

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**CYLINDER HEAD THERMOMECHANICAL FATIGUE TEST RIG DESIGN
AND IMPLEMENTATION**



M.Sc. THESIS

Armin MAHPOUR

Department of Mechatronics Engineering

Mechatronics Engineering

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**Armin MAHPOUR
(518171038)**

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Thesis Advisor: Dr. Ali Fuat ERGENÇ

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**SİLİNDİR KAFASI TERMOMEKANİK YORULMA TEST DÜZENEGİ
TASARIMI VE UYGULAMASI**

YÜKSEK LİSANS TEZİ

**Armin MAHPOUR
(518171038)**

Mekatronik Mühendisliği Anabilim Dalı

Mekatronik Mühendisliği

Tez Danışmanı: Dr. Ali Fuat ERGENÇ

MAYIS 2019

Armin MAHPOUR, a M.Sc. student of ITU Graduate School of Science Engineering and Technology 518171038 successfully defended the thesis entitled “CYLINDER HEAD THERMOMECHANICAL FATIGUE TEST RIG DESIGN AND IMPLEMENTATION”, which he/she prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

Thesis Advisor : **Dr. Ali Fuat ERGENÇ**
Istanbul Technical University

Jury Members : **Dr. Nuri Solak**
Istanbul Technical University

Prof. Dr. Orkun ÖZENER
Yıldız Technical University

.....

Date of Submission : **03 May 2019**

Date of Defense : **11 June 2019**





To my family,



FOREWORD

Thermomechanical fatigue in materials is an important topic in materials science. In this thesis with the science of mechatronics and automation come together to improve and test the produced materials. I am grateful for unlimited advises of Dr. Ali Fuat Ergenç and Dr. Nuri Solak. I am thankful to Ford Otosan for unlimited technical support, supplying devices and instruments. Besides my appreciation for my advisors and Ford Otosan, I would like to thank my family and Gizem Kaya for endless support, encouragement, and love, I could not do without them.

May 2019

Armin MAHPOUR



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ABBREVIATIONS

PLC	: Programmable Logic Controller
PID	: Proportional Integral Derivative
AFR	: Air-Fuel Ratio
TC	: ThermoCouple
FT	: Flow Transmitter
PT	: Pressure Transmitter
IO	: Input Output
DI	: Digital Input
DO	: Digital Output
AI	: Analog Input
AO	: Analog Output
SP	: SetPoint
PV	: Process Value
NG	: Natural Gas
SG	: Strain Gauge
Dyno	: Dynamometer
RPM	: Round Per Minute
TMF	: Thermomechanical Fatigue
LD	: Ladder
FBD	: Functional Block Diagram
ST	: Structured Text
SFC	: Sequential Function Chart
SCADA	: Supervisory Control and Data Acquisition



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CYLINDER HEAD THERMOMECHANICAL FATIGUE TEST RIG DESIGN AND IMPLEMENTATION

SUMMARY

The cylinder head is the part of the engine located over the engine block. Several parts such as valves, injectors, and spark plugs are located on the cylinder head itself, which are crucial parts of the engine unit. The importance of the cylinder head, not only depends on the parts located on it but also its durability to damage mechanisms.

Damage mechanisms are arising from the fuel combustion under the cylinder head. These mechanisms are wear, corrosion, thermomechanical fatigue, and high cycle fatigue. Each time the engine is used, or increased to high RPM and reduced to lower RPM while it is working, the engine unit's temperature also increases and decreases and it causes thermomechanical fatigue. On the other hand, fuel explosion, movement of the pistons and valves cause high cycle fatigue and wear on the cylinder head. Exposition of the cylinder head to the environmental impacts such as humidity, which causes corrosion.

To improve the durability of the cylinder head to these damages, various geometrical and material designs are proposing by many automotive companies. Each design is tested and analyzed by the thermal and structural programs but the complexity in geometrical parts of the design brings problems in modeling the design.

The prototypes of these designs are testing with dyno test systems. Dyno test systems are for measuring force, torque or power of the engine. Therefore, in dyno test, engine unit with all its parts such as turbo, gearbox, etc. must be assembled and proper engine fuel must be used as it is in a regular vehicle. Therefore, there is fuel combustion in dyno test, which can cause damages on the cylinder head over time. As a result, the thermomechanical fatigue can be studied. As a load for the engine, depending on the type of the dyno test rig, an AC or DC motor or even hydraulic system can be used. The duration and fuel consumption of the dyno test is quite long and costly. The other disadvantage of the dyno test for studying the cylinder head durability for thermomechanical fatigue is that, in case of failure in the other parts of the engine, or the engine load, interferes the whole test.

With the science of mechatronics and automation, cylinder head thermomechanical fatigue test rig is designed to expose the cylinder head to the factors, which cause thermomechanical fatigue in a controlled and a quite fast way. With this test rig, test duration and fuel consumption are reducing considerably. Also in this type of test, most parts of the engine are removed from the engine. Therefore, the possible failure of the other components is prevented.

Thermal map of cylinder head during the test can be obtained with the measuring instruments on the cylinder head and fed to the thermal and structural simulation programs to increase the accuracy of the cylinder head model and the relating analysis.



SİLİNDİR KAFASI TERMOMEKANİK YORULMA TEST DÜZENEGİ TASARIMI VE UYGULAMASI

ÖZET

Otomobil motorunda, bloğun üstünde bulunan parça silindir kafası olarak adlandırılır. Silindir kafasının en önemli görevi yanma odasının üst kısmını oluşturmaktır. Bir diğer görevi ise supapların, enjektörlerin veya bujilerin üzerine konumlandırılmasıdır. Silindir kafası araç motorunda önemli kılan sadece üzerinde yer alan parçaların olması değil aynı zamanda silindir kafasının hasar mekanizmalarına dayanıklılığıdır.

Yüksek güce ve verimli yakıt tüketimine sahip olmak her müşterinin beklentisidir. Öte yandan, egzoz emisyon değerleri EURO standartları tarafından belirlenen aralıkta olmalıdır.

Müşterilerin beklentilerini karşılamak ve standartlara uymak için, otomotiv şirketleri yanma odasına verilen yakıt ve havanın sıkıştırma oranını artırır. Bu işlem, silindir kafasındaki hasar mekanizmalarını yoğunlaştırır.

Hasar mekanizmaları, silindir kafası altındaki yakıt yanmasından kaynaklanmaktadır. Bu mekanizmalar aşınma, korozyon, termomekanik yorulma ve yüksek çevrimli yorulmadan oluşmaktadır.

Araç her kullanıldığında veya çalışırken yüksek devire çıkıp-inmesi durumunda, motor ünitesinin sıcaklığı da artar, azalır ve termomekanik yorulmaya neden olur. Öte yandan, yakıt patlaması, pistonların ve valflerin hareketi yüksek çevrimli yorulmaya ve silindir kafasının aşınmasına neden olur.

Ayrıca silindir kafası, korozyona neden olan nem gibi çevresel etkenlere de maruz kalır.

Silindir kafasının bu hasarlara karşı dayanıklılığını arttırmak için birçok otomotiv şirketi tarafından farklı geometriye ve malzemelere sahip olan tasarımlar yapılır. Her tasarım, termal ve yapısal analiz programları tarafından analiz edilir.

Ancak tasarımın geometrik kısımlarındaki karmaşıklık, silindir kafasının doğru şekilde modellenmesinde problemler oluşturur.

Bu tasarımların prototipleri dyno test sistemleri ile de test edilebilir. Dyno test sistemleri motorun kuvvet, tork veya gücünü ölçmek içindir. Bu nedenle, dyno testinde, turbo, şanzıman vb. motor ünitesinin tüm parçaları monte edilmeli ve normal araçta olduğu gibi uygun motor yakıtı kullanılmalıdır.

