation. There would be undesirable consequences of a failure in the component at engine level tests. Also, testing a component without making analysis can cause a vicious circle of trial and error. Therefore, the validation steps should be carried out accordingly before next level of validation effort begins. This is very important especially in an engine design process where lots of sophisticated components and sub-systems comes together.

There are several different systems engineering handbooks that can be utilized for validation methodology and methods. For air vehicles which will be certificated

base on the requirements of the European Aerospace Certification Agency should demonstrate the means of compliances based on the “Appendix to AMC 21.A.20(b) - Means of Compliance Codes” [8]

There are several levels of compliance methods in the validation rigor. Those levels can be listed in Table 2.1.

Table 2.1: Appendix to AMC 21.A.20(b) - Means of Compliance Codes

Type of Compliance	Means of Compliance	Associated Documents	Compliance
Engineering evaluation	MC0 : - Compliance statement - Reference to Type Design documents - Election of methods, factors - Definitions	- Type Design documents - Recorded statements	
	MC1: Design review	- Descriptions - Drawings	
	MC2: Calculation/ Analysis	- Substantiation reports	
	MC3: Safety assessment	- Safety analysis	
Tests	MC4: Laboratory tests	- Test programmes - Test reports - Test interpretations	
	MC5: Ground tests on related product		
	MC6: Flight tests		
	MC8: Simulation		
Inspection	MC7: Design inspection/ audit	- Inspection or audit reports	
Equipment qualification	MC9: Equipment qualification	Note : Equipment qualification is a process which may include all previous means of compliance.	

It is crucial to decide and agree with the all parties about the means of compliance methods and scope of the efforts. It is common practice to demonstration of the compliance with different methods for such a complex component of the engine.

3. COMBUSTION CHAMBER INTERFACE

3.1. Ignition Configuration

As aerospace authorities requires very high reliability, it is very crucial to guarantee ignition on all operating conditions. Tremendous amount of work should be put on the ignition method design and testing. The tests performed on the ground level are not sufficient to validate the design. The combustion chamber should be tested on the test rigs before the engine tests are not started. In engine level, altitude test facilities which can simulate the conditions on altitude at ground should be used to demonstrate successful ignition at different conditions. Therefore, experience and previous tests are valuable asset for the ignition design.

Ignition configuration has crucial role on the design process of the fuel system since the combustion chamber interface requirements are specified accordingly. There are several different ignition methods for gas turbines. After selection of the method, the parameters can be put on the table for the fuel system design.

3.1.1. Pyrotechnic

In the combustion chamber, fuel-air mixture may not be in needed range at every location. Therefore, low energy release at wrong location is sometimes not enough to successful ignition. Wrong placement of the igniters can lead to false starts. Pyrotechnic materials are high energy density compositions that can release higher energy in very short amount of time. This means the energy is spread to the combustion chamber. Ignition can be made at the spot where the right fuel-air ratio is exist. Therefore, the false ignition risk is minimized. This makes pyrotechnic ignition perfect choice for the situation where the ignition must be guaranteed [3].

It is common practice to use pyrotechnic ignition at the engines which are designed to use at missiles. As they need to be ignited only once and the ignition should be guaranteed at every operating conditions, the pyrotechnic ignition is well-suited method. Additionally, it does not require heavy exciter units to energize the igniters. It is cost effective and light-weight method to ignite the gas turbine engines.

The fuel injectors of the missiles are designed to be capable of supplying fuel at high flows that is needed for the maximum power. Generally, there is no extra feature used for the engine starting because it comes with a cost and weight. The fuel systems used with the pyrotechnic ignitions are adjusted to supply high fuel flows at the engine starting because the fuel injectors are designed for high fuel flows and their atomization capability at the low fuel flows are poor. In addition to starting with high fuel flow, the fuel system also designed for rapid increase after the ignition because the engine can be blown out after the ignition and additional ignition chance does not exist. Therefore, it is needed to speed up to idle condition fast to minimize the risk of blown out at the transient operating conditions.

The disadvantage of the pyrotechnic ignition is that it does not meet relight requirement. The pyrotechnic igniters are single-use components. This means that relight cannot be performed with the pyrotechnic ignition. In addition to that, single-use nature of the system cannot meet maintainability and cost requirements.

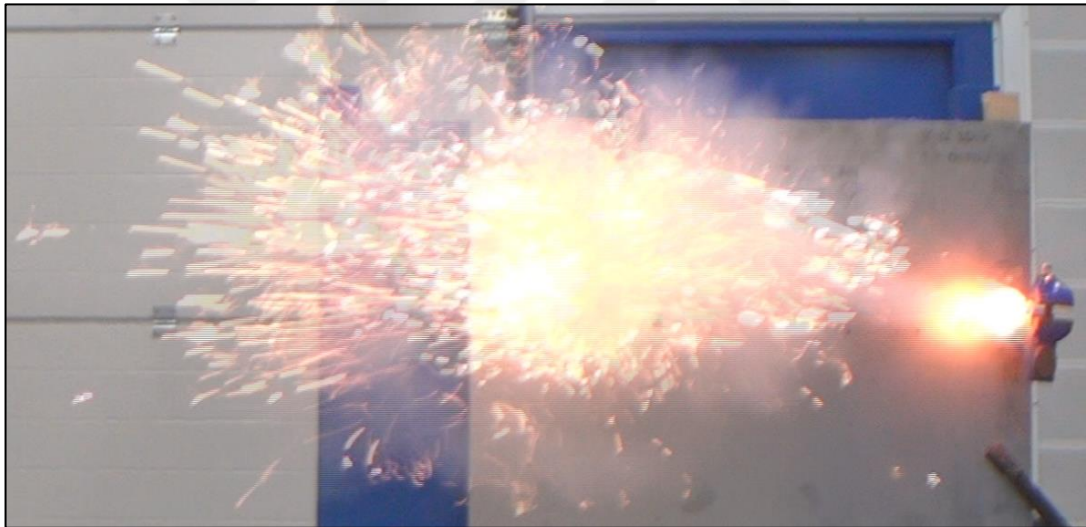


Figure 3.1: Pyrotechnic Ignition Test

3.1.2. Duplex/Piloted Fuel Injector

As the name suggests, duplex fuel injectors are integration of two injectors together. They have two separate fuel lines feeding two separate fuel nozzles integrated together as illustrated in Figure 3.2 [3]. The fuel injectors work with two different modes. First, a pilot stage of the injector opens up. Second stage opens with the fuel flow increase

and passing a certain threshold. As shown in Figure 3.3, the injector can atomize fuel to very fine particles at both low and high fuel flows. This two stage fuel injection enables to better control ignition of the engine since the pilot stage can produce good atomization at the low fuel flows. For higher fuel flows, second stage step in and can deliver high flows. Hence, the ignition performance is not reduced while still required high flows are ensured.

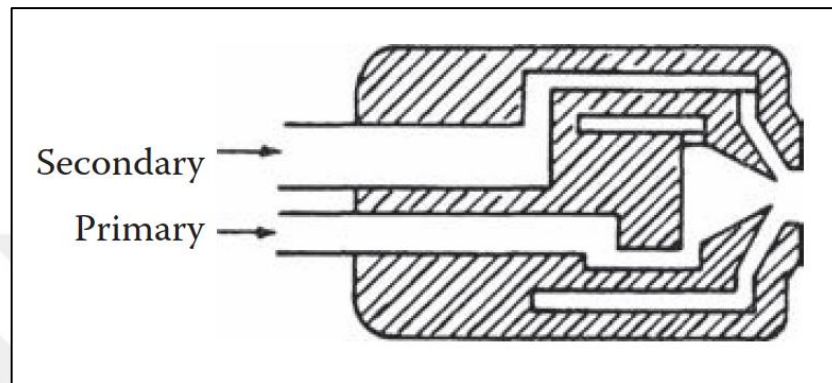


Figure 3.2: Simplified Cross Section of the Duplex Fuel Injector

The duplex fuel injectors are relatively new technology. Complexity of the duplex fuel injector is higher than the simplex fuel injectors which do not have two stage injection. Even the simplex fuel injectors are complex and costly parts since they are manufactured with micro machining with very tight tolerances. Combining two injection structure to single unit is tough process. On the other hand, most modern gas turbine engines use duplex fuel injectors not only for ignition but also for lean burning the fuel. The duplex fuel injectors give possibility to supply low levels of fuel in the operation without risking the engine to blown out.

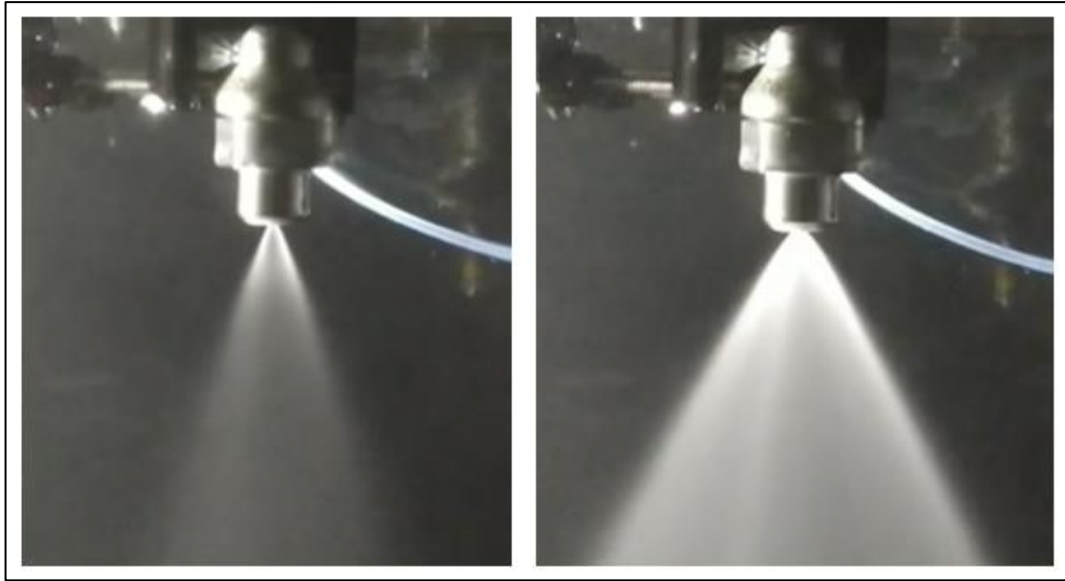


Figure 3.3: Duplex Fuel Injector Tests

The turboshaft engines generally use simplex fuel injectors. One of the reasons behind is that there was no technology available on the times first the engines were designed. There are few turboshaft engines that were designed in the recent time. The other reason is to keep the cost low by using simplex fuel injectors. In addition to manufacturing costs, the duplex fuel injectors are expensive in terms of designing and validation.

3.1.3. Torch Ignition

Some gas turbine engines have separate fuel injectors just to make ignition of the engine. Those are called pilot fuel injectors. This method is used to decrease the chance to not providing the ignition. The pilot fuel injectors and igniters are designed and located accordingly to form a torch flame. This torch flame has dramatically higher energy than the solely igniters provide. Therefore, the main ignition is made with torch flame rather than the spark. In terms of combustion chamber design, using the torch igniter is more practical way since it gives capability to design main fuel injectors optimized for the operating conditions and pilot fuel injectors optimized for the ignition.

The pilot fuel injectors must be switched off after the engine ignition is achieved because they create hot spots at the combustion chamber exit profile. Consequently,

they can damage nozzle guide vanes with overheating the ones facing these hot spots. Also, turbine blades can be damaged because of the thermal stresses caused by hot spots. Therefore, control of the pilot fuel lines are essential.

In terms of the fuel system design, the torch ignition comes with a work load. The fuel system complexity increases because the pilot fuel injectors should be supplied from different fuel line and the fuel flow should be divided into two as main and pilot fuel lines. The division is not simple as it sounds since the pressures that the lines create are different. Therefore, the fuel pressures allocated for the main and pilot fuel lines should be adjusted. This is done with separate valves. The additional valve assembly and fuel lines causes total weight increase. Additionally, the total number of fluid connections increases which also increases the fuel leakage risk. The control system also get affected by this since additional valves means additional interface for the control system.

This method is frequently used in the turboshaft engines. One of the reasons is that this was a common method in the sector when the most of the turboshaft engines are designed. Secondly, it give flexibility in the design phase since the main and pilot fuel injectors can be designed and tested separately. In this way, less risk is taken since the injectors can be optimized better for their purposes.

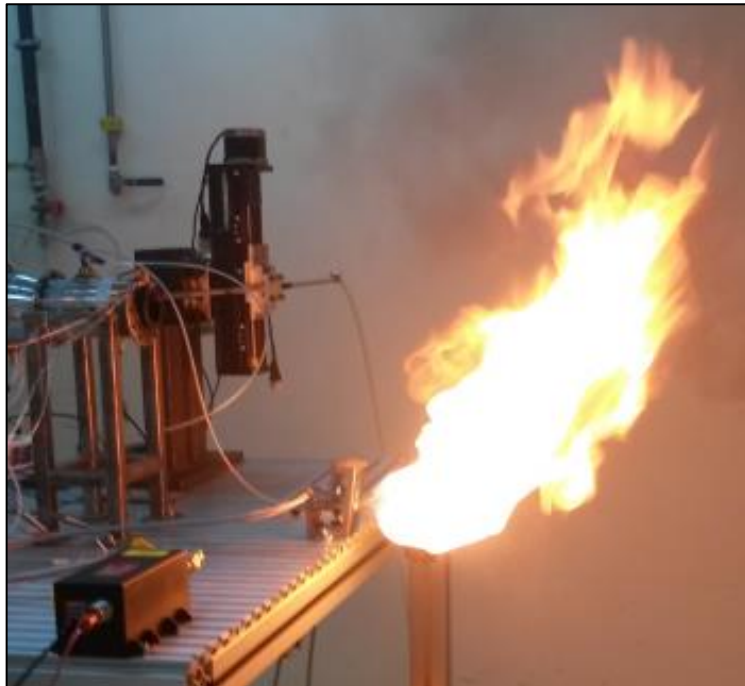


Figure 3.4: Torch Ignition Test

3.2. Implementation

The ignition configuration choice and its implementation are important step for both the combustion chamber and fuel system designs. The first option is using pyrotechnics for the ignition. It seems good option in terms of ignition performance, weight and simplicity but it cannot meet relight, maintainability and cost requirements. Therefore, it is not an option for the turboshaft engines.

The duplex fuel injector and torch ignition both have pros and cons. The duplex fuel injector is better for fuel system design since it eliminates the valve assembly to make the pilot fuel injectors work. On the other hand, the torch ignition is better for the combustion chamber design since it is simpler structure, easier to design and manufacture.

The ignition is broad subject, it requires experience, test and field data. As a new player in the gas turbine engine market, the data unfortunately unavailable. The ignition problem can be vital depending on the design phase of the development project because an ignition problem may found at very later in the project. This pose a risk to the development project. Because of that reason, duplex fuel injectors are not chosen. It is harder to optimize the design and make a design change in the later phases of the project. Even though the duplex fuel injectors are state of the art, it is safer choice to introduce such a technology after a field experience is accumulated.

The T700 engine family is a good example to follow because the initial engine configuration T700-700 is used torch ignition method. The flow diagram of the T700-700 illustrated at Figure 3.5 [9].

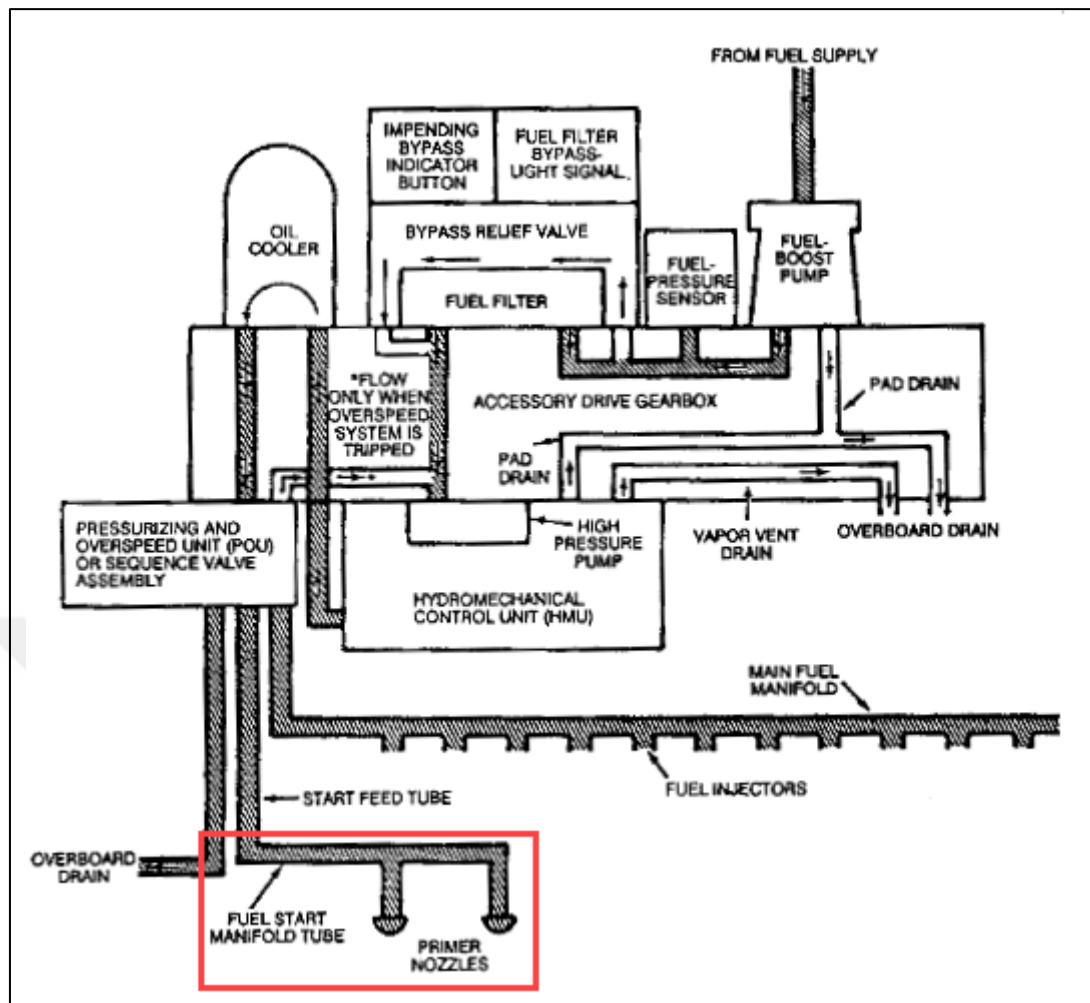


Figure 3.5: T700-700 Engine Fuel System Flow Diagram

The field experience accumulated with this initial configuration. Eventually, the pilot fuel injectors and fuel lines are removed with the later configurations of the engine family. The flow diagram of the T700-701 illustrated at Figure 3.6 [9]. Also, it was not needed to switch the fuel injectors with duplex fuel injectors. It is understood that satisfactory ignition performance could be obtained with simplex fuel injectors.

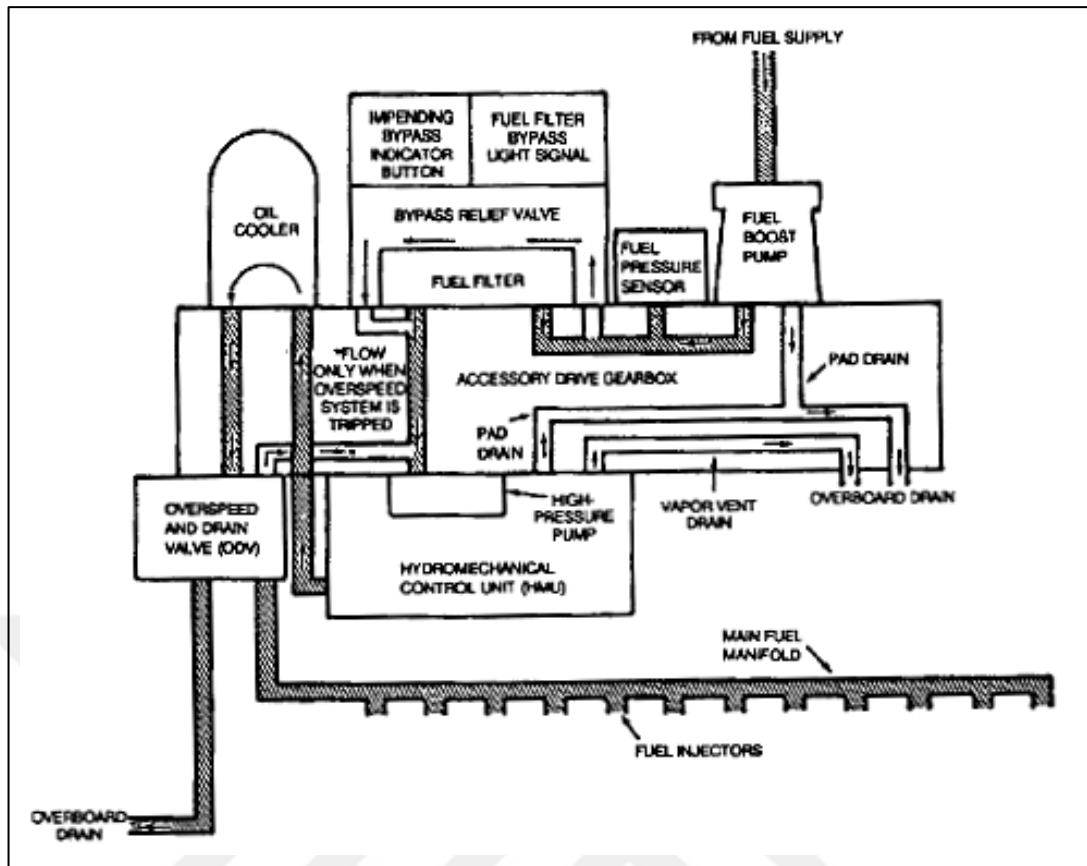


Figure 3.6: T700-701 Engine Fuel System Flow Diagram

The torch ignition method offers broader range of design choices. In addition to that, there are numerous parameters can be adjusted independently without making major design changes by using torch ignition method. Fuel schedules, cone angles, injector and igniter positioning can be adjusted later on the project to optimize ignition performance. There may be a need to make design changes with design assurance test outcomes as the engine development project is clean sheet design and the combustion chamber of the engine is un-proven previously. Consequently, the torch ignition method is chosen for the engine ignition because it offers risk mitigation in the design and test phases. The general assembly of the torch ignition is indicated in Figure 3.7.

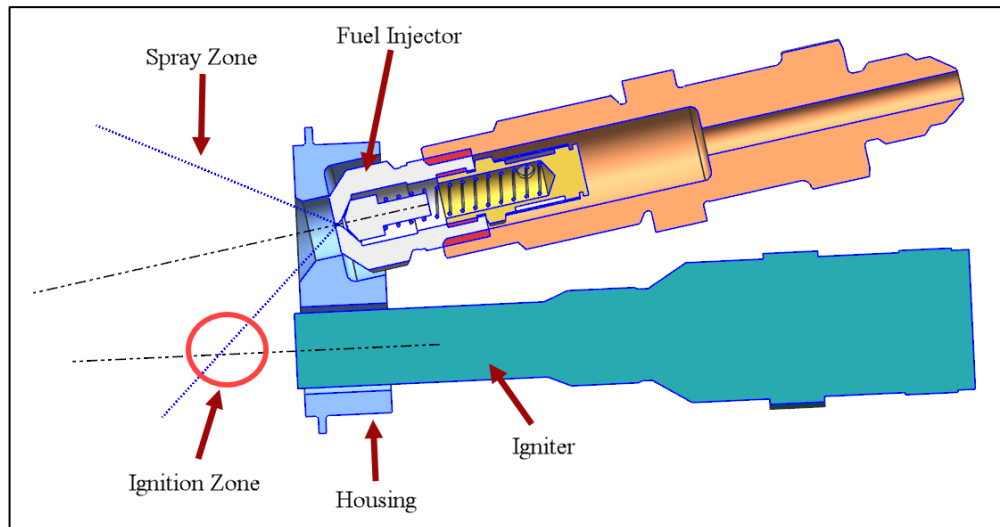


Figure 3.7: The Torch Ignition Assembly

3.3. Purge/Cooling Air

The temperatures inside the combustion chamber can easily damage the pilot fuel injectors. The tip of the injectors should get into the flame tube of the combustion chamber to ignite main fuel injectors but this location comes with its drawback. The pilot fuel injectors are directly exposed to the flame inside the flame tube. Also, the pilot fuel injectors are prone to damage since they have very tight tolerance manufacturing process. Any change in the geometries can cause spoiling the spray quality of the pilot fuel injectors. The cooling air should be supplied to the pilot fuel injectors to prevent damage.

The combustion chamber is placed behind the compressor in the flow path of the engine. Therefore, the pressure inside the combustion chamber is high. To supply cooling air to the pilot fuel injectors, it is needed to take the air from a point which has higher pressure than the combustion chamber. In the engine, this level of pressure only exist at the exit of the compressor. A tube is placed to the compressor exit to take this air to supply the pilot fuel injectors. The tube is connected to the flow divider assembly. The assembly supply the air when the pilot fuel injectors are not supplied with fuel.

After certain speed the pilot fuel injectors are switched off. The pilot fuel injectors and supply tubes remain full with fuel after the ignition process. Thus, the remained fuel drips with the help of the gravity over the time. This process can causes

coking on the tip of the pilot fuel injectors since the pilot fuel injectors get heated up as they face inside of the combustion chamber. The coking is the process which the fuel burns and carbon deposits form on the metal surface. To prevent coking, the pilot fuel lines should be cleared from the fuel after the ignition [3]. The cooling air is also used for this process. The process is called purging the pilot fuel injectors. The pressurized air pushes the remaining fuel inside the lines relatively faster. Therefore, the fuel does not burn on the tip of the fuel injector.

There is little air pressure difference exist between the inlet of the purge air and the pilot fuel injector tip. The flow calculations should be made to ensure the required air flow is provided. If enough air cannot be supplied to the injectors, the fuel can clog the fuel injectors rapidly. A clogged fuel injector is indicated in Figure 3.8.



Figure 3.8: Used Pilot Fuel Injectors – Unclogged / Clogged

The fuel system should perform the purging of the pilot fuel lines. The control of the purge air should be established properly. There are several valve arrangements suitable for this process. Moreover, the transient operation should be carefully controlled because the fuel and air lines may leak to each other. Over the time, fuel deposits can clog the lines and injectors.

4. FUEL SYSTEM DESIGN

The fuel system design begins with specifying the sub-system requirements. These requirements originated from interfaces, system and functional requirements. The main function and requirement of the fuel system is to supply of the fuel to the engine. JSSG document states the fuel system requirement as: “Fuel system calibration should be conducted to insure the engine fuel system is supplying the required amount of fuel at the required pressures for operation throughout the environmental conditions and operating envelope of the engine. This includes both starting and augmentation operation.” [4].

There are several different topics of the requirements such as maintainability, fuel contamination, fuel pump inlet conditions and vibration loads but these requirements are not investigated in this study to not drift away from the main subject which is functional integration of the fuel flow divider and investigation of the transient performance.

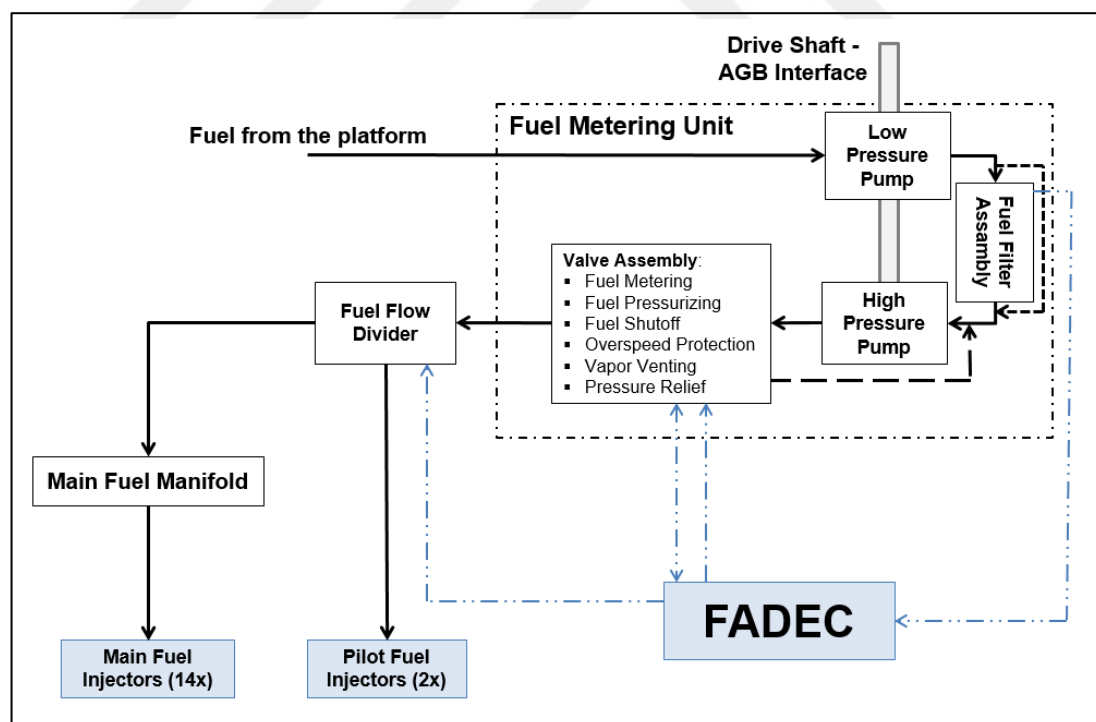


Figure 4.1. Fuel System Flow Diagram

The fuel system basically should provide filtering, pressurization and metering of the fuel to comply with the fuel supply requirements. The fuel filter, metering assembly, low and high pressure pumps are essential components of the fuel system. The main functions are carried out by these components. In addition to that, other components can be added to the fuel system according to the configurations of the combustion chamber and engine. For instance, complex valve assemblies can be added to use the hydraulic pressure of the fuel system.

Turboshaft engines are comparably small sized gas turbine engines. Engine envelopes are limited and there are not many available locations that external components can be mounted. Additionally, the accessory gearbox design space is constrained and the available drive pads are limited. Therefore, it is crucial to keep the components and subsystems compact. It is considered an effective way to pack these components into a single unit. Packaging of the components as much as possible brings advantages such as there is no need for tubing to connect the components, the low and high pressure pumps are driven from the same AGB pad. By doing so, one housing is reduced from the design and consequently the total weight and envelope are decreased.

The fuel metering unit is the first component placed in the fuel system flow diagram. It provides the fuel supply of the engine. The unit has a needed valve structure to meter the fuel according to the signals coming from FADEC. The unit has built-in pressure compensation which means it can deliver needed fuel flow independent from the engine pressure changes.

In the fuel system, it is decided to use a fuel metering unit used at the same horsepower class turboshaft engine. It is intended to cut development cost down and take no further risk of developing a new unit. On the other hand, combustion chamber configuration is different at the engine where the unit is used. Therefore, it is needed to make a different fuel system design from the benchmark engine to be able to use the same fuel metering unit.

The chosen ignition configuration dictates to supply two different fuel lines which route the fuel to the main and pilot fuel injectors. The metered fuel should be divided between these lines.

The flow numbers for the main and pilot fuel injectors are set 3.6 and 1.3 respectively by combustion chamber design. The fuel injectors are the main pressure loss source in the system. The fuel pressure needed for the system depends closely on the

fuel passing through a single injector. Therefore, the number of the fuel injectors in the system is a parameter in the fuel system design. Increasing the fuel injector number that is connected to the same line decreases the fuel pressure for same amount of total fuel flow. The main and pilot fuel injectors' numbers are 14 and 2 respectively. The fuel injector number varies between the systems since the pressure balance can be adjusted with injector numbers. For example, 12 and 4 combination is used in some engines. [10]

$$FN = \frac{\dot{m}_L}{\sqrt{\Delta P_L}} \quad (4.1)$$

In this thesis study, the units are deleted and the values are normalized because of the company confidentiality policies. The pressures of the lines according to the fuel flow in each line are plotted in Figure 4.2 and Figure 4.3. The characteristic of the main and pilot fuel lines are differ dramatically. For example, fuel pressure of 10 can cause fuel flow of 45 on the main fuel line while it is only 2.4 for the pilot fuel line.

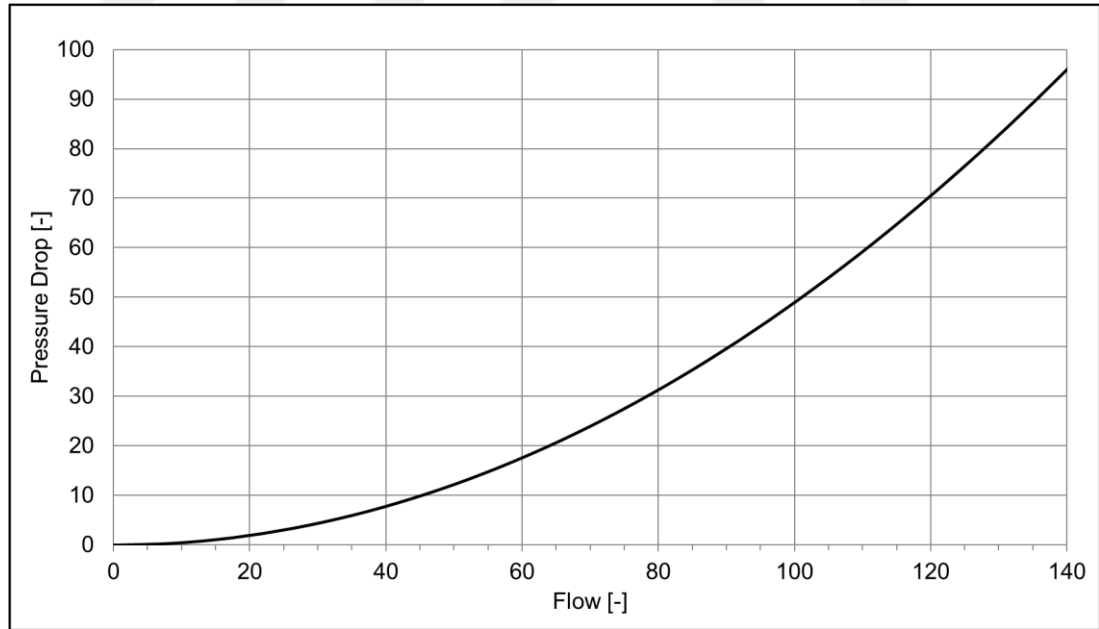


Figure 4.2: Main Fuel Line Flow vs. Pressure Drop



Figure 4.3: Pilot Fuel Line Flow vs. Pressure Drop

The needed fuel supply modes are indicated below:

- Starting Mode: pilot fuel line active / main fuel line close

In this mode, the fuel is only supplied to pilot fuel injectors. The ignition of the atomized fuel injected by the pilot fuel injectors are made.