Bu nedenle, dyno testinde zamanla silindir kafasına zarar verebilecek bir yakıt yanması vardır ve termomekanik yorulma incelenebilmektedir. Motor yükü olarak dyno test donanımının tipine bağlı olarak bir alternatif veya doğru akım ile çalışan motor veya hatta hidrolik sistem kullanılabilir.

Dyno testinin süresi ve yakıt tüketimi oldukça uzun ve maliyetlidir. Bir diğer dezavantajı ise, motorun diğer parçalarında veya motor yükünde arıza olması durumunda tüm testi engellemesidir.

Mekatronik ve otomasyon bilimi ile, silindir kafası termomekanik yorulma test düzeneği tasarlanmıştır. Silindir kafasını termomekanik yorulmaya maruz bırakan etkenler, kontrollü ve hızlandırılmış bir şekilde bu test düzeneği ile silindir kafasına uygulanmıştır.

Bu test düzeneği ile test süresi ve yakıt tüketimi önemli ölçüde azaltılmış, ayrıca bu tip testte, motorun çoğu parçası motordan çıkarılmıştır. Bu nedenle, diğer bileşenlerin olası arızası önlenmiştir.

Termo mekanik yorulma test düzeneği, ölçüm cihazları, aktüatörler, kontrol cihazı ve çeşitli bileşenlerden oluşmaktadır.

Yüksek debili endüstriyel hava vantilatörü ile beslenen hava ve şehir hattından gelen doğalgaz, brulor içinde karışarak yanma için yakıtı oluştururken, gelen hava ve doğalgaz debilerini kontrol etmek için gereken debi ölçer ve vanalar her silindir için ayrıca yapılmış hatların üzerine monte edilmiştir. Debilerin kontrolünde ise PI kontrolörü kullanılmıştır.

Monte edilen cihazlar ile hava ve yakıt oranını değiştirerek, yanma odasındaki yakıt patlaması motorun orijinal yakıt kullandığı zaman ki patlamaya benzetilebilir. Sonuç olarak, silindir kafası gerçekçi termomekanik yorulma faktörlerine maruz kalabilir. Bu tip testte, diğer bileşenlerin muhtemel arızalarının önlenmesi yanında, test süresi yarı yarıya azalır ve yakıt maliyeti oldukça düşer.

Yanmayı gerçekleştiren brulor ise, ayrıca bir brulor kontrol ünitesi tarafından kontrol edilmekte ve yanma kalitesinin düşmesi durumunda veya havanın yetersizliği yüzünden alevin sönmeye durumunda, doğalgaz akışını keserek olası tehlikeli durumların önünü almaktadır.

Brülör kontrol ünitesi, brülör haznesinin içerisinde bulunan tespit probuna iyonizasyon akımı uygular. İyonizasyon akımı alternatif akımdır. İyonizasyon akımı, tespit probu üzerinden brülörün haznesine ve son olarak toprağa akar. Alev gözetimi, alevin iletkenliği ve doğrultucu edici etkisinden yararlanılarak gerçekleştirilir. İyonizasyon sinyali yükselticisi yalnızca iyonizasyon sinyalinin doğru akım bileşenine tepki verir. İyonizasyon probu ile şasi arasındaki kısa devre, alternatif akıma neden olduğundan brülör kontrol ünitesi doğalgaz beslemesini keser.

Ayrıca, iyonizasyon akımı mikro amper seviyesinde olması gerekmektedir. Yüksek değer de akım ise brülör kontrol ünitesinin doğalgaz akışını kesmesine sebep olur.

Yakıt karışımı brulor tarafından yakılarak silindir kafasını ısıtır ve istenilen termomekanik yorulma etkenleri silindir kafasında uygulanır. Termomekanik yorulma sadece metalin ısınmasında değil, aynı zamanda ısınan metalin soğumasında da gözükmektedir.

Soğuma esnasında oluşan termomekanik yorulmayı hızlı bir şekilde silindir kafasına uygulamak için soğutma fazında yakıt kesilerek, silindir kafası ve motor bloğunda normal araçta olduğu gibi soğutma sıvısı geçirilmektedir.

Bu test düzeneğinde ise soğutma sıvısı olarak etilen gliköl kullanılmıştır. Etilen gliköl, yaygın olarak antifrizlerde ve buzlanma önleyicilerde kullanılan bir maddedir. Etilen

glikol renksiz, kokusuz aynı zamanda orta derecede zehirli olan bir kimyasaldır ve donma ve kaynama noktası sırasıyla çok düşük ve yüksek olduğu için, soğutma sıvısı olarak tercih edilmiştir ve çoğu araçlarda kullanılmaktadır.

2000L tankta yer alan etilen glikol, sürücüye bağlı olan bir pompa tarafından silindir kafası ve motor bloğundan geçirilerek yüksek kapasiteli su soğutma cihazına aktarılır ve tanka geri beslenir.

Pompa sürücü vasıtası ile soğutma sıvısının debisi istenilen değerlerde tutularak ısıtma ve soğutma fazlarında farklı debilere sabitlenir. Ayrıca, motor bloğunun girişinde ve çıkışında yer alan basınç transponderleri sayesinde soğutma sıvısının basıncı gözlemlenir.

Isınan silindir kafasında yer alan birden çok termokupl sayesinde sıcaklık ölçülür ve kontrol cihazına beslenir.

Test sırasında silindir kafasının termal haritası, silindir kafasındaki ölçüm aletleri ile elde edilmiş ve elde edilen veriler termal ve yapısal analiz programlarına sunulmuştur. Bu sayede elde edilen silindir kafası modeli ve analiz doğruluğu arttırılmıştır.



1. INTRODUCTION

Cylinder head is more important than other parts of the engine unit. Automotive companies not only have to consider the expectations of the customers but also have to take account of the legal regulations have to take account of the legal regulations.

Having high power and efficient fuel consumptions are customer's expectations. On the other hand, exhaust emission values should be within the range determined by the EURO standards. In order to fulfill the expectations of the customers and compatible with standards, automotive companies increase the compression ratio of the fuel and air supplied to combustion chamber. This action intensifies the damage mechanisms on the cylinder head.

By designing the parts of the engine with different geometries and materials, these problems can be overcome. Cylinder head is the most complex part of the engine unit. Therefore, the analysis of this part is a problem in the thermal and structural analysis program. The geometry and the material of the designs on the cylinder head are the tricks of the automotive companies which they are competing on [1].

Engine dynamometer (dyno) test is a device to measure force, torque or power of the engine. In a dyno test, the engine unit is fully assembled and the crankshaft of the engine is coupled to a dynamometer with coupling. To run the engine, proper fuel depending on the type of the engine is fed to the engine. In this type of test, effects of the thermomechanical fatigue can be studied on the cylinder head [2].

Possible failure of the other parts of the engine unit during the test or even failure in the dyno test device are some disadvantages of the dyno test which can interrupt the whole test. The other and the most important disadvantage of the dyno test is that the duration of the test and fuel consumption of the engine is quite high and costly. These are the unfavorable parts of the dyno test for studying the thermomechanical fatigue of cylinder head only.

1.1 Purpose of Thesis

In the design of the thermomechanical fatigue test rig, it is aimed to overcome these obstacles and reduce the test duration and fuel consumption.

In the thermomechanical fatigue test rig, all parts of the engine unit except the engine block, the cylinder head and the parts located on it is removed. In this way, the possible failure of other components of the engine unit such as turbo, injectors or pistons is prevented. As a fuel, natural gas is fed to the engine block from the bottom of the engine block with enough air to have stoichiometric combustion. With controlling the natural gas and air to the combustion chamber, AFR can be controlled.

Consequently, by changing AFR, fuel explosion in the combustion chamber can be stimulated as an original fuel type of the engine. In result, the cylinder head can be exposed to realistic thermomechanical fatigue factors. In this type of test, besides the possible failure of other components is prevented, test duration is halved and fuel cost is highly reduced.