- Transition Mode: pilot fuel line active / main fuel line active

In this mode, the main fuel line is opened and both the pilot and main fuel lines become active. The fuel flow to the pilot line should be preserved. It should not get effected from opening of the main fuel line.

In relight situation, the starting mode is skipped. The relight is made on the transition mode.

- Normal Operating Mode: pilot fuel line closed / main fuel line active.

When healthy ignition of the engine ensured, the engine speed is increased to the self-sustaining speed. After the engine speed reach the self-sustaining speed, the pilot fuel line is closed.

The starting fuel flow requirements drive the fuel pressure requirements of the engine. The pressure balance and ignition flow rates required for the fuel injectors are crucial at the fuel flow divider design. During the starting procedure needed fuel flows are at 3 - 4.5 at the pilot fuel line and 12.0 -18.0 at the main fuel line. When both lines

are active the required fuel flows for the both lines should be supplied by the fuel flow divider. The calculated pressures in the fuel lines are indicated in Table 4.1. Fuel pressures needed for the lines are different. Therefore, they cannot be supplied with the fuel from the same line. Because of that reason, splitting the fuel outlet of the fuel metering unit is not an option.

Table 4.1: Fuel Line Parameters on Starting

	Fuel Flow [-]	Gage Pressure [-]
Pilot Fuel Line	3.5	22.5
Main Fuel Line	15.0	1.1

One of the main design requirements of the combustion chamber design is air temperature profile of the outlet stream. Hot or cold spots in the air stream poses a risk to damage turbine parts. The hot spots can cause melting or early creep failure of the nozzle guide vanes in the turbine module. Also, the turbine blades are exposed to cycling thermal loads. In every revolution, the blades are heated up on the location where the combustion chamber induced hot spot exist. This phenomena causes fatigue load on the blades. When pilot and main fuel injectors are active, the extra fuel supplied by the pilot fuel injectors create two hot spots on the combustion chamber. In light of these reasons, the pilot fuel line should be controllable. It should be closed when the successful ignition is achieved and the engine is speeded up.

4.1. Placement of Unit

One of the main design aspects of the fuel flow divider is unit integration to the turboshaft engine. There are several design concerns and requirements that should be considered. Two different philosophy can be followed. Those are integrating the unit to the FMU and making a separate unit. This is one of the biggest trade-off in the fuel system design since it affects not only the design process but also the certification, system performance and maintenance.

Table 4.2: FFD Placement Trade-Off

	Single Integrated Unit	Separate Two Units
Fire Protection	*	
Filling Times and Engine Response		*
Weight and Envelope	*	
Design Flexibility		*
Development Cost		*

4.1.1. Fire Protection

In the fuel system design, one of the toughest design requirements is fire protection. The CS-E 130(b) Fire Protection [11] requires

“Except as required by CS-E 130(c), each external line, fitting and other component which contains or conveys flammable fluid during normal Engine operation must be at least Fire Resistant. Components must be shielded or located to safeguard against the ignition of leaking flammable fluid.”

As CS-E requires the fuel system components should be fire resistant which means the units should be tested for 5 minutes of fire. The casing, fluid connections and valves are the points where the attention should be placed. The fire test is required to comply with the fire safety requirements. The unit cannot be used after the fire test. The test requires special kerosene burner and calibration setup [12]. Because of that reasons it is expensive to perform fire test. The burner and the setup is indicated in Figure 4.4 [13].



Figure 4.4: Fire Test Burner and Setup

Making integrated unit is beneficial in terms of fire safety because it reduces number of casings and fluid connections. On the other hand, making separate unit creates necessity to make two tests. Also, it is harder in terms of the unit design because making integrated unit gives opportunity to put the vulnerable parts to deeper inside. In the engine design process, fluid connections should be minimized. More the fluid connections are more the sensitive areas to both leakage and fire hazard.

4.1.2. Filling Times and Engine Response

The response time of the engine changes with the tube sizes and lengths. The response times increases with making the tubes longer between combustion chamber and fuel control valves. The fuel lines are empty at the engine starting. There are filling times of these lines while the engine starting process. Additionally, there is an engine starting time limit. Therefore, fuel line filling times takes a part of this time budget.

It is better to place the valves closer to the combustion chamber. The location of the fuel flow divider can be adjusted according to the fill time requirement if it is decided to make the unit separate from the FMU. It is a big advantage in terms of filling time of the fuel lines and reaction time of the engine. On the other hand, the

FMU drive pad is located on the front side of the accessory gearbox. If the FFD is integrated to the FMU the tube length between FFD and combustion chamber will be longer.

4.1.3. Weight and Envelope

The weight budget and the design envelopes are limited especially for the turboshaft engines as they are smaller. Therefore, slight weight and envelope reductions are crucial. The total weight and envelope can be reduced by integrating the valves to the fuel metering unit and making compact design as much as possible. A single housing for both units offer decrease in weight and total envelope.

Although the total envelope and weight are lower, placing a higher weight and bigger envelope to a single place is a design challenge. The control of the weight distribution on the engine and allocation of the available space to the components can be done more easily with separate unit. It is harder to integrate single bigger unit to the engine than separate smaller units.

4.1.4. Design Flexibility

The FMU is highly complex unit comprise of housing, pumps, filter and valves. Integrating new valves will increase the complexity of the structure which is already highly complex. A casting geometry is used for the mounting of the control valves in the FMU. Modifying the casting geometry need effort and the existing documentation should be renewed. Therefore, implementing single unit design with integrated FFD requires significant effort. This effort should be payed again if any design changes needed in or after the development project.

Possible design modification may be needed with the feedbacks coming from the test activities. Taking into consideration that the development project is first of its kind for the company, there is no risk mitigating experience available for the project. It is highly likely that need for design modification will emerge during the project.

It is expected that integrated design takes more than two years to design, test and validate. According to the size of the design change, the whole design cycle can be

performed or shorter update can be implemented. On the other hand, it is expected that new separate FFD design cycle takes 8-12 months. Therefore, choosing two separate units design allows more design flexibility and faster modification implementation.

4.1.5. Development Cost

Using the FMU which is used in the certified engine has a huge benefit in terms of the development cost. The interfaces and the environments are different in two engines but many of the test requirements can be met with similarity report. Also, the development cycles, manufacturing drawings and quality control procedures are settled for the FMU. This brings benefit to the project. On the other hand, making modifications on the unit may not affect the design of the FMU much but still it comes with a work load. Addition of the FFD unit to the fuel system only changes the outlet interface of the FMU. The fuel pressure rates and the schedules are main difference but they can be tested and calibrated in the FADEC software. It is estimated that making modification on the FMU is four times costly.

4.2. Fuel Flow Division Alternatives

The intended function can be provided with different valve and control configurations. It is dependent on the design requirements and control system interface. The system should supply the needed flows and purge air. The pressure difference across the purge air and pilot fuel injectors is small. There should be as small as possible restrictions exist on the system. On the other hand, the purge air has very high temperatures up to 500 °C. The temperature can cause damage on the elastomeric seals and solenoid valve. Therefore, a valve can be introduced to prevent damaging of these parts. There are three possible configurations that can work as intended functions but they differ from each other in terms of performance.

The pressures needed for the main and pilot fuel lines do not allow both injectors work simultaneously at the starting since the pilot fuel line require higher pressures. This pressure difference should be balanced to simultaneous operation, in other words, ignition of the main fuel injectors by the pilot fuel injectors.

4.2.1. Mechanical Sequential System

The turboshaft engines that are designed before 1990's have mechanical control systems. Early turboshaft engines are controlled fully mechanical systems. The introduction of the electrical control is started with the technological advancements. In early days, electrical control systems are introduced with mechanical back-up systems. It is a tradeoff to use mechanical or electrical system to divide fuel flow. [7]

Mechanical systems can provide good reliability in case of an electrical failure. The wiring harness or FADEC fault can cause false activation of the valve and consequently hot spots on the engine because of the pilot fuel injectors. On the other hand, cost and complexity of the systems is high. An example of the mechanically controlled flow divider is given in Figure 4.5 [14].

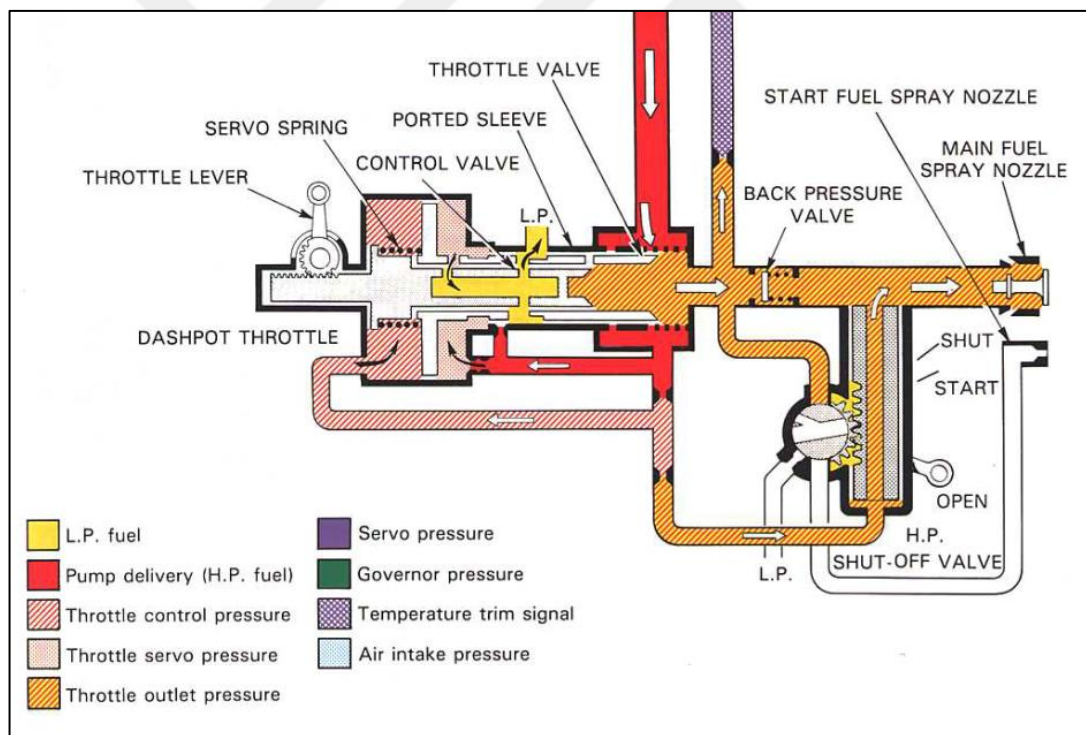


Figure 4.5: Mechanical Flow Division

4.2.2. 2-Way Solenoid and Check Valve

Two way solenoid valve is one of the basic elements used in flow control systems. They have two positions which are on and off. Either the solenoid valve can be open or close in non-energized position. It is called as “normally open or normally closed”. If the used solenoid is normally closed configuration the valve do not let the flow go through at the non-energized condition. The solenoid creates magnetic field with the energizing. The magnetic field pushes the plunger and the valve opens up. The basic working principle of a two way solenoid valve is indicated Figure 4.6 [15].

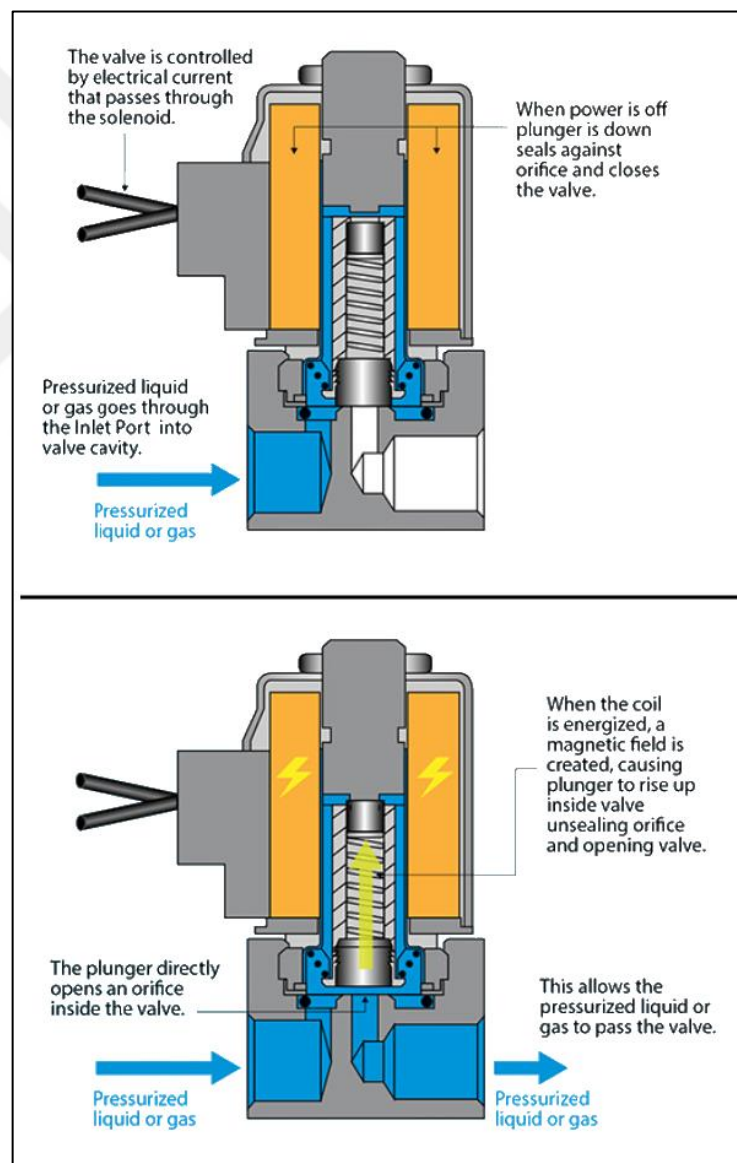


Figure 4.6: 2-Way Solenoid Valve Working Principle

In this configuration, the solenoid can only control the fuel side. Therefore, the purge air line should be controlled with another component. A check valve is good option for the control because it does not need electrical governance. Therefore, the risk of electrical fault is reduced. The check valve normally allows the air pass through. This provides purge air. When the fuel is supplied to the pilot fuel line, the fuel pressure forces the valve to close position. This prevents the fuel leakage to the compressor air.

Two of the basic valve types are used in this configurations. The 2-way solenoid and the check valve have simple structures but using two valve instead of one valve makes the system more complicated because the valves may not operate as intended when they are put together. For instance, the passage between the solenoid and check valve cannot be purged and the coking of the remaining fuel can occur in this area.

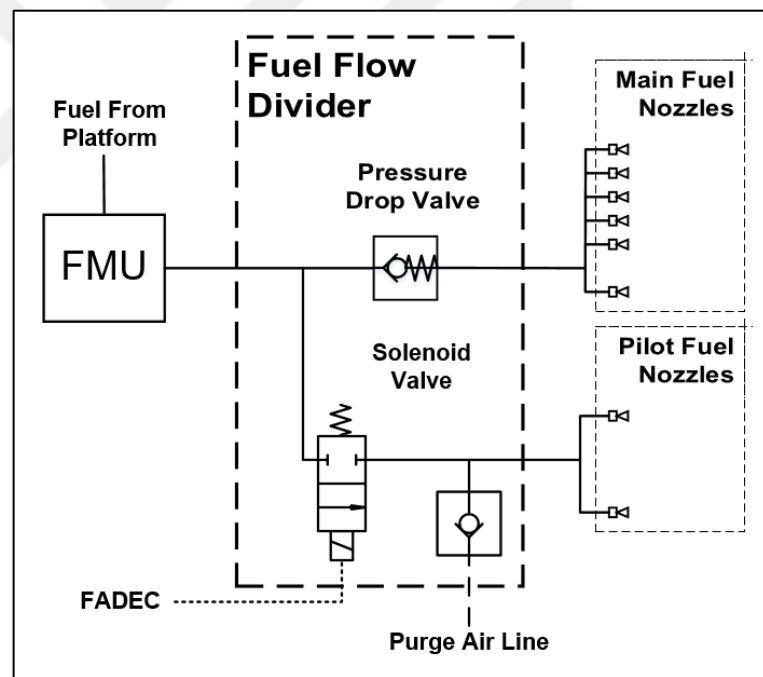


Figure 4.7: FFD Configuration with 2-Way Solenoid and Check Valve

4.2.3. 3-Way Solenoid

3-Way solenoid valves are commonly used to direct fuel between lines. They offer compactness for unit designs. The basic schematic is given in Figure 4.8. Three way

solenoids have one preference direction as incorporated spring anchors the position of the valve. The fuel supply line to the solenoid is normally closed. When the solenoid energized the fuel supply line and pilot line connected. In de-energized position purge air and pilot fuel lines are connected. [16]

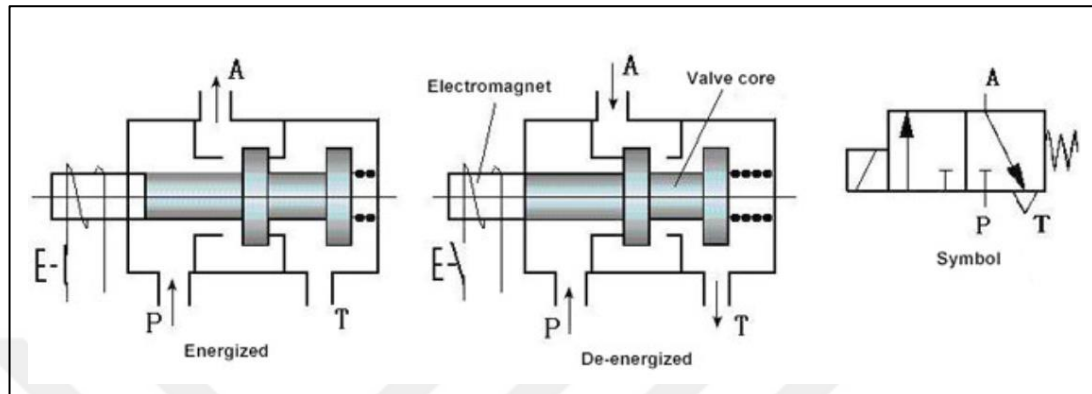


Figure 4.8: 3-Way Solenoid Valve Representation

The 3-way solenoid valve structure are more complex than 2-way solenoid valve but the overall system layout is simpler with one less valve structure. Additionally, the complexity further decrease with less mounting interfaces and internal passages by eliminating a valve from the unit. In terms weight and envelope, the valve is bigger and heavier than 2-way solenoid but overall weight and envelope considerably smaller especially because of the simpler and smaller unit body.

The main disadvantage of the 3-way solenoid valve configuration is the hot air that is passing through the solenoid valve. In the 2-way configuration the hot air can be isolated from the solenoid which is prone to the high temperatures. The effect of the hot air passing through the valve is expected to be small because the air flow rate is small and the valve is cooled with the fuel that is flowing to the main fuel line.

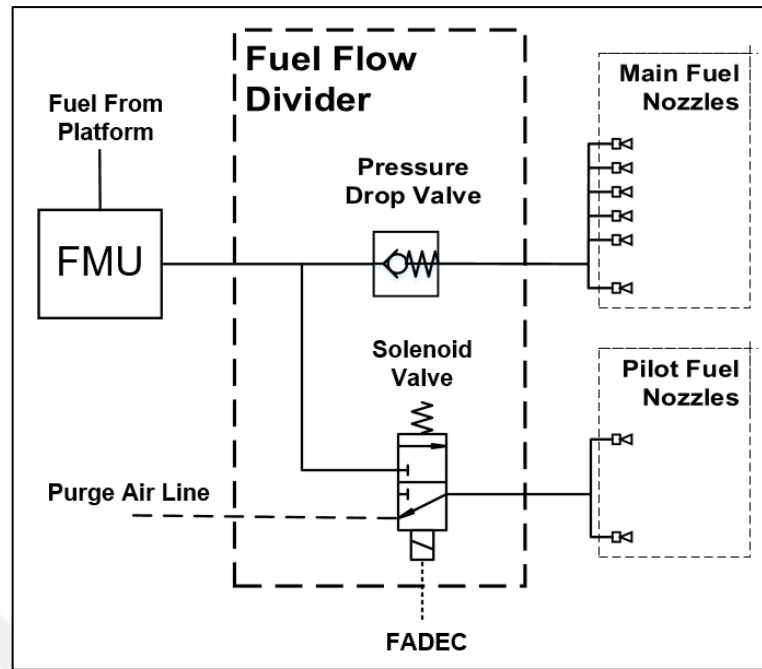


Figure 4.9: FFD Configuration with 3-Way Solenoid Valve

4.3. Implementation and Flow Network

The 3-way solenoid valve configuration is selected for the FFD design as it offers fewer parts, less complex system layout and weight advantage. A flow network analysis model is prepared for the system design. It is necessary to use an analysis model because the design iterations needed to be done for the valve selection, unit design and validation of the concept.

The fuel injectors are main restrictions in the fuel system that create back pressure in the system. There are several different hydraulic components in the fuel system in addition to the fuel injectors. Other fluid-carrying components also generate pressure drop in the system. It is crucial to analyze the pressure drops in the lines because they can affect the fuel flow distribution between the lines. The FFD controls the pressure distribution between the lines and injectors. The pressure sources on the lines should be considered when designing and setting the FFD.

The flow analysis forms the basis for the validation activities in addition to the design process. The fuel and air flow calculations are under the demonstration of MOC 2. The MOC 4 and 5 efforts are made with comparing the test results and analysis.

Therefore, the analysis results are important as the test results. Additionally, bringing out a problem in the analysis phase provide huge benefit in terms of cost and time.

The Simcenter Flomaster program is used for network modeling of the fuel system. It enables quick design iterations in the system. The tubing, components and fuel injectors are modelled in the program. The fuel flow rates and the pressures are read on the inlet and the outlet of the components. The pressure losses in the system analyzed and their effect to the fuel distribution in the system is investigated.

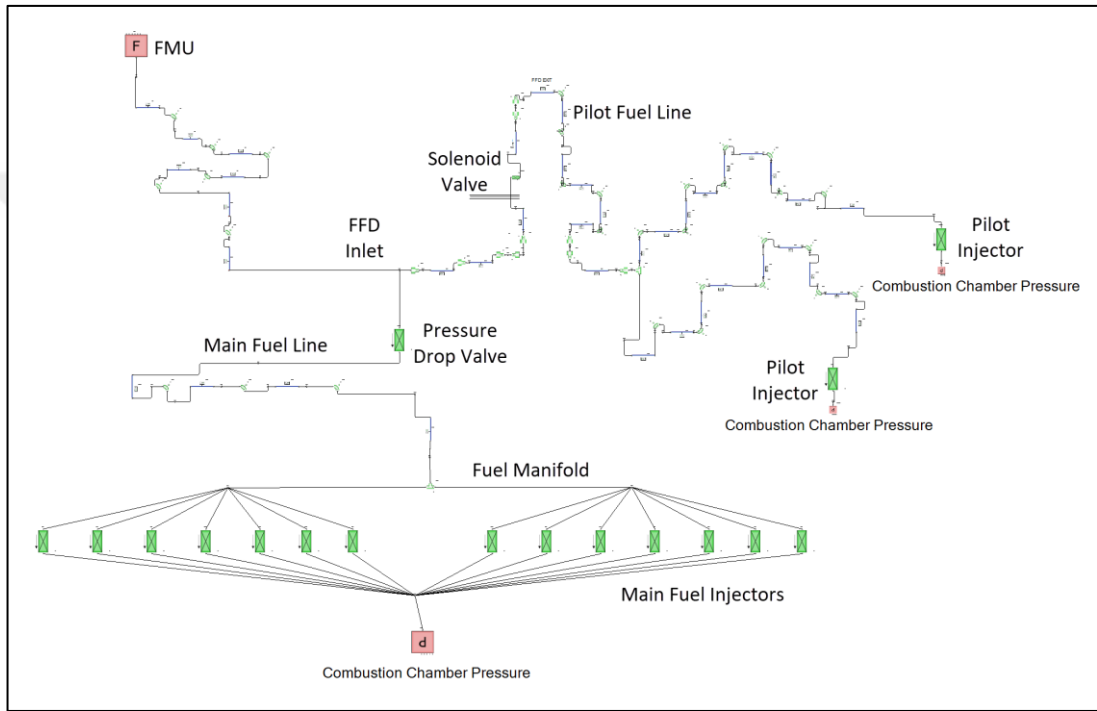


Figure 4.10: Flomaster Flow Analysis Model

The tube and line losses are calculated with taking into account of friction and minor losses. The friction losses are calculated with using Darcy's Equation as recommended in "AIR1657A - Handbook of Hydraulic Metric Calculations" [17] and "ARP24E - Determination of Hydraulic Pressure Drop" [18]:

$$\Delta P = \frac{f \left(\frac{L}{D} \right) \rho v^2}{2} \quad (4.2)$$

The density of the fuels are taken from Figure 4.11 [19].

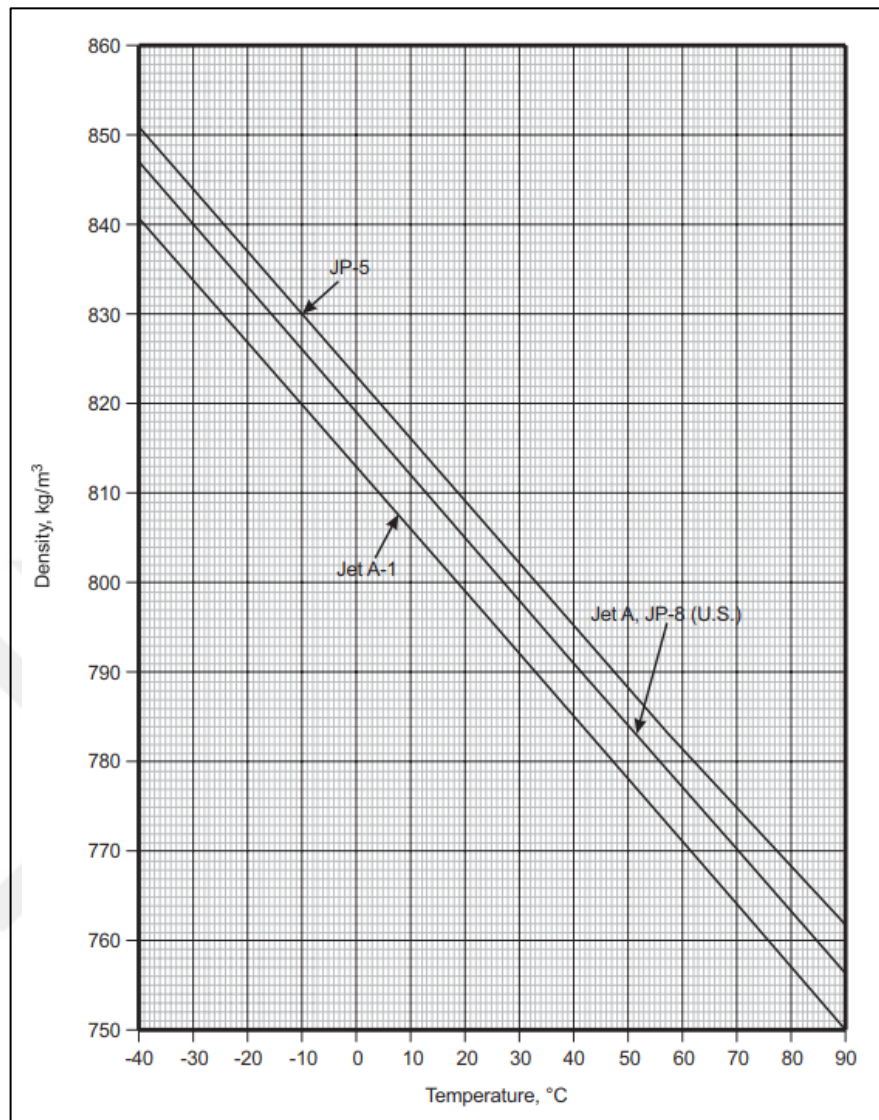


Figure 4.11: Fuel Density Values of Commonly Used Fuels

The Darcy Friction Factor should be calculated to use the Darcy Equation. The friction factor calculation method changes with the flow characteristic. For laminar flow friction factor is:

$$f = 64/Re \quad (4.3)$$

For turbulent flow friction factor is

$$f = 0.316/Re^{0.25} \quad (4.4)$$

For transition region it is recommended to use the friction factor as 0.042. However, AIR1657 suggests that using the turbulent flow regime assumption is more conservative. Also, more detailed approach is to use Colebrook Equation for friction factor [20].

$$\frac{1}{\sqrt{f}} = -2 \log \left(\frac{\varepsilon/D}{3.7} \right) + \frac{2.51}{Re\sqrt{f}} \quad (4.4)$$

The Moody Chart is combination of the experimental results and Colebrook Equation with addition of laminar regime friction factors [20].

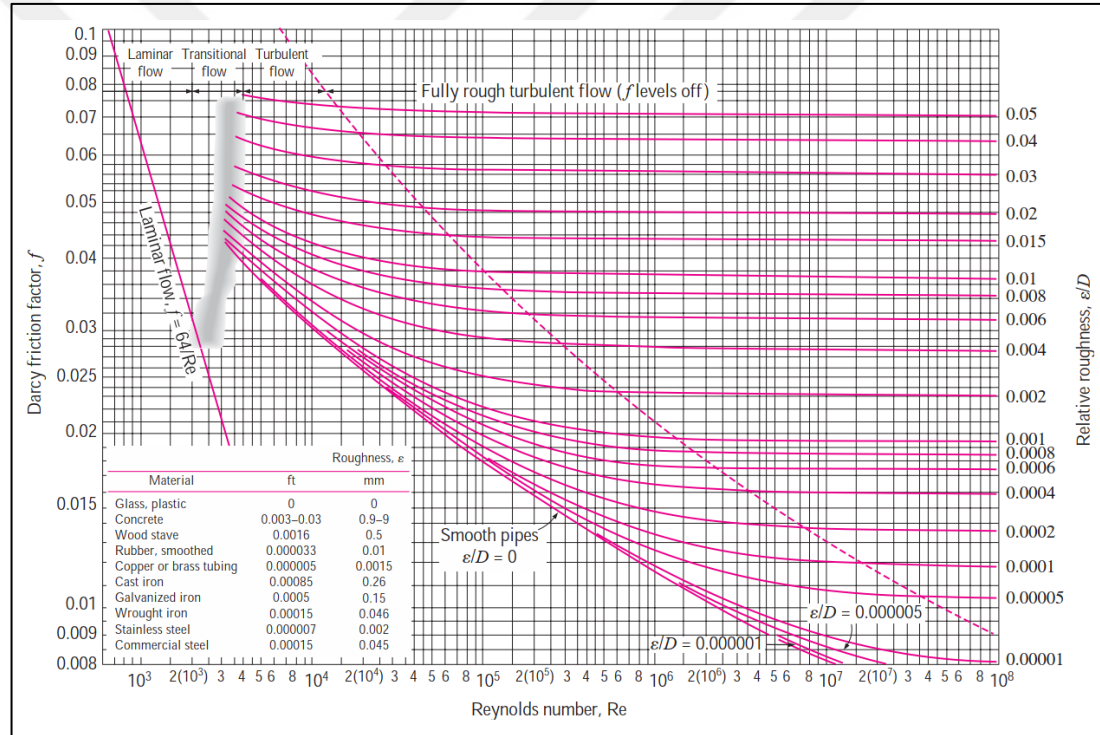


Figure 4.12: Moody Chart

The Reynolds Number calculations are made to use Moody Chart and AIR1657 suggested equations.

$$Re = \frac{\rho V}{\nu} \quad (4.5)$$

The kinematic viscosity of the fuels are taken from Figure 4.13 [Coordinating Research Council, 2004].