Thermal map of cylinder head during the test can be obtained with the measuring instruments on the cylinder head and fed to the thermal and structural simulation programs to increase the accuracy of the cylinder head model and the relating analysis.

1.2 Literature Review

Thermomechanical fatigue on cylinder head is a huge issue if the automotive companies have to satisfy their customers and be in the defined standards. For testing the durability of the cylinder head to thermomechanical fatigue factors, the common way is to use thermal and structural analysis programs such as ABAQUS and ANSYS. Also, the engine dyno test is a good way to test a cylinder head prototypes.

Also Carlos Carvalho Engler-Pinto Jr. in his studies at “thermomechanical fatigue analysis of cast aluminum cylinder heads” developed a thermal fatigue test rig [3]. His system is designed in a way that it is only capable of to stimulate start/stop cycles. In his tests, he raises the temperature in the cylinder head, later on, he cools down the same point by direct contact of the coolant. His schematic representation can be seen in figure 1.

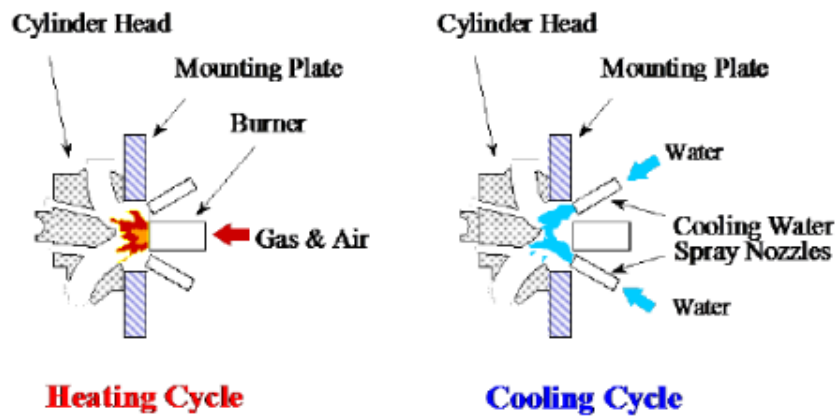


Figure 1.1 : Carvalho Engler Thermal fatigue test rig representation.

“Iabg” company in Germany also developed the cylinder head test bench. Their cylinder head test bench can be used time-lapse simulations of the thermomechanical fatigue cycles for cylinder head. Our thermomechanical test rig design is very similar to “Iabg”’s companies cylinder head test bench [4].

2. SYSTEM COMPONENTS OF THE TEST RIG

2.1 Overview

TMF test rig is composed of various measurement devices, actuators and controllers to have proper feedback and control over the system. Software with its SCADA interface is developed. Software is capable of implementing several scenarios and control options on the system. It also includes data logging and real-time data observing systems. These components are;

- Flow transmitters
- Pressure transmitters
- Actuators (Valves)
- AC drive
- Industrial air ventilator
- Burners
- Thermocouples
- Lambda sensors
- PLC

2.2 Flow Transmitters

Flow meters are devices to measure the flow rate of a liquid or a gas passing through the pipeline. There are several types of flow meters such as rotameter, venturi, orifice, ultrasonic, and turbine meter. Different type of flow meters has a different principle for measuring the flow rate. Flow meters can only display the value of the flow rate, and cannot transmit it to the controller or data monitoring system.

In most of the industrial applications, there is always a need for process control, data collection or at least data monitoring. For this purpose, flow transmitters are crucial devices for data transmission.

Flow value can be transmitted in the form of milliamps, direct current voltage, pulse and etc.

The flow transmitter is used in TMF test rig is made by cs-instruments. These flow transmitters are working with calorimetric measuring principle and there is no need for additional temperature and pressure compensation. It can measure between 0-720 m^3/h in air pipelines and 0-170 m^3/h in natural gas pipelines of the test rig. The flow transmitter can be seen in figure 2.1.



Figure 2.1 : CS-Instruments VA520 Flow Transmitter.

These flow meters also have a screen on them that actually make them flow indicator and transmitter. These flow transmitters transmit flow rate value in the form of 4-20mA to PLC. The flow rate unit can be changed as m^3/min , l/min, l/s, kg/h, kg/min, kg/s, and cfm. They have also integrated Modbus output which makes them to easily transfer parameters easily via Modbus. There is a separate flow transmitter on each pipeline of air and natural gas.

Pt45, Pt1000 sensors are used for measuring the flow rate and can operate between -30°C and 80°C . The operating pressure is up to 16 bar which is quite enough for TMF test rig.

Since these flow transmitters are working with calorimetric principle, they are very sensitive against disturbances. Therefore, it is necessary to ensure the recommended straight pipeline length in the inlet and outlet of the flow transmitter.

The air pipeline is 1 1/2" and the natural gas pipeline is 1" in diameter. The minimum inlet pipeline length which recommended by the manufacturer as 15 times of the diameter in the inlet and 5 times an outlet. The minimum length in both sides of the flow transmitter can be seen in figure 2.2.

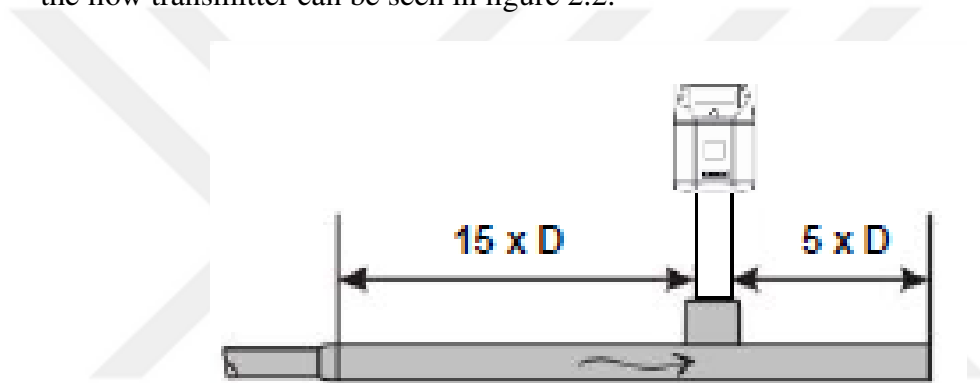


Figure 2.2 : Representation of minimum length in both side of flow transmitter.

The dimensions of the flow transmitter can be seen in figure 2.3.

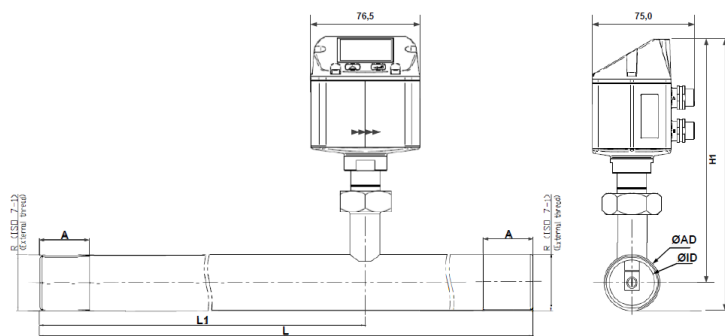


Figure 2.3 : Dimension of flow transmitter.

2.2.1 Calorimetric Principle

The flow transmitters, which works with the calorimetric principle, actually use the physical laws of heat transports in flows. There are two technical solutions, continuous and regulated heating [5].

2.2.1.1 Continuous Heating

Flow transmitter is consisting of a probe with two temperature sensors integrated into it. One of the sensors is continuously heated with wire-wound with constant heating power and measures the temperature of the heating element. The other sensor measures the temperature of the medium in the pipeline.

The temperature difference measured by these two sensors depicts the flow rate. The higher the flow velocity of the medium in the pipeline, causes less temperature difference. While the medium flowing past the probe tip fastly, fewer molecules in the medium touch the behind of the probe, therefore the more cooling effect is appearing.