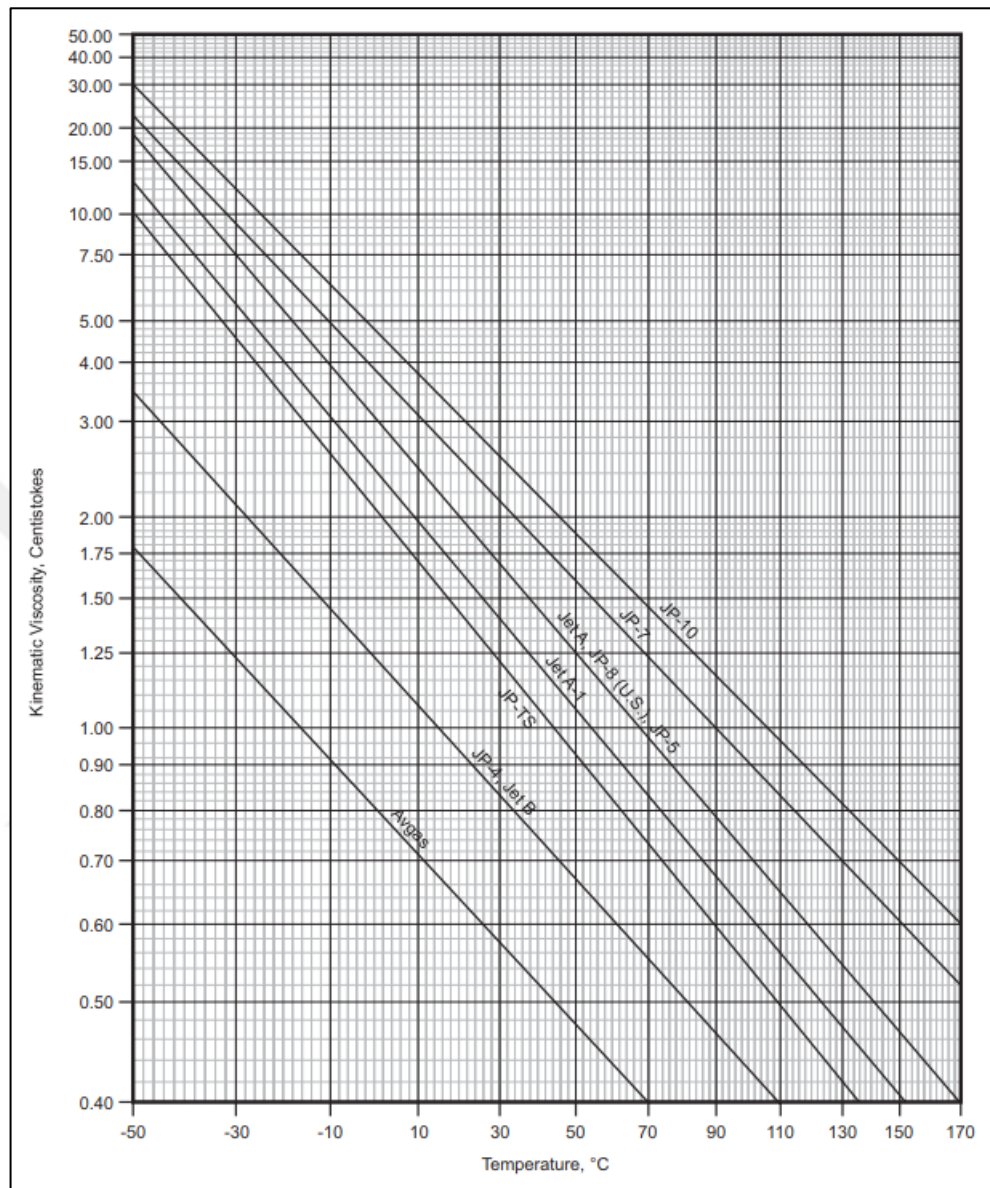


Figure 4.13: Kinematic Viscosity Values of Commonly Used Fuels

The tubes and the lines that carry the fuel are modelled geometrically at the flow network. The surface roughness, fuel temperature and flow rate are the inputs of the analysis. The frictional losses are calculated by the analysis program by using the formulas explained and Moody Chart.

There are bends, fittings and tees in the fuel system. These components interrupts the smooth flow of the fuel. They induce pressure drop to the system. They are called

Minor Loses. The minor losses are calculated with the loss coefficient of the feature. The loss coefficient is calculated with the formula 4.6. It is basically derived from the test data of the feature [20].

$$K_L = \frac{h_L}{V^2/(2g)} \quad (4.6)$$

The pressure lose caused by the minor losses is calculated with the formula below.

$$\Delta P = \frac{1}{2}K_L\rho V^2 \quad (4.7)$$

The flow features in the system is modelled in the Flomaster. The built-in loss coefficients in the program used for the calculation of the minor losses.

The valve test curves provided by the suppliers are entered to the program for the valve pressure lose calculations. As the valves are complex components, trying to model them with using the physical features inside the valve bodies are not the right way. Because of that they are tested and the valve curves are drawn by the suppliers.

The design point for the FFD is taken as transition mode where both lines are operative. This point is selected because the ignition of the main fuel injectors cannot be made without the pilot fuel injectors. Therefore, both lines should be in the required fuel flow ranges. The input parameters for the flow analysis are given in Table 4.3. The FMU supply fuel flow is independent from the system pressure. Therefore, the main input is the flow at the FMU component. The combustion chamber pressure may affect the pressure balance of the system. It is also used as an input parameter in the flow analysis. The pressure setting is not an input for the program but the characteristic of the valve is set accordingly. It is crucial to make this setting since it is primary component that is used for the pressure balancing.

Table 4.3: Flow Analysis Input Parameters

Total Fuel Flow [-]	22.5
Combustion Chamber Pressure [-]	1.5
Pressure Drop Valve Setting Pressure [-]	21.8

The pressure and flow distribution on the inlet and outlets of the FFD are read from the analysis results. The analysis results are given in Table 4.4. It is seen that the required flow at the interfaces can be met with this configuration. The pressure losses across the system well balanced.

Table 4.4: Flow Analysis Results on FFD Inlet and Outlets

	Flow [-]	Pressure [-]
Fuel Inlet	22.5	25.13
Main Fuel Line Outlet	19.1	3.3
Pilot Fuel Line Outlet	3.4	22.76

The valves, fittings and the plugs are packaged in an assembly as indicated in Figure 4.14. The analysis proved that the selected valve configuration and inner fuel channels are appropriately designed. The MOC 2 - Analysis validation of the design is performed. The results will be forming basis for the MOC 4 - Laboratory Test and the MOC 5 - Ground Test activities.

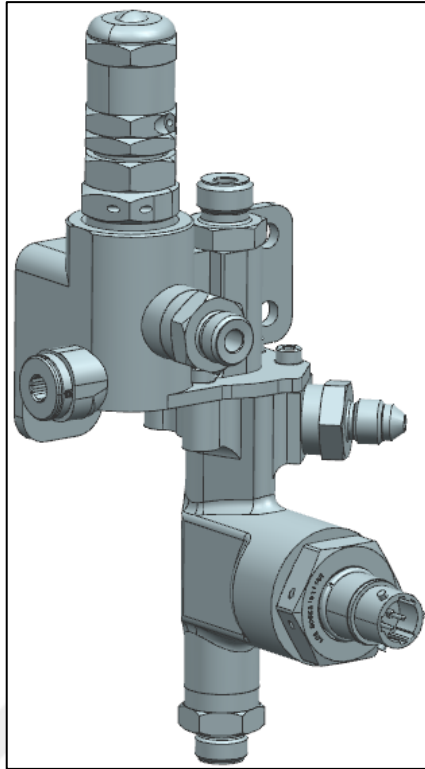


Figure 4.14: Fuel Flow Divider

5. COMPONENT TESTS

The rig test systems are planned and established to the validation under MOC 4. First step of component tests begin with design assurance and acceptance tests performed at the component supplier. In this system, the main aim is validation of the unit and its sub-parts. The test procedure is prepared accordingly for this purpose with different tests to observe valves and unit performance.

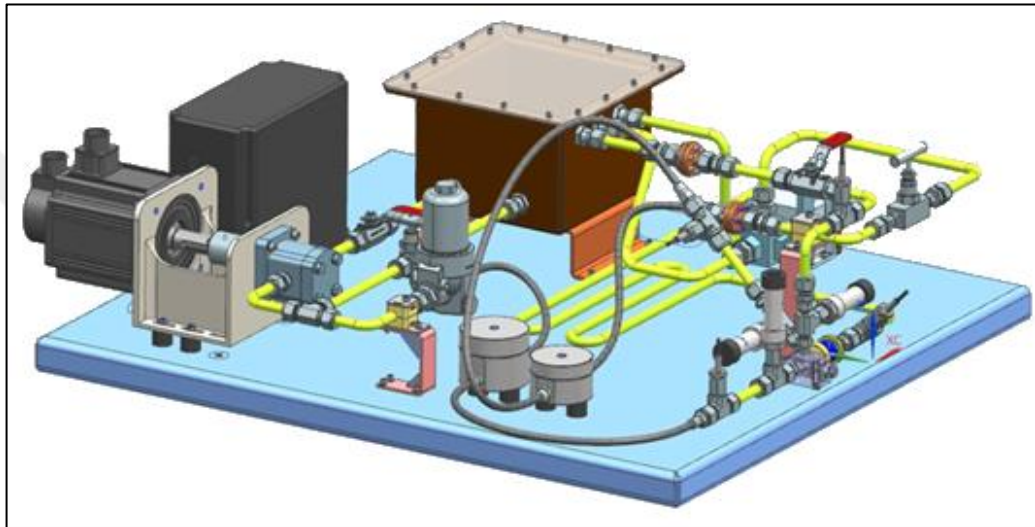


Figure 5.1: Supplier Component Test System

The component level tests are made with pressure controlled system because one of the main functions of the unit is to control pressure between the lines. Therefore, it is decided to go forward with controlling the inlet pressure rather than the fuel flow. It differentiates from the interfaces in the engine since the fuel metering unit provide fuel flow control rather than pressure control. Therefore, the unit can be tested with different pressures and differences between the lines can be measured.

In this system, main flow is provided with a gear pump. It is risky to pump the fuel with a gear pump since it is a positive displacement pump and can cause over-pressure across the test system. A controllable pressure relief valve is placed in parallel to the pump. This valve bypasses the extra flow to the pump inlet and make the test system pressure controlled. Down the line there are a fuel filter and an inlet pressure sensor. At the outlet of the unit, main and pilot lines are instrumented with pressure

sensors. The fuel injector pressures are simulated with needle valves. The valves are manually adjusted to the fuel injector characteristics by measuring the flows and pressures on the lines. Flowmeters are placed on both lines but different models are used because the flow ranges are different in the lines. The lines end at the fuel tank which has glass cover to visually inspect the flows.

The sensor calibrations and accuracies should be in line with the system and engine test instrumentations. As first step of test, wrong measurement can lead a failure that can propagate to higher levels. The requirement for the fuel mass flow measurement of the engine is referring to “ARP1217 - Instrumentation Requirements for Turboshift Engine Performance Measurements” [21]. The recommend practice define the flow measurement accuracy as $\pm 2\%$ and repeatability of the value measured as $\pm 0.5\%$. Accuracy and repeatability are required over the full scale. Flow measurement is made in $\pm 0.5\%$ to better calibrate the unit. Also, this practice applied to other supplied units.

The pressure measurement is not defined in a requirement. Therefore, it is defined by the design team to better understand the unit performance. It is defined as $\pm 0.5\%$ of full scale. This is defined as a limit value. The actual sensor capability is better than this value.

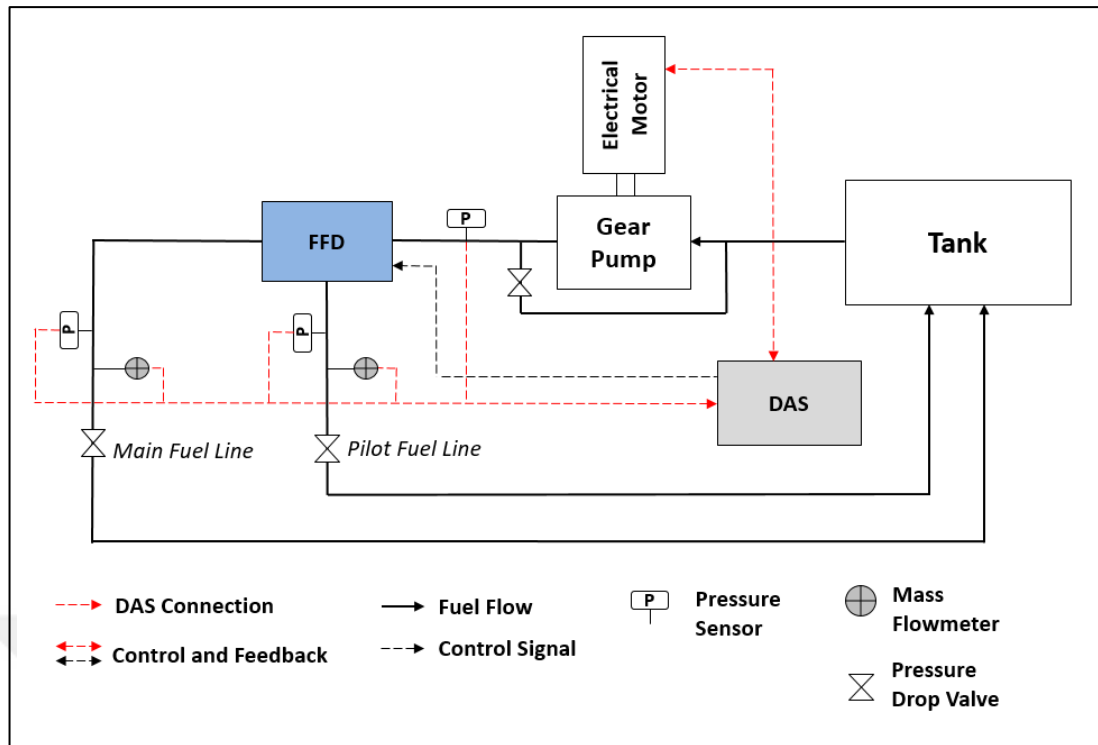


Figure 5.2: Acceptance Test System Layout

Acceptance test procedure are defined with the supplier as a requirement to get certificate of conformance for each unit shipped. It is a common practice for a line replacement unit of the engine to pass acceptance test before the shipping. Also, it is a must for this unit since it can directly affect the engine performance. Any deviation at the unit performance can cause failed start and any failure at the sealing can cause external leakage; consequently fire. The unit's test data also important parameter for the fault analysis as it gives data to evaluate unit alone. The acceptance procedure involves following test:

1. Static external leakage test
2. Static internal leakage test
3. Solenoid leakage after energizing when purge air line closed
4. Solenoid leakage after energizing when purge air line open
5. Pressure drop valve characterization
6. Solenoid pressure drop measurement

The acceptance test procedure data is crucial input for the validation process. The data can be used to design assurance, understanding statistical differences between the units and valve characteristics. The pressure drop valve characterization test is used for validation of the unit performance. The unit works in the engine similar manner. Therefore, the data is useful measure to compare the unit performance through the different tests and compliance levels.

The procedure of the pressure drop valve characterization test indicated below:

1. Direct fuel to the main fuel line and adjust main fuel line pressure according to the fuel injector data.
2. Direct fuel to the pilot fuel line and adjust pilot fuel line pressure according to the fuel injector data.
3. Shut all the fuel flows and bring the unit standstill condition.
4. Open the solenoid valve.
5. Start to pump fuel to the system and log the inlet-outlet pressures and flows.
6. Increase the inlet pressure to the proof pressure.

The opening pressure test result are piloted in Figure 5.3. The test is started with no pressure at the system. The inlet pressure is increased gradually at the test. The inlet and outlet pressures are recorded. The main line gage pressure stays at zero while the inlet and the pilot line pressures are increasing. The valve works as intended and blocks the main fuel line flow until the inlet pressure reaches the threshold value. After the threshold point, the fuel flow at the main fuel line is established without any blockage or oscillation at the flow. There is no instability at the opening phase of the valve. A slight inlet pressure drop occur at 95 inlet pressure but the outlet pressures react in parallel to the inlet pressure drop. There is not unexpected behavior encountered on the valve at opening pressure test.

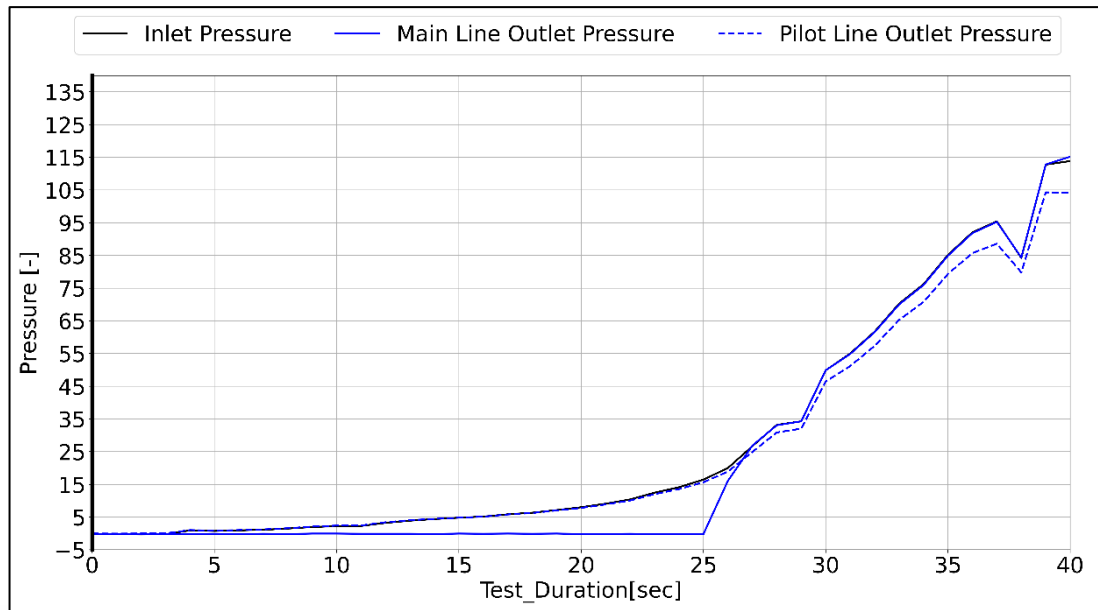


Figure 5.3: Opening Pressure Test

The closing pressure test performed because small differences between the opening and closing pressures are expected phenomena. During the valve closing, the flow at the valve creates hydrodynamic effects on the valve. This effects can cause different opening and closing characteristics at the valves. The closing pressure test result are piloted at Figure 5.4. The inlet pressure is high at the beginning of the test. The inlet pressure are decreased during the test and the outlet pressures are recorded. As expected, small pressure difference between closing and opening pressure is observed in the test. 1.5 difference is measured. The difference is in the acceptable range. On the other hand, it increases the valve stability since the valve do not have unstable point where it opens and closes with pressure oscillations in the system.

The inlet and pilot line pressures increase at the closing point of the valve. It is not expected behavior. The probable reason is the sudden change in the flow causes pressure increases in the open lines. It is not examined further since the pressure increase is seen in short duration and the amount is in the acceptable range.

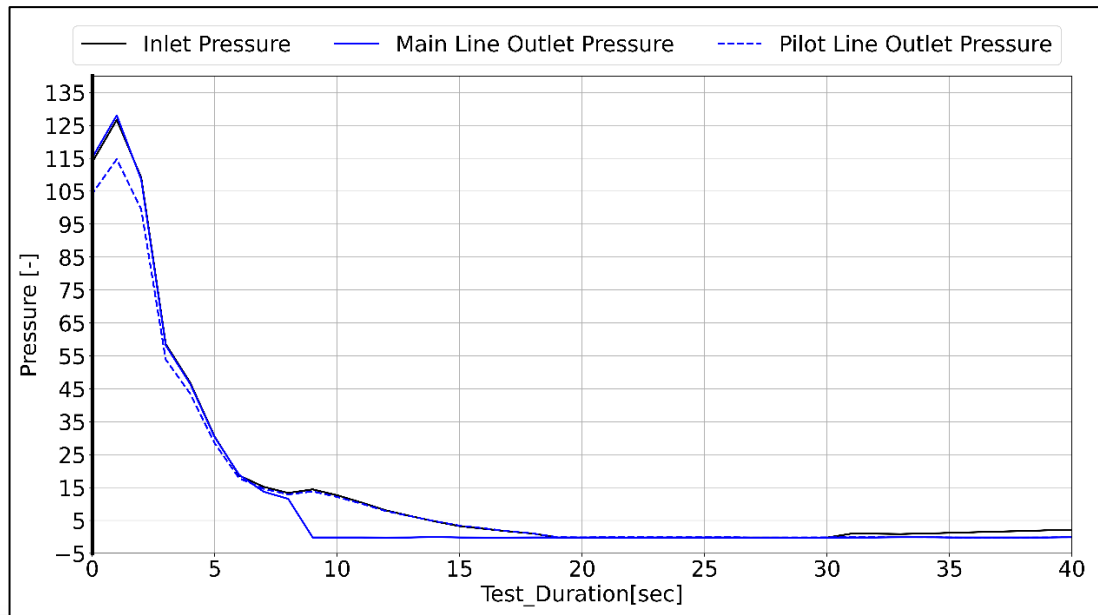


Figure 5.4: Closing Pressure Test

It is crucial to have required pressures in both main and pilot lines at the transition mode. It is provided with the added pressure drop on the main line with the valve. The pressure drop across the transition region with different inlet pressures are plotted in Figure 5.5. The valve pressure drop decreases with the main line pressure increase. Thus, the pressure in the pilot fuel line is not lost. The pilot line pressure stays unaffected from the opening of the main fuel line and pressure increase in the inlet. The pilot fuel line pressure follows the inlet pressure. The pilot line pressure is not affected from the valve position which is best case scenario. The intended function in the transition region is ensured. The main line pressure reaches the inlet pressure level with the overall pressure increase. The pressure difference between the main line and inlet negligible after a point. It is beneficial for the system to minimize the pressure losses.

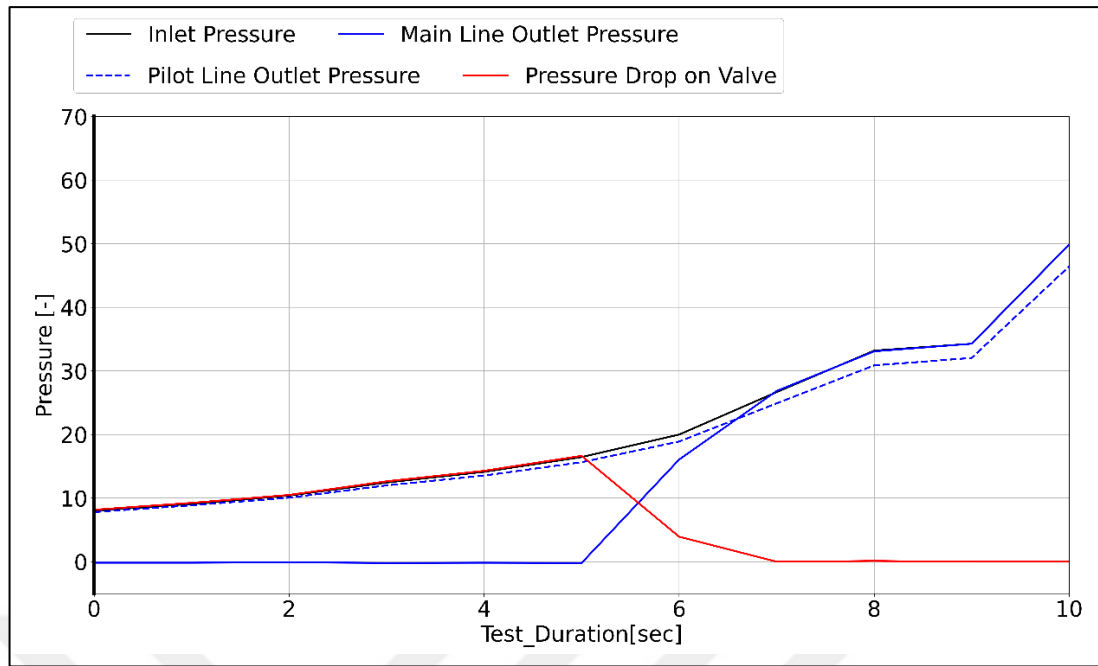


Figure 5.5: Pressure Drop on Valve

The pressures in the lines and drop across the valve are tested. The fuel flow measurement also taken to compare with the pressure data and make cross-check between the results. There is no fuel flow up to threshold pressure as the main line pressure stays at zero. The pilot line fuel flow gradually increase with the inlet pressure. The fuel injector flow is proportional to square root of the pressure. Therefore, the fuel flow does not increase linearly with fuel pressure.

The objective is to conform that the fuel flow is not interrupted or decreased in the transition mode. The pilot line flow continues smoothly in this period. The Figure 5.5 and Figure 5.6 verify each other. The pressure difference between the lines disappear but the flow is not interrupted in the process. The intended function of the fuel flow divider is validated in the component level.

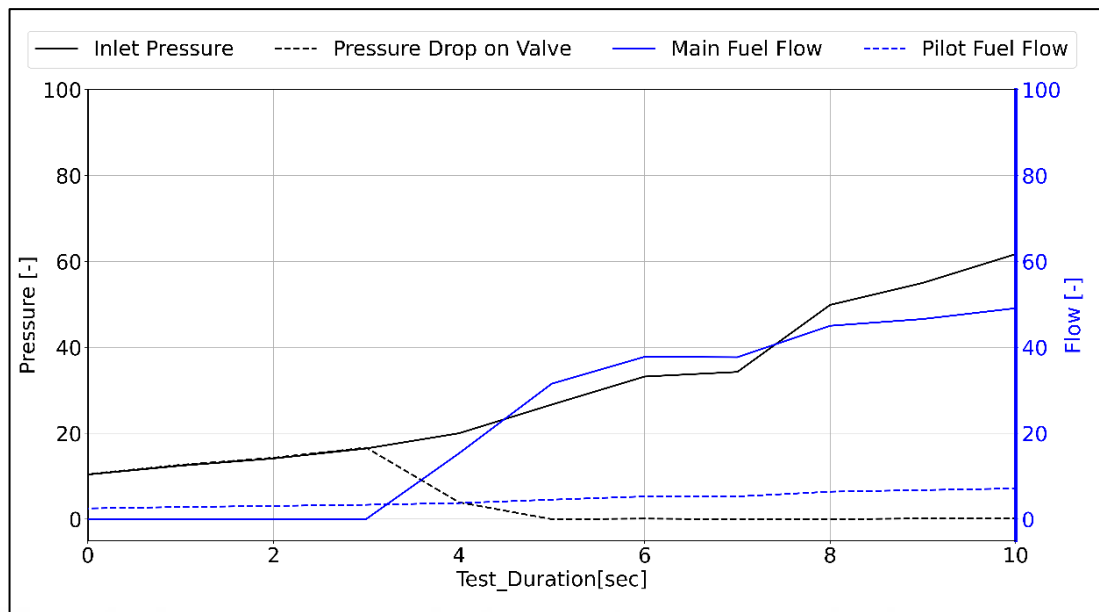


Figure 5.6: Fuel Flow on Main and Pilot Fuel Lines

6. FUEL SYSTEM RIG TESTS

Complete fuel system test rig is established apart from the supplier acceptance test system. The aims of the rig test system are listed below:

- Cross-checking each unit's conformance to the supplier reported values.
- Conforming and improving performance of the engine control system integration with the fuel system.
- Testing the unit with flow controlled environment rather than pressure controlled.
- Measuring the system performance at non-design points.
- Diagnosing the faults encountered in the engine tests by simulating the conditions at the rig test.

The engine control is vital since any failure at the control can lead to much bigger failures in the engine tests such as overspeed and overtemperature. For turboshaft engines only control is performed through the fuel control. Therefore, the integration of the fuel system components to each other and the fuel system integration to the control system have significant role to pave the way to the engine tests.

The fuel system test rig layout is indicated in Figure 6.1. In the test rig, it is tried to simulate mechanical, functional and electrical interfaces of the fuel system. In the engine, the fuel metering unit is connected to the accessory gearbox. The fuel metering unit is driven by high speed electrical motor in the rig. The main and pilot fuel injectors are simulated with needle valves. It is tried to simulate the engine air pressure with controllable throttle valves. Electrically the fuel metering unit and fuel flow divider are connected directly to the FADEC. The FADEC communicates with data acquisition system through the CAN line.



In the test system, the fuel metering unit directly makes suction from the tank and pumps the fuel to the flow divider. As the metering regulation is done in the unit, there is no flow control valve exist before and between the units. The fuel metering unit controls the fuel flow. Unlike the component tests, the fuel flow divider receives fuel from flow controlled system. This enables to test the pressure fluctuations and transient responses. It is tried to simulate fuel system as much as possible. Therefore, instrumentation is not made in between the units since it can create extra pressures and

changes in the transient response. The fuel flow divider outlets are instrumented with 2 flowmeters, 2 pressure and a temperature sensors in each line. The instrumentation bench indicated in Figure 6.2.



Figure 6.2: Instrumentation Bench Fuel System Test Rig

The calibration of the fuel system is done with this test rig because of that the flow measurement is critical. The flowmeters can lose the calibration over the time. Cross-checking of the flowmeters is helpful to catch any drift in the calibrations. Flow measurement is made in $\pm 0.5\%$. Same accuracy is defined for both ATP's of the FMU and FFD. Therefore, the rig measurements do not fall short in terms of accuracies of the supplier measurements. Additionally, it is in line with ARP1217's engine fuel flow measurement requirement [21].

The pressure measurement accuracies are defined as $\pm 0.5\%$ of full scale. The value is defined as a limit. The actual sensor capabilities are better than this value. In the rig test, the pressure measurement is not significant as FFD acceptance test since the flow measurements are main intent of the rig tests. On the other hand, it is

important to get comparable data from all of the tests. Therefore, pressure measurement is made with same accuracy in both tests.

The temperature measurement is key part of the mass and volumetric flow calculations. The flowmeters used in the system are turbine type which means they measure flow volumetrically. They have built-in temperature sensor to make volumetric to mass conversion. Additionally, one of the sensors placed to the lines are read volumetrically and separate temperature measurements are added to system. The test system makes the conversion with the temperature measurement. This enables cross-checking of the flowmeters.

The pump and valve characteristics change with fuel temperature because viscosity of the fuel drops with temperature and this makes fuel less frictional. The FMU heats up the fuel as much as 30 °C, hence temperature measurement is important. Temperature measurement generally cannot be made very accurately since K-type thermocouples are widely used and capable to measure around $\pm 1^\circ\text{C}$. Even so, the value is sufficient for temperature measurement. The temperature only used for density calculations. Therefore, it is not affecting any parameter directly.

The test procedure is prepared according to the system operation at the engine level. The fuel flow schedules are determined by taking into consideration of engine starting and operation. The test scenario is loaded to the FADEC. The test objective is to validate that the FADEC and fuel system work together and the fuel flows in the lines are in parallel with the required values. The FADEC placed the inside the control system setup and connected to the system with CAN line. The control system and data acquisition system are indicated in Figure 6.3.



Figure 6.3: Control System and DAS of Fuel System Test Rig

In the tests, it is observed that the FMU cannot supply fuel accurately at the low fuel flows. As low fuel flow regimes are transient, it is not critical to have accuracy in these operating conditions but the pilot fuel flow control has significant effects on the engine. Lower fuel flow values can cause false start. It is decided that the fuel is supplied greater than the FFD threshold value by the FMU. By doing so, more precise control over the pilot fuel flow is aimed. The pilot fuel is set by FFD threshold value and the extra fuel is directed to the main fuel line. The main fuel line is empty on the engine starting. Therefore, extra fuel flow does not directly go into the combustion chamber. It also helps to fill the fuel manifold.

The fuel flow inputs and expected flows are tabulated in Table 6.1.

Table 6.1: Fuel System Starting Simulation Test Steps

Step	Inputs		Expected Flows		Condition
	Fuel Flow	FFD Command	Main Flow	Pilot Flow	
1	6	Open	0	6	The pilot line fill period
2	6	Open	3	3	Pilot active / Main manifold fill
3	14	Open	11	3	Pilot active / Main active
4	18	Open	15	3	Same with Step 3 increased flow
5	18	Close	18	0	Pilot closed

The starting simulation test results are plotted in Figure 6.4. It is observed that the fuel flows slightly diverge from the expected values but overall system behavior is perfectly matching the required characteristic. There are two predicted reasons for this divergence. One of them is setting of the needle valves which simulates the fuel injectors cannot be made very precisely. The other reason is the instrumentation and tubing create back pressures in the system. They affect the pressure balance in the system. Despite differences from the expected flow values, the test showed that the system and FADEC are capable to supply the fuel as demanded. The required starting fuel schedules are supplied.

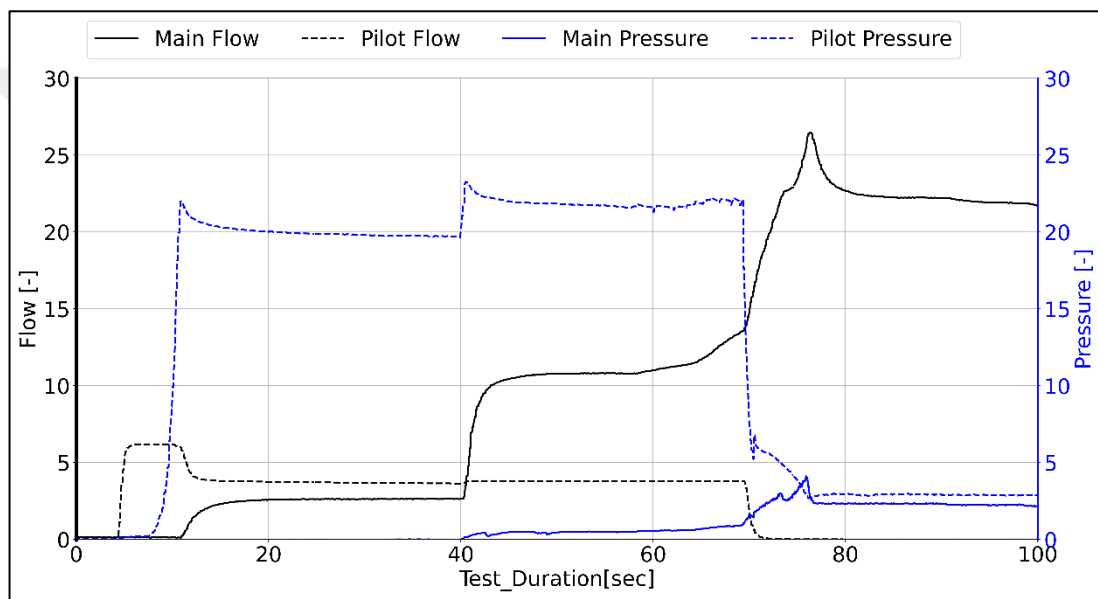


Figure 6.4: Fuel System Starting Simulation Test

The system responses are measured during fuel flow changes. The valves used in the system have springs inside. They are loaded with the fuel pressure. The changes in the fuel flow distort the force balance in the valve springs. Therefore, a time needed for the valves to react the changes. Additionally, the amount of the distortion at the fuel flow is important. It can create instability and overtemperature conditions on the engine. Reactions in the lines are tested with step changes in the fuel flow as indicated in Figure 6.5. The fuel flow is increased in two step while both lines are active. Then, the fuel flow decreased in the final step.

It is important to get smooth transient response in the fuel flow to not cause overshoot in the engine speed. It is observed that the fuel flow rates in the main and pilot fuel lines do not overshoot or undershoot. On the other hand, pressure peaks in both main and pilot lines are formed after the flow rate increase. They do not have significant consequences because the primary aim is to control the fuel flow. Therefore, as long as the fuel flow rates do not affected, the pressure overshoots are acceptable on the system.

After the flow rate decrease, some flow fluctuations are measured on the main fuel line. Although the amplitude of the flow fluctuation is small, the characteristic in the transient response is noted. The fluctuations in the fuel flow should be damped in the engine level since it can cause higher engine speed fluctuation with the excitation caused by the control system.