2.2.1.2 Regulated Heating

The probe construction is the same as continuous heating, but there is a difference in heating the sensor. In this solution, the temperature measured from two sensors must be kept the same with regulated heating power. As the flow velocity changes through the pipeline, the temperature measured by the unheated sensor changes and heating power must be regulated in order to measure the same temperature. The applied heating power depicts the flow velocity of the medium in the pipeline.

2.3 Pressure Transmitters

The pressure transmitter is a device that converts pressure to an electrical signal. Various pressure transmitters are existing in the market with different types of output such as digital output pressure transmitter, voltage/current output transmitters and etc. Yet all the pressure transmitters convert the pressure to an electrical signal with the same principle [6].

The pressure transmitter located on the air pipeline can measure between 0-100 mBar. The other two-pressure transmitter located on the coolant pipeline to measure the coolant pressure in the inlet and outlet of the engine block can measure between 0-3 Bar. These transmitters can operate between -40°C and 135°C, which is suitable if the coolant temperature were considered. The pressure transmitter, which located on the natural gas pipeline, can measure between 0-100 mBar. Except for the pressure transmitter located on the natural gas pipeline, the other transmitters are looked the same and can be seen in fig 2.4.



Figure 2.4 : Air and Natural Gas Pressure Transmitters left to right.

2.3.1 Piezoresistive Pressure Transmitter Principle

The electrical current pass through the piezoresistive material can be changed by compressing or straining the material. Pressure sensors use the semiconductor silicon as a piezoresistive material. The force applied on the silicon makes it more resistive to the electrical current and change in resistance is linear [7].

Multiple thin wafers of silicon between protective layers are connected to the Wheatstone bridge. Wheatstone bridge passes a small current through the silicon wafers and with changing in the resistivity of the silicon wafers by force applied on it, the current changes proportionally and this change indicates the pressure.

2.4 Actuators (Valves)

To change the flow rate of the fluid or the gas passing through the pipeline, a mechanical device which called valve, must be located on the pipeline. Valves can be adjusted using a geared or direct mechanism to the valve stem. Therefore, human interaction is required. There exist different types of valves in the market such as ball, butterfly, cock or plug, gate or sluice, globe, needle, poppet, and spool. Different types of valves have different mechanisms to adjust the flow rate passing through them.

Valves are usually made of plastic or metal and composed of several parts. The outer part which is made of metal is called the seat and it also has a soft part of plastic or rubber to be the absolute tight enclosure. The inner part which opens and closes is called the body which fits in the seat while the valve is closed. The tightness of the

valve is extremely important to prevent any leakage of the medium that passes through the valve to prevent any accidents or explosion in some cases. In figure 2.5 the major parts of the plug valve can be seen.

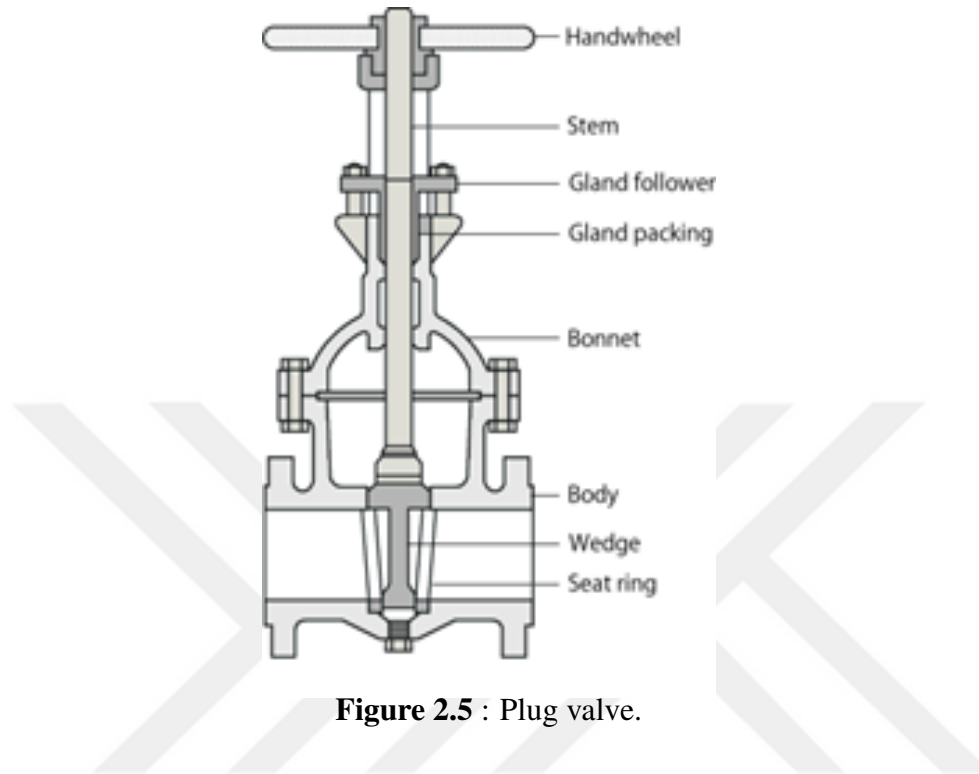


Figure 2.5 : Plug valve.

Actuators are mechanisms to eliminate the need for human interaction for adjusting the valves. Actuators are mechanisms that need an energy source to move the mechanical parts of the valves. This energy can be electric current, pneumatic pressure or hydraulic pressure. Actuators can be designed in a way that in case of failure of the actuator, the valve will stay open or close. Also, they are defined by their operation as linear such as a ball or plug valves or quarter-turn such as gate valves.

Actuators are actually designed for applications that human interaction is dangerous, impossible or inaccessible.

For controlling the flow rate of the air and natural gas in TMF test rig, valve actuators which made by Siemens company are used. These valves are composed of two major parts as proportional controlling element and actuator.

Proportional controlling element is simply a plug valve which has 90 degrees angular rotation. Proportional controlling element designed for fitting between counter-flanges, for integration into gas trains. In figure 2.6 the proportional controlling element can be seen with its mounting plate.

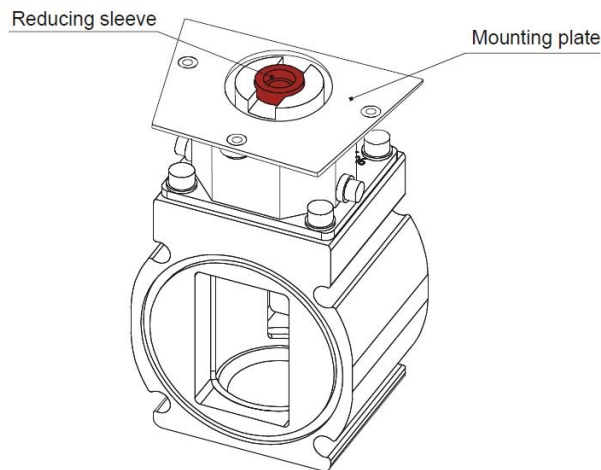


Figure 2.6 : Plug valve.

The actuator part is composed of the Synchronous motor up to 18 Nm torque. The actuator has a designed lifetime of 250,000 start cycles under load with a related torque in the entire rotation angle range. These actuators can be controlled proportionally by electric current between 4-20mA. It also has an input terminal for emergency situations to fully close or open the valve.

The lower part of the actuator is made of die-cast aluminum and the upper part of the actuator is made of heat-resistant plastic to protect the electrical circuit of the actuator from environmental factors. The actuator itself can be seen in figure 2.7.



Figure 2.7 : Actuator.

The internal electric circuit of the actuator can be seen in figure 2.8.