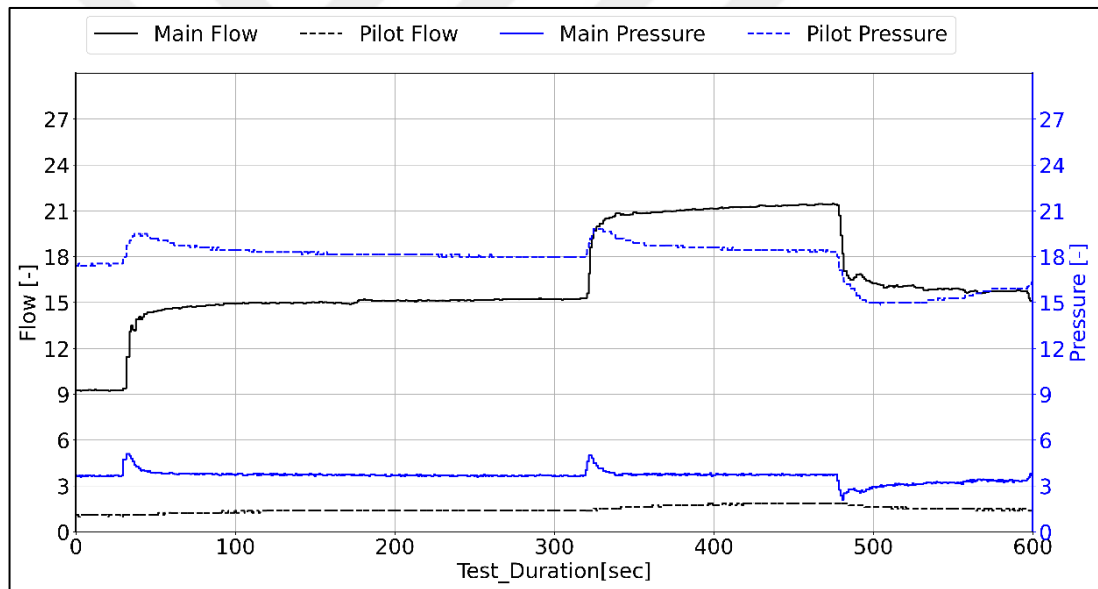


Figure 6.5: System Responses at Fuel Changes

The steady state flow measured in the test rig to observe fuel system characteristic at long run. It is studied that the system can supply stable fuel flow along the engine operation. 100 seconds of the test data gathered during the steady state test. The data is plotted in Figure 6.6. The fuel system can supply stable fuel in the long run as any increase or decrease are not observed in the test data.

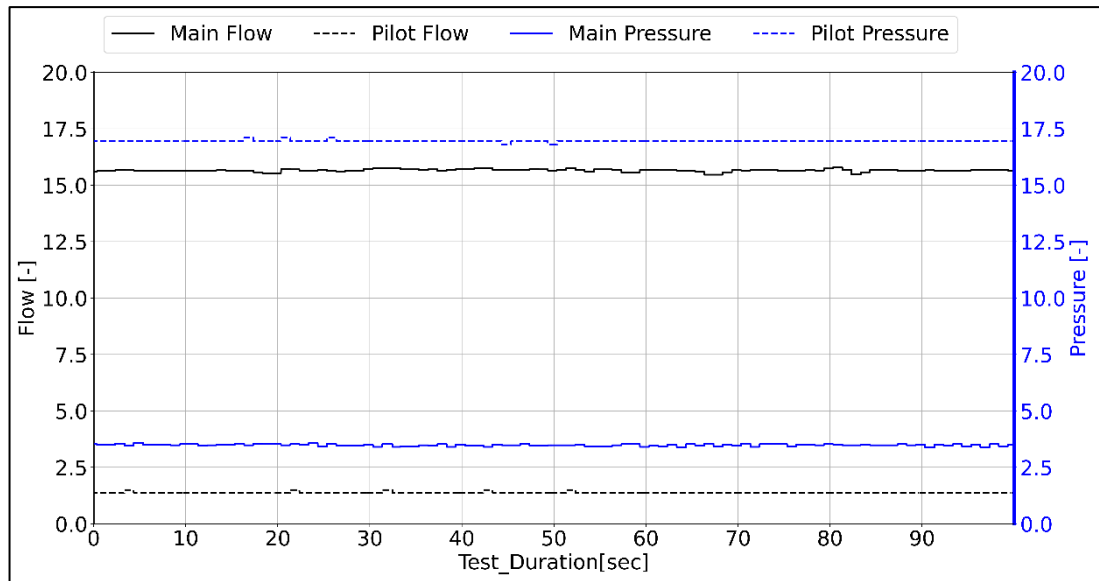


Figure 6.6: Steady State Fuel Supply Test

In the second part of the test campaign, the assembled tubing and fuel injectors are connected to the fuel system test rig for further investigation of the pressures and flow numbers. It is aimed that the combustion chamber interface of the system is simulated properly with the pressure drop valves. The mappings of the fuel pressures are done as plotted in Figure 6.7 and Figure 6.8. It is seen that the interface pressures are coherent with the calculations.

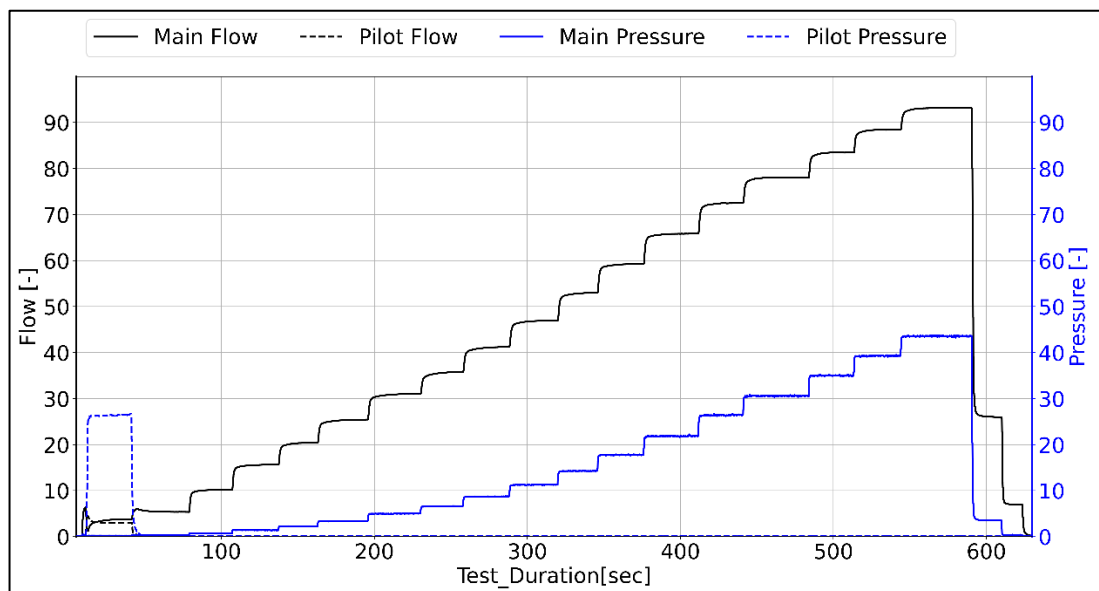


Figure 6.7: Combustion Chamber Interface Mapping

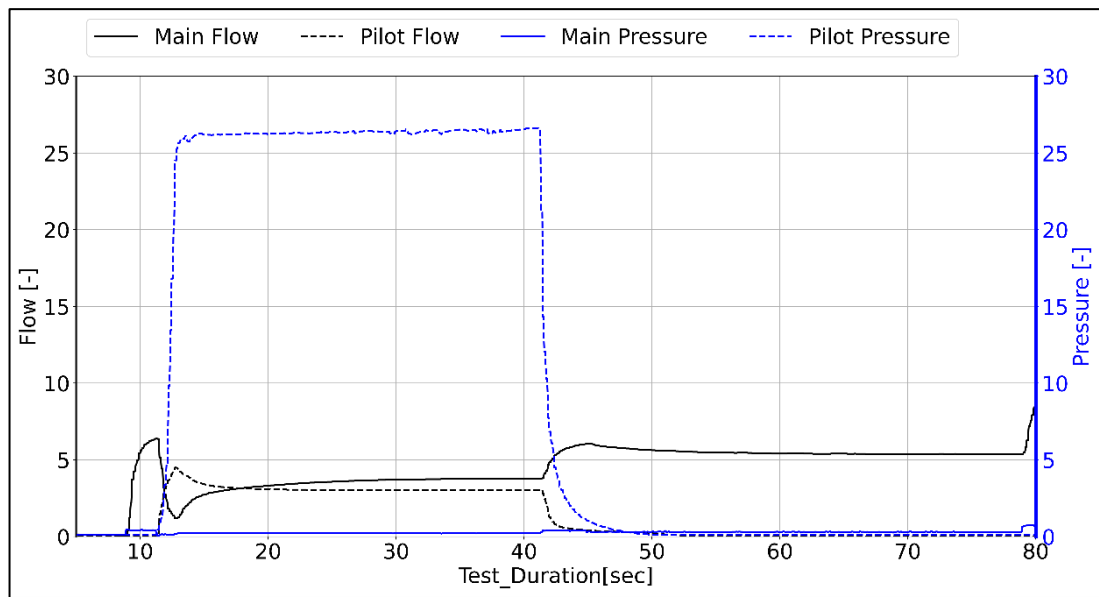


Figure 6.8: Mapping of the Pilot Line

7. ENGINE TESTS

The engine tests at the ground level are final part of the FFD's validation process. The engine tests correspond to MOC 5 level. The fuel system and its components are tested in the actual working environment which means vibrations, temperatures and engine air pressure are added to the equation. The simulated interfaces in the rig tests give a way to the actual interfaces on the engine. Also, the ignition and purge air performance can be evaluated with the engine tests. In the rig tests, performance of the fuel system can be observed but there is no fuel injector mounted on the system, the purge air is never tested since it is very hard to pressurize and heat up the air to certain level and the pressure fluctuations caused by the engine cannot be simulated. Therefore, it is decided to use MOC 5 engine testing as the part of the validation strategy.

The engine tests are configured with two different setups. Before the whole engine tests, it is planned to perform the core engine tests which is the engine without accessories. This test campaign offers opportunity to use actual fuel system with heavy instrumentation. Heavy instrumentation cannot be done when the fuel system is mounted to the engine since there is not enough room to put flowmeters and pressure gages. Therefore, it is a good chance to make just core engine test and supply the fuel from the auxiliary systems. In these core engine tests, the fuel system itself is put on the auxiliary system. Therefore, actual engine and fuel system used in these tests. Additionally, the fuel supply lines are instrumented heavily before connected to the engine. The instrumentation is made similar to the fuel system rig test.

The core engine tests are also used as intermediate step in between fuel system rig tests and whole engine tests since they have characteristics from both tests. The instrumentation is made similar to the rig test. The both tests directly connected to the combustion chamber, in other words, actual engine itself. Therefore, it gives good quality data for the system validation. Also, the data can be used to compare the system characteristics in a failure case. For instance, the engine vibration can cause fuel fluctuations and consequently, engine speed fluctuation. The core engine test can give good clue to system performance with no engine vibration since the fuel system is mounted onto the stable ground supports.

7.1. Core Engine Tests

The engine configuration tested at the core engine tests are shown in Figure 7.1. The fuel supply circuit layout is indicated in Figure 7.2. It is mainly has similar structure with the fuel system rig test setup because it is intended to make comparison between these tests. The close loop system of the rig test are different in this configuration. As there is no fuel return from the engine, the fuel is supplied in one direction and always the system takes unused fuel from the tanks. The fuel lines are instrumented before they are connected to the engine tubing. The similar instrumentation parameters and sequence are selected with the fuel system test rig setup.

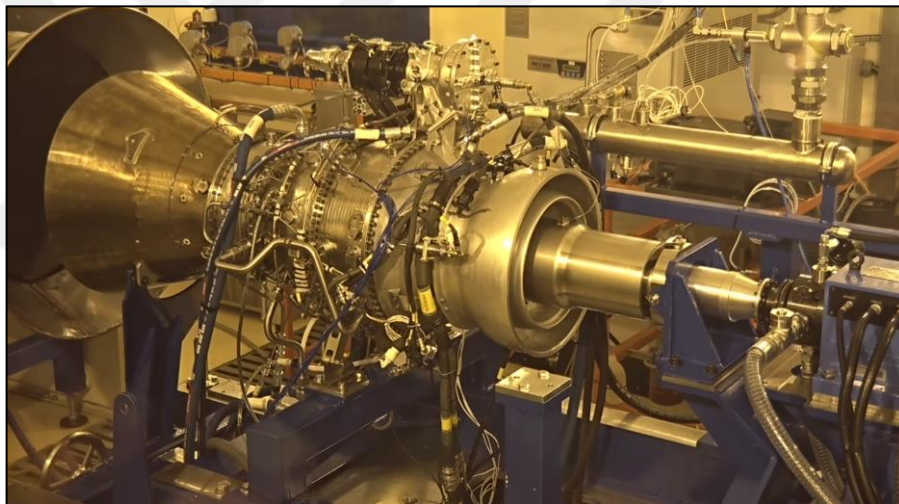


Figure 7.1: Core Engine Test

A pressure and temperature sensor are located at the inlet of the fuel system. Instrumentation at the inlet of the engine is crucial for the comparison with the whole engine tests because it is the only point that can be instrumented at the whole engine tests. The intended data comparison is done with the data gathered from these sensors.

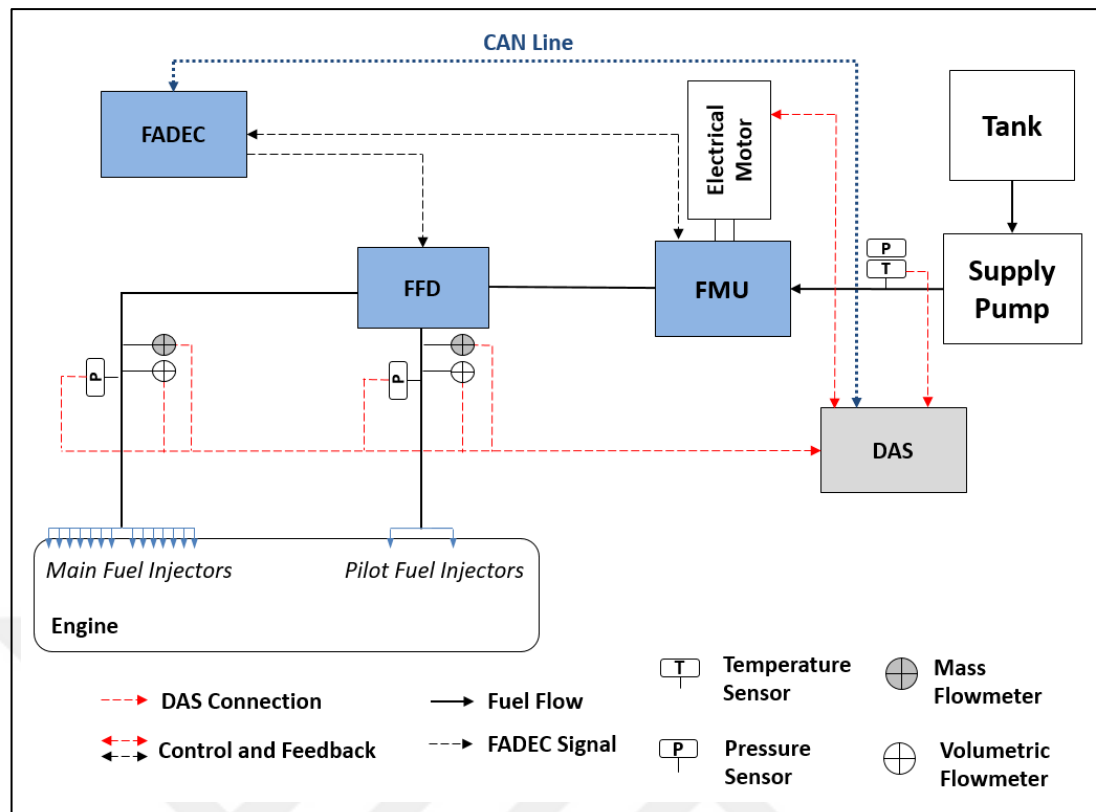


Figure 7.2: Core Engine Test Fuel Flow Diagram

The manifold and pilot line filling time period is one of the phenomenon that cannot be tested at the system level because it is needed to connect the combustion chamber interfaces to the fuel system. Despite the fuel system is connected to fuel manifold and combustion chamber, the core engine tests cannot give the same result with whole engine tests because the tubing are different in each application. It is needed to use long hoses to connect the lines between externally driven fuel system and the core engine. It increases the volume that should be filled in the starting. Still, the phenomenon can be tested with core engine test but the times differ from the actual application.