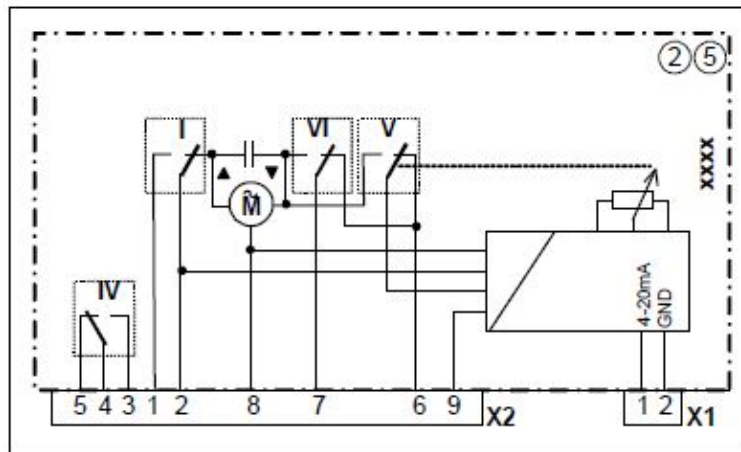


Figure 2.8 : Electric circuit of actuator.

The X1 is a low voltage terminal for 4-20mA input connection and the X2 is a high voltage terminal for actuator supply, emergency open/close input and auxiliary connections.

2.5 AC Drive

AC drive is a device for changing the speed of the AC motor by changing the voltage and frequency of the power supplied to the AC motor. The nameplate volts/hertz ratio of the AC motor must be preserved to prevent excessive heating of the motor and maintain proper power factor.

The electronic devices that are controlled by the microprocessor make varying the voltage and the frequency in the output of the AC drive. It also has rectifier and inverter units. The rectifier converts the AC voltage to DC voltage and inverter changes the DC voltage back to the AC voltage.

In TMF test rig, the AC drive made by Allen-Bradley Company in figure 2.9, is used in the same purpose. PowerFlex is the given name to the AC drive by this company. In the TMF test rig, The AC motor pump, which is made by the Grundfos Company, is used for pumping the coolant to the engine block.

The aim of using AC drive for this pump is to control the flow rate of the coolant in both heating and cooling cycles.

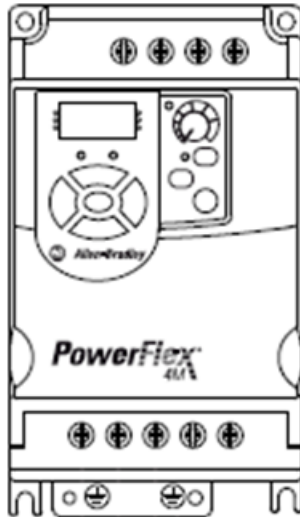


Figure 2.9 : AC drive.

This product is capable of protecting the AC motor from overload current and by entering the volts and hertz on the nameplate, it preserves the volts/hertz ratio. 4-20mA electric signal is the communication way between this product and PLC.

The other communication electrical signals such as 0-10V or RTU protocol can be selected in the configuration of the device.

The wiring of the power lines and communication lines can be seen in figure 2.10 and 2.11.

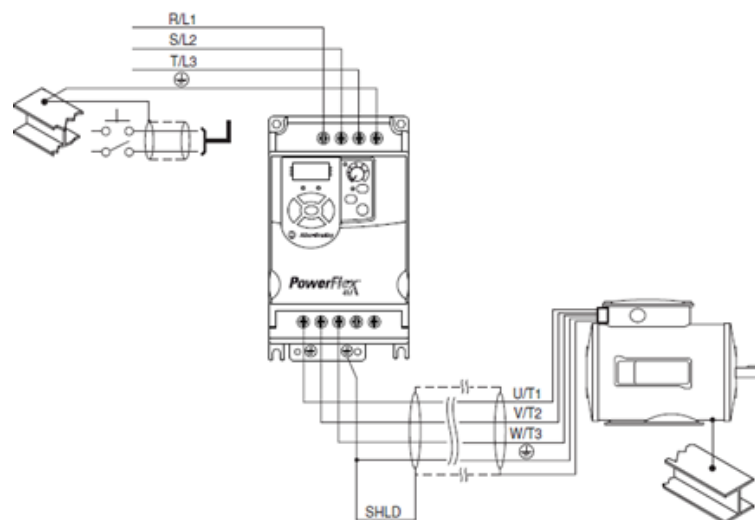


Figure 2.10 : AC drive wiring diagram.

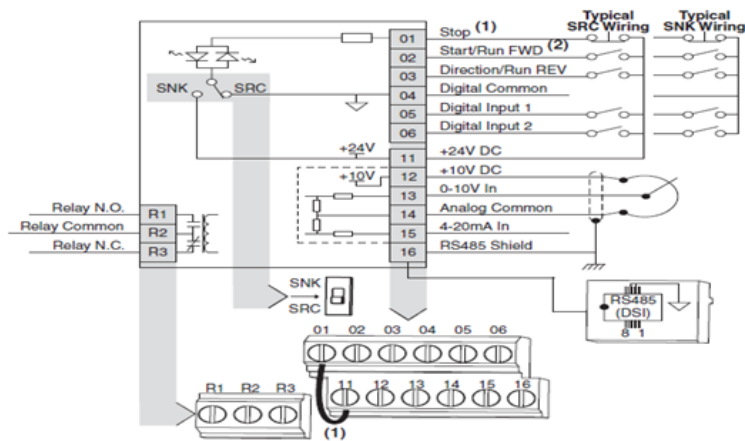


Figure 2.11 : Control circuit of the AC drive.

2.5.1 Working principle of the AC Drive

AC drive is simply consisting of three sections: the rectifier unit, DC bus, and inverter. These three sections can be seen in figure 2.12.

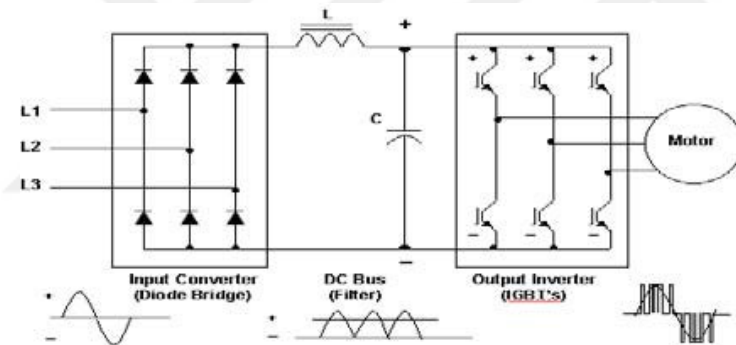


Figure 2.12 : AC drive working principle.

Firstly, the supply voltage is passed through the diode bridge which converts the AC voltage to DC voltage. Later on, it passes through an LC filter, to eliminate any harmonics that could be generated during the AC to DC conversion. Finally, it passes through the six switching elements generally IGBTs which are driven by PWM, that converts the DC voltage to quasi-sinusoidal AC voltage supply to the AC motor [8].

AC drives have benefits such as reducing the power consumption at lower speeds, increase the rotary components at lower speeds, reduce noise and vibration and having high power factor.

2.6 Air ventilator

An air ventilator for feeding air to TMF test rig with the aim of mixing air with natural gas is used. This air ventilator is basically a centrifugal fan. Centrifugal fans also called as blowers are different with axial fans in working principle.

In axial fans, the air flow is created by blades rotating around an axis that draw air in parallel to that axis and force air out in the same direction. The flow rate of the axial fans is quite high but low in pressure. Therefore, for pumping the air through the pipeline is not suitable. But their low power consumption makes them useful in many applications.

However, in the centrifugal fans, the pressure of the outlet air is highly increased by a fan wheel. The fan wheel is a series of blades mounted on a circular hub. Centrifugal fans push the air radially and the direction of the air in the outlet is changed usually by 90 degrees from the direction of the inlet air [9].

Since the air pressure in the outlet of centrifugal is high, they are ideal for high-pressure applications as TMF test rig. They also have benefits such as high durability, easy maintenance, and high versatility. The example of the axial fan and centrifugal can be seen in figure 2.13.

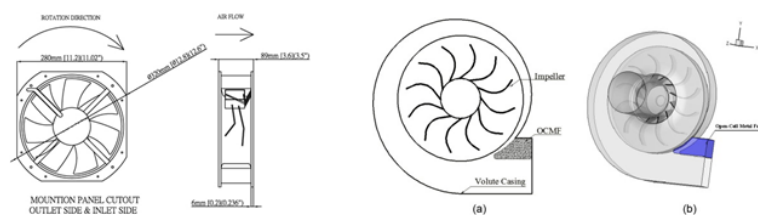


Figure 2.13 : Centrifugal fan.

The BYK90 model of the centrifugal fan made by the İncircioğlu company is used in the TMF test rig. The body of the fan is well designed to prohibit any vibration and air leakage.

The electric motor speed is up to 3000 RPM and it directly coupled to the impeller. The maximum flow rate of the centrifugal fan is $1000 \text{ m}^3/\text{h}$ and the static pressure is 800mmss at 20°C . The supply voltage is three phases and power consumption of the fan is 7.5 KW .

The performance curve of the centrifugal fan can be seen in figure 2.14.

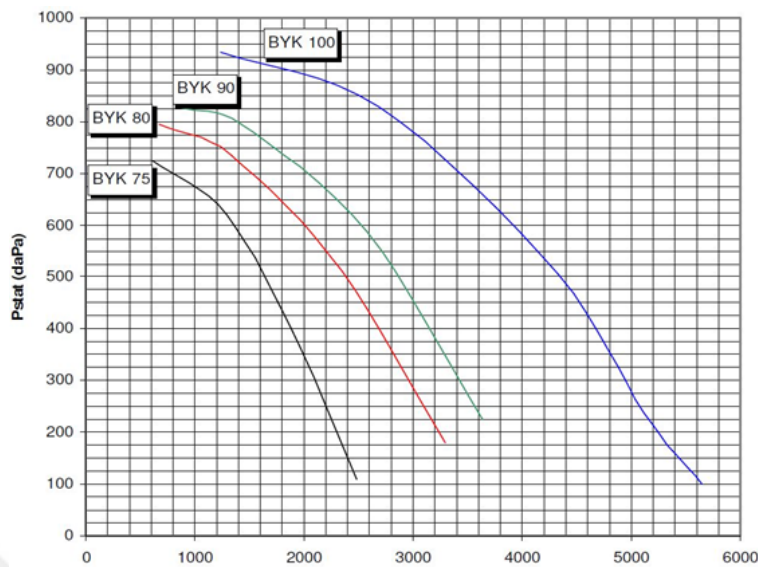


Figure 2.14 : Performance of centrifugal fan.

2.7 Gas Burners

The gas burner is a mechanical device for mixing the fuel with an oxidizer such as air to produce a controlled flame. The flame can be used in different purposes such as illumination or heat. Gas burners have many usages in the industry such as brazing and welding. There are also domestic and commercial gas burners such as gas stoves and cooktops [10].

BP M 5 GV S/30 model of the Riello brand gas burner is used in the TMF test Rig. The gas burner is a blown-air burner which can operate with natural gas, LPG, lean gas and gas with low calorific power.

Burner operation may be automatic or semiautomatic, and the burner is equipped with electric ignition and detection electrode. Max. thermal power is 58 kW (50.000 kcal/h) and min. thermal power is 5 kW (4.125 kcal/h). Because of its flexibility, this burner may be adjusted with a wide capacity range up to a 10:1 ratio. With this feature, it is possible to reduce or increase the combustion energy.

In the TMF test rig, the burners are controlled by the Siemens brand gas burner controller. In figure 2.15 the dimension of the gas burner can be seen.

As it can be seen in figure 2.16, the gas burner has the air inlet, gas inlet, detection, and ignition probes.

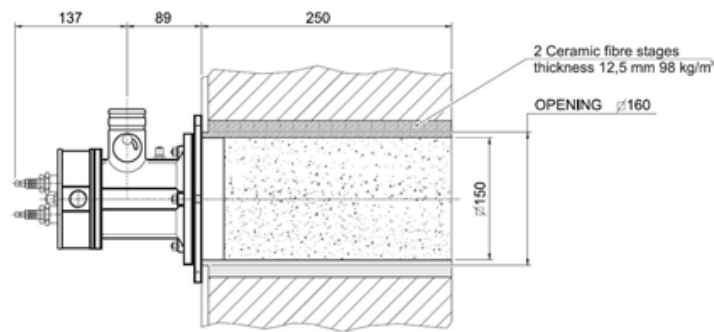


Figure 2.15 : Dimensions of gas burner.

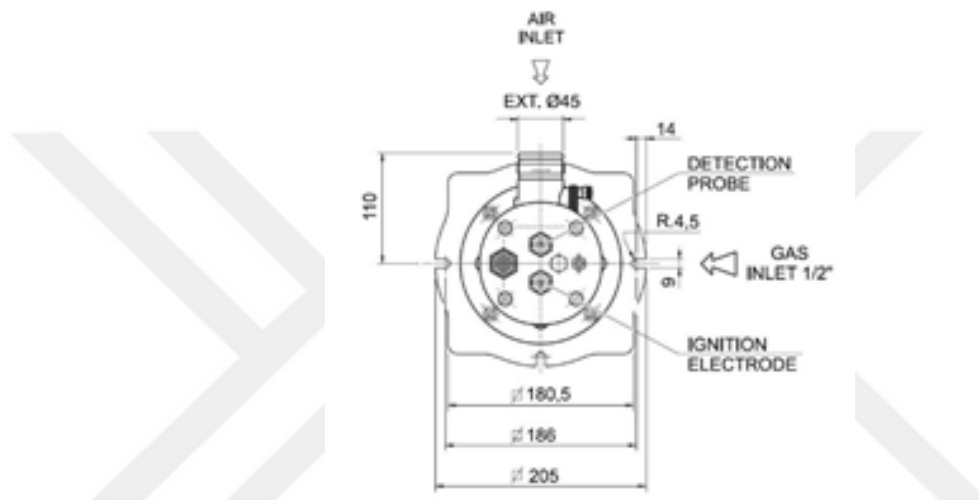


Figure 2.16 : Components of gas burner.

2.8 Gas Burner Controller

LME 44 model, Siemens brand gas burner controller is used in the TMF test rig. This controller is for startup and supervision of the gas or oil burners. The flame is supervised by an ionization probe or flame detector. In case of flame extinction, or improper flame quality, the controller shuts the fuel inlet valve to the burner and stops the process. The controller can be seen in figure 2.17 also the terminal connection of the controller can be seen in figure 2.18.



Figure 2.17 : Gas burner controller.

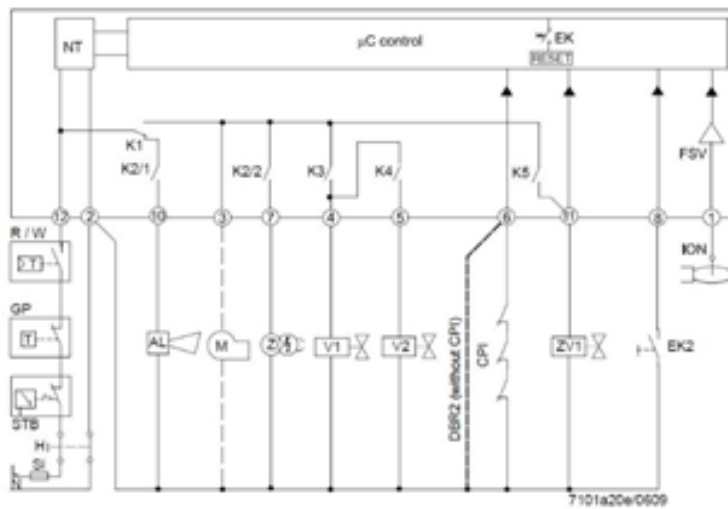


Figure 2.18 : Wiring diagram of gas controller.