The fuel flow is started at 2 seconds in the tests. The pilot fuel line is empty at the beginning of the test. The pressure drop valve closes the main fuel line up to the cracking pressure. Therefore, all of the fuel flow directed to the pilot fuel line at the beginning of the test. The pressure rises on the pilot fuel line when the line is filled. In the figure, it can be seen that flow to the main fuel line begins at this point. The fuel flow to the fuel manifold is low between 8 and 12 seconds. In this period, pilot line is working which means that the pilot ignition has not been achieved. After the FADEC

senses the ignition, it increases the fuel flow to the main fuel line but pressure at the main fuel line does not increase. It means that the fuel manifold is not filled with fuel and the fuel injectors do not start to work. The pressure in the main fuel line increases at the 14th second. It takes 2 seconds to fill fuel manifold after the main ignition.

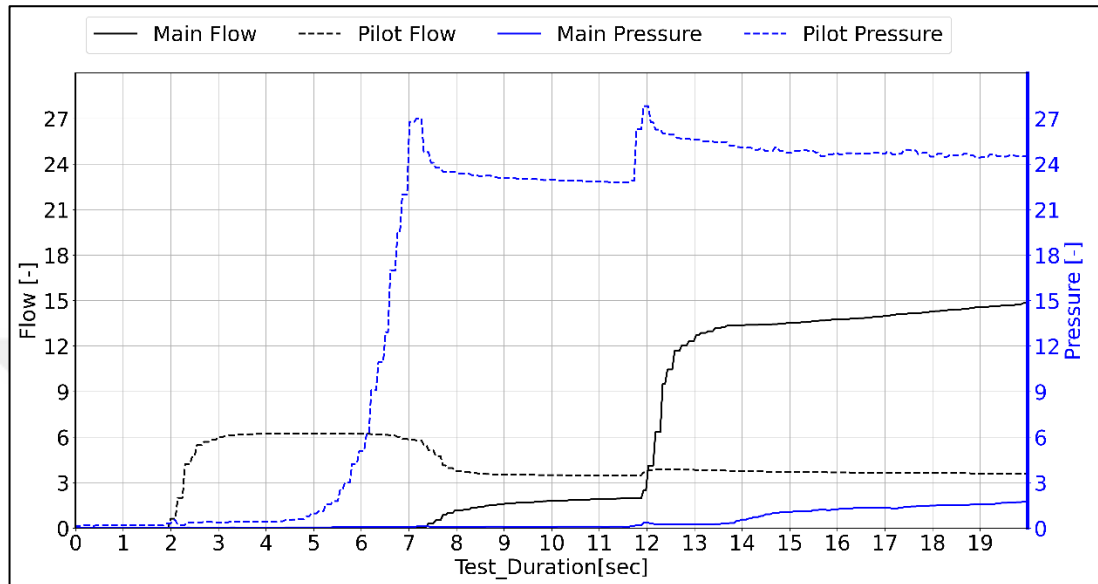


Figure 7.3: Fuel Manifold Filling Time

All of the measured parameters in the core engine test drawn in Figure 7.4. The engine light up is achieved 10 seconds after the pilot fuel injectors start to work. Steep increase in the PTIT temperature observed with light up. FADEC sensed PTIT increase and increased the total fuel flow at 26th seconds. Additional fuel flow directed to the main fuel line. Engine speed increases after the main fuel injectors are lighted up. The filling time delay also observed in the PTIT curve gradient. At the time point 28, the PTIT temperature curve gets steeper which indicates the main light off. The engine speed up is achieved with main fuel flow increase while the pilot fuel flow follows straight line.

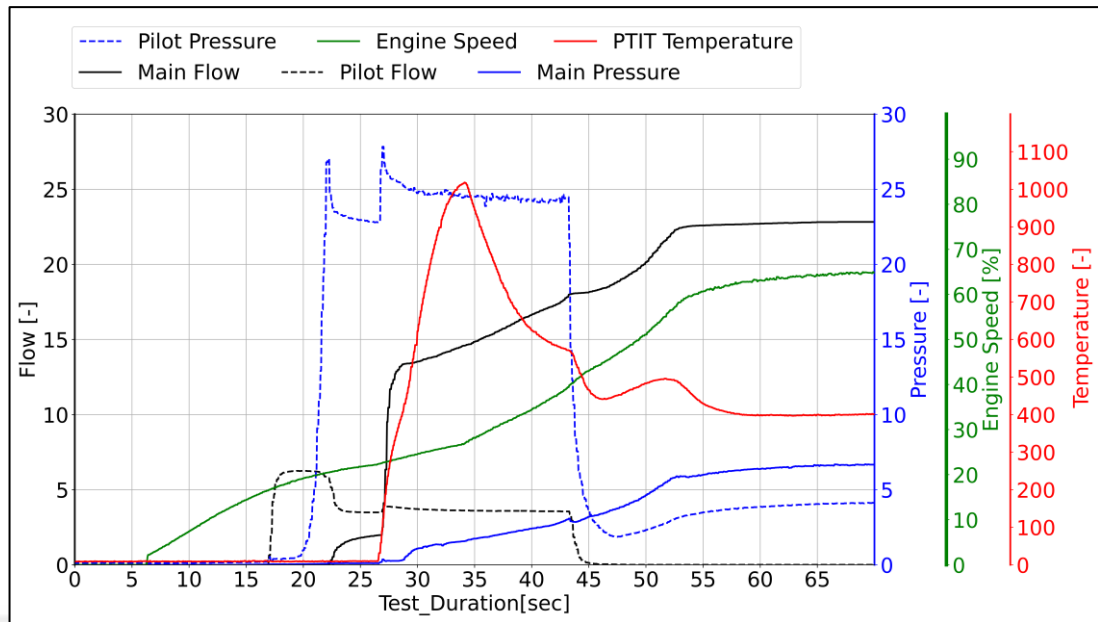


Figure 7.4: Core Engine Test Data

The system level scenario is compared with the engine test data. It is observed that fuel flow divider worked as intended and major events in the engine tests are recorded.

7.2. Whole Engine Tests

The whole engine tests are final step at the validation process. The engine configuration tested at the whole engine tests are shown in Figure 7.5. In this configuration, all of the systems are mounted to the engine. The system is tested with all of its interfaces.

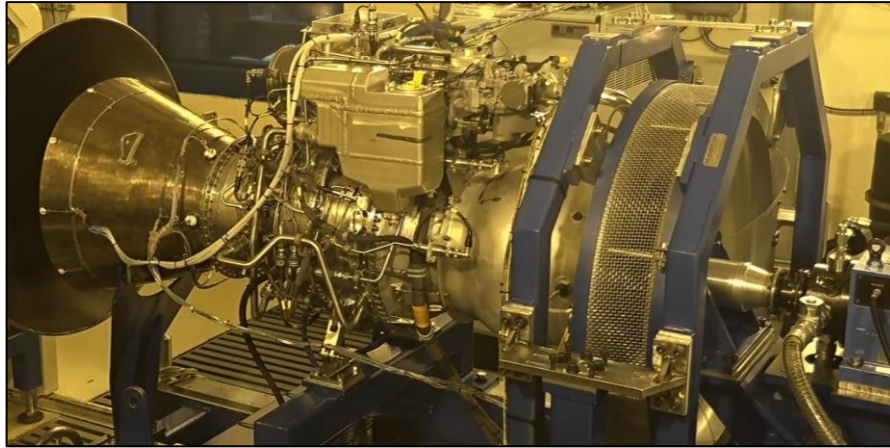


Figure 7.5: Whole Engine Test

The fuel supply system used in the whole engine tests are indicated in Figure 7.6. The only location that can be instrumented is the fuel inlet of the engine which is just before the FMU in the system layout. Main aim in these tests is to compare available data and engine behaviors with other test campaigns. By doing so, performance of the system can be estimated.

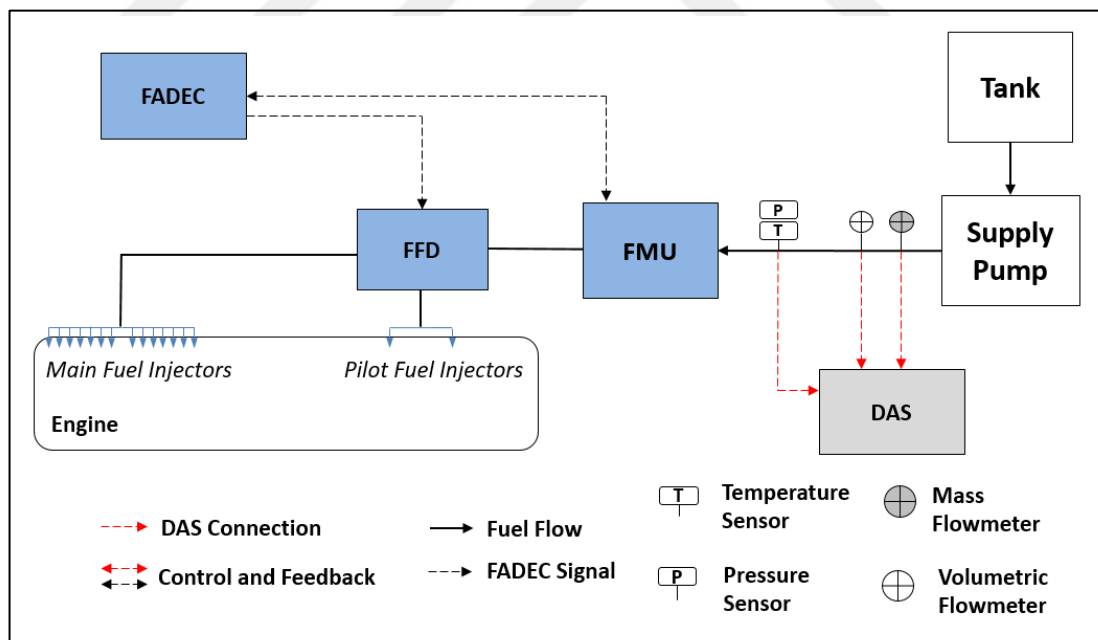


Figure 7.6: Whole Engine Test Fuel Flow Diagram

The tracked measurements in this configuration are the engine speed, the PTIT temperature and total fuel flow. The engine speed change points and their timings

indicate the transient responses of the engine. The PTIT temperature timing and the peaks indicate combustion chamber condition which means the burned fuel. The fuel flow measurement at the engine inlet indicates total fuel supplied to the engine and the FADEC commands. The measurements are given in Figure 7.7.

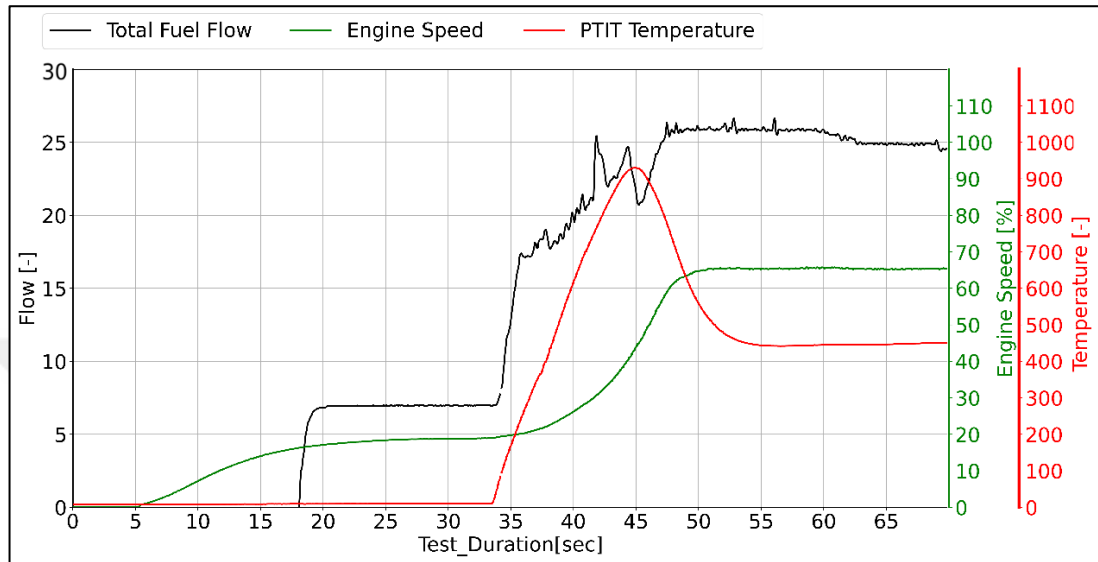


Figure 7.7: Whole Engine Test Data

Smoother PTIT and engine speed curves compared to the core engine tests refer to better transient performance in these tests. It is interpreted that the shorter tubing and smaller volumes between the units and the combustion chamber induced better transient performance on the engine. The PTIT temperature peak is slightly lower than the core engine tests. Probable cause is lower pilot fuel flow than the core engine tests. It is an expected result since the tubing pressure losses can affect the flow balance. Although it seems that the flow balance deviate from the other tests, no delayed start or slow acceleration is encountered on the tests. As the matter of fact, the lower PTIT values are better for the engine health while the engine still can be started successfully.

8. CONCLUSION AND RECOMMENDATIONS

8.1. Conclusions

The system and interface requirements that have significant effect on the fuel flow divider design for the turboshaft engine fuel system investigated and the validation activities are presented. The combustion chamber interface is main driver of the fuel system design. The ignition methods were evaluated for the possible usages in the turboshaft engine. The pyrotechnic ignition was not selected since it cannot meet the maintainability and relight requirements. The duplex fuel injectors requires previous design experience which was not available for the time being. The torch ignition method was selected as it offers decreased chance of false start, high flexibility at the ignition design and late design changes. The implementation of the ignition configuration to the engine and the purge air were addressed.

The design and reasoning of the fuel system layout explained. The fuel injector pressure values were calculated. The starting procedure to use the torch ignition was specified. For the selected ignition configuration, the fuel flow should be divided between two different fuel lines which are named main and pilot fuel lines. Different fuel pressure values are needed to operate these lines with specified fuel flow rates. Therefore, the fuel flow divider was introduced to perform pressure adjustment between the lines. The placement of the unit was one of the essential design trade-off that should be made on the system design. The alternatives were considered in terms of fire protection, filling times, weight, envelope, design flexibility and development cost.

There are three different valve layout can be utilized for the specified fuel flow division requirement. These are mechanical sequential, 3-way solenoid and 2-way solenoid with check valve. The alternatives were considered and the 3-way solenoid valve was selected for the design since it offered fewer part, less complex system layout and weight advantage. The flow network was established in Flomaster program. The pressure drops in the system were calculated for the system layout. Successful operation of the proposed solution was demonstrated in the analysis. The analysis formed base for the MOC 2 validation activities.

The test activities are split into three main levels which are component, system and engine tests. The component tests were done in the supplier. The test setup utilized for the component tests was pressure controlled. As the main aim of the FFD is to pressure balancing between the lines, testing of the unit with controlled pressures on the interfaces was crucial at the component level. The tests were done and the validation of the unit in the MOC 4 and component level was made.

The fuel system rig test was done with FMU, FFD and FADEC. The combustion chamber interface was simulated with the test system and heavy instrumentation was made to the fuel lines. The integration of the fuel system components to each other and the fuel system integration to the control system were tested in the rig. Number of significant problems were found, particularly the integration with the control system and leakages. The leakages on the components were found and fixed. The electrical interfaces of the FFD was wrong. The solenoid could not be driven. After the fixes, the system successfully tested. It was decided that the system responses and functioning were suitable to go forward with the engine tests. The fuel system rig tests formed remaining part of the MOC 4 validation activities.

The MOC 5 validation activities cover engine tests. The engine test campaigns were done in two different configurations. The core engine tests were done without the accessories installed onto the engine. It enabled the heavy instrumentation of the fuel lines. The engine behavior was observed with the fuel commands. The measurements on the fuel lines validated that the fuel can be supplied as in the system tests. The engine parameters which could give idea about instantaneous fuel supply were recorded. It was planned to use them to make comparison between the core and whole engine tests.

The final step of the test activities was the whole engine tests where the integration of the components to the engine was done. All of the simulated interfaces gave way to the actual interfaces in the engine. For the first time, the engine induced heat and vibrations put into effect in the tests. The instrumentation could not be made between the components. The health of the fuel system was monitored through the secondary measurements such as PTIT temperature, engine speed and total fuel flow. These values are compared with the core engine test data. By doing so, successful operation of the fuel system validated and tests were done.

In summary, the concept selection for the component of the turboshaft engine and proof of concept have been done. Integration of a component to a turbine engine is comprehensive process. In this case, the integration process was given for the fuel flow divider. The validation plan proposed and the validation was made. The general picture for the test activities was drawn from the test setups to the results. The approach can form a sample case for the component design and validation.

8.2. Recommendations for Future Work

To continue this research, the following work is recommended:

1. The environmental tests are not included in this study. They form equipment qualification part of components. The tests are done according to the applicable environmental test standards. As they are not unique for components, it is not needed to mention this topic. It is recommended to evaluate the environmental test to point out the specific parts of the tests that are unique for the component.
2. The test campaign did not cover endurance test of the engine. The endurance test is not a specific component or system test but there can be some issues emerge on the test in the fuel system or component. It is recommended to examine the results of the test whether the component or system performed unexpectedly.
3. The flight tests are not in the scope of the engine development project. Therefore, there is no flight test addressed for the validation plan. In the future, the flight tests would be performed with the engine. The specific test and instrumentation request would be made to monitor the component or system performance.

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BIOGRAPHY

The author started his career as Mechanical Design Engineer on gas turbine engine industry. He is currently working as a Validation Engineer in fuel systems of the gas turbine engines.