2.8.1 Detection probe working principle

Gas burner controller applies an AC voltage to the detection probe located in the burner barrel. Therefore, the ionization current starts to flow between the detection probe and the burner barrel and finally to the ground. The flame surveillance is accomplished by making use of the conductivity and rectifying the effect of the flame. The flame signal amplifier only responds to the direct current component of the flame signal. A short-circuit between the ionization probe and ground causes the burner to initiate lockout since it cause alternative current. Also, the current quantity must be in microamps. In figure 2.19, the flame equivalent circuit is illustrated.

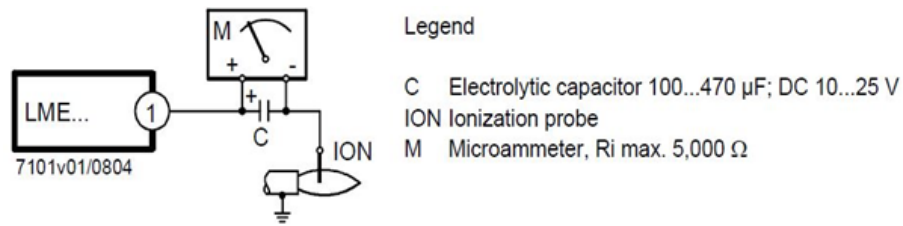


Figure 2.19 : Flame equivalent circuit.

2.9 Thermocouples

For exact measuring of the temperature, many sensors and devices have been invented throughout history. The temperature scale is the first device that invented which converts the temperature to meaningful quantities. Later on, with advanced technology, new methods for measuring the temperature are created. Nowadays the important devices that can measure the temperature very accurately are an infrared thermometer, Langmuir probes, pyrometer, resistor temperature detector (RTD), Thermistors and Thermocouples [11].

2.10 K-type thermocouple

In the TMF test rig, for measuring the temperature on the cylinder head and the engine block, thermocouples are used. Thermocouples are made of two wire that also made of distinct metals. These two wires are welded at one end. This point is also called a junction. While this junction exposed to change in temperature, a voltage appears between to wire. By measuring the voltage on the other end of wires, the temperature can be obtained via the thermoelectric voltage table.

Thermocouples are in different types. The thing that makes them different from each other is lying on the which metal that is made of. Type J, K, T, and E are made of the base metals while the R, S, and B are made of the noble metals. Each type of the thermocouples has its own characteristics such as durability, vibration resistance, chemical resistance and most importantly the measurement range.

The K-type thermocouple is used in the TMS test rig for temperature measuring. The k-type thermocouple is made of Nickel-Chromium and Nickel-Alumel. The k-type thermocouple is the most common one since it is cheap, accurate, reliable and has a

wide range of measurement. The k-type thermocouple can measure between -270°C and 1260°C with the accuracy is $\pm 0.75\%$. In figure 2.20, an example of the K-type Thermocouple can be seen.



Figure 2.20 : Dimension of gas burner.

2.11 Lambda sensor

Lambda sensor which also called an oxygen sensor is an electronic device that measures the ratio of the oxygen in the gas or liquid developed by the Bosch Company. The sensing element is made of a thimble-shaped zirconia ceramic which coated on both sides with the platinum layer. On the side is the reference side and the other side is for exhaust [11].

The most common application of the lambda sensor is the measurement of the exhaust oxygen ratio in the internal combustion engines. By measuring the oxygen ratio in the exhaust, the AFR can be manipulated to increase the performance of the internal combustion engine.

Lambda sensor is fundamental devices in electronic fuel injection and emission control systems. They are located in the exhaust of the engine and help to determine if the AFR of the combustion engine is rich or lean. Therefore, it prevents from entering the unburnt fuel and oxides of the nitrogen to the atmosphere.

Lambda is a mathematical calculation representing air/fuel ratio. The figure is derived by dividing the actual air/fuel ratio of the engine by the theoretically correct value [14.7:1]. Rich mixtures produce Lambda values that are less than one, leaner mixtures are higher than one. Lambda is a compromise between power [$\lambda < 1$] and economy [$\lambda > 1$] as shown in figure 2.21.

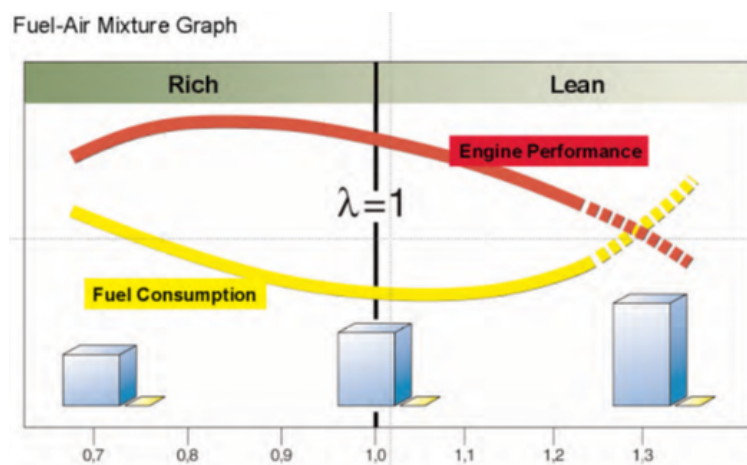


Figure 2.21 : Lambda parameter and engine performance versus fuel consumption.

Oxygen Sensor output voltage will range between 100 - 900mV. Rich mixtures (low oxygen) will produce high voltage, lean mixtures (excess oxygen) will produce low voltage. Oxygen Sensors operate at a minimum temperature of around 360°C. The average output from the lambda sensor is around 450mV. The stability of sensor operating temperature is a function of the heater, as well as the physical position on the vehicle.

In figure 2.22, the lambda sensor can be seen.



Figure 2.22 : Lambda sensor.

2.12 Programmable Logic Controller (PLC)

PLC is a specialized device for controlling machines and processes in the industry. It consists of a central processor unit, memory, and communication port. PLC is designed to survive in the harsh environment of the industry and has a response in a limited time to the operations to avoid any unintended and fault operations and keep the system safe.

PLC can be in different sizes that can fit in the pocket of a jacket or needs an electrical panel to be installed. Smaller PLCs have fixed input and output pins and are for very small operations. However, in the bigger PLCs that are called “modular”, I/O modules can be added or subtracted. Some of the PLCs have their own rack and I/O modules can be simply slid into the rack. But the other types of PLCs are panel type and must be installed to the electrical panel.

The PLC used in the TMF test rig is modular and panel type which requires DIN rail to be installed that made by the Allen-Bradley company. The model of the PLC

is 1769-L24ER QB1B and has embedded discrete I/O with 16 sinks/source 24V DC input and 16 sources 24V DC output. The voltage supply for the PLC is 24V DC. The PLC can be seen in figure 2.23.

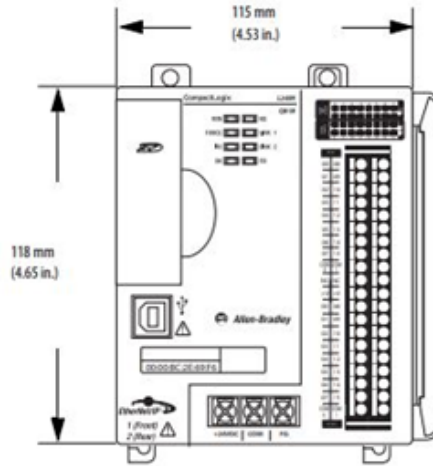


Figure 2.23 : Programmable logic controller.

An expansion 1769-IF4XOF2 I/O module is added from the right side of the PLC to have extra analog input and output. This module has four voltage input, four current input, two voltage output, and two current output. The analog voltage input of the device is between 0 and 10.5V DC. The analog current input of the device is between 0 to 21 mA. The analog voltage and current outputs of the device are the same as the inputs. The decimal representation of both inputs and outputs are between 0 and 32640.

The expansion I/O module can be seen in figure 2.24 with its terminal wiring.

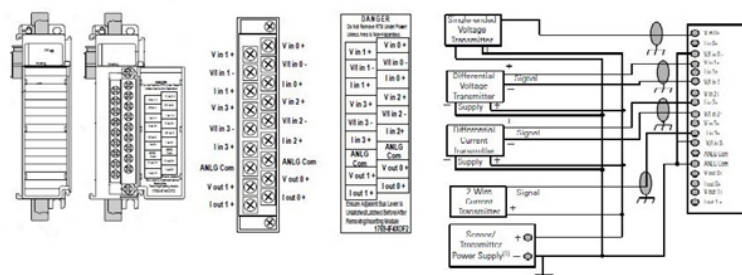


Figure 2.24 : Expansion I/O module.

However, the I/O number of the expansion I/O module is not sufficient for the TMF test rig. Therefore, the remote I/O modules with several DI, DO, AI and AO are used to have enough I/O points. These remotes I/O modules also made by the Allen-Bradley company and the benefit of these I/O modules are that they can be installed far away

from the PLC and communicate through the Ethernet/IP protocol. Their small size and high I/O number on each I/O module makes them very useful in the field.

These remote I/O modules which called "Point I/O" modules, needs a power supply and a device with an Ethernet/IP to operate and communicate with PLC. The 1734-AENT adapter is a device capable of supplying the Point I/O modules and communicate them with PLC. This adapter needs to be installed on a DIN rail as it can be seen in figure 2.25.

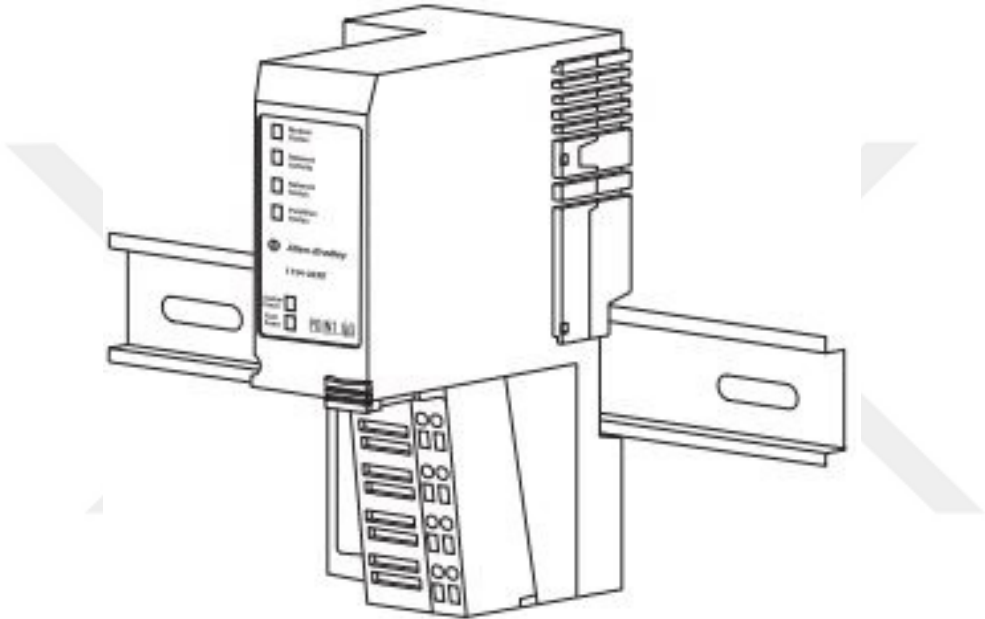


Figure 2.25 : I/O Base on DIN rail.

The detailed illustration for the adapter can be seen in figure 2.26.

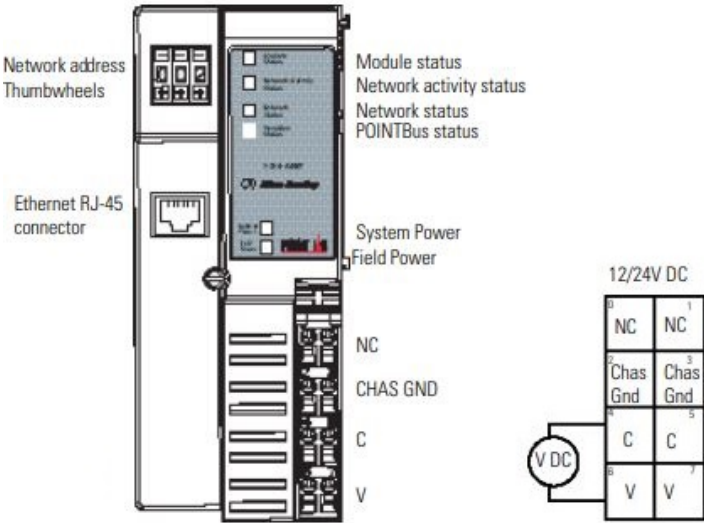


Figure 2.26 : I/O Adapter.

The Point I/O modules are connected to this adapter by simply sliding the module next to the adapter from the right side. Point I/O modules can be a DI, DO, AI, AO and etc. In the TMF test rig, five AO, three DI, three DO, 6 AI and 12 thermocouple inputs are added to this adapter.

All of the Point I/O modules at first must be added to the proper base shown in figure 2.27.

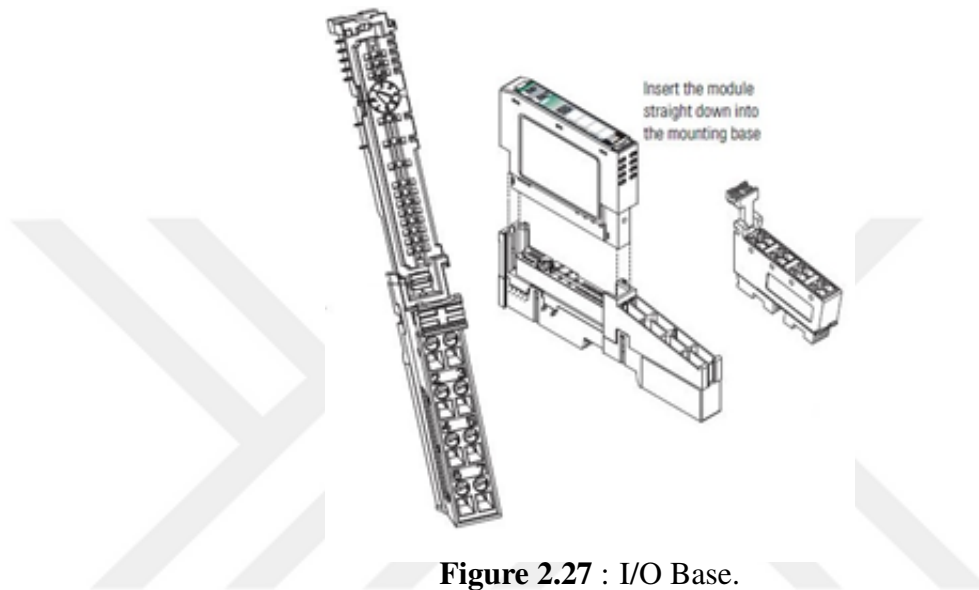


Figure 2.27 : I/O Base.

2.12.1 1734-OE4C Analog current output module

This module has four single ended, non-isolated analog outputs. The current resolution is $0.32\mu\text{A}/\text{cnt}$ over 0-21mA. It is configurable to 4-20mA applications. The I/O module and wiring illustration can be seen in figure 2.28.

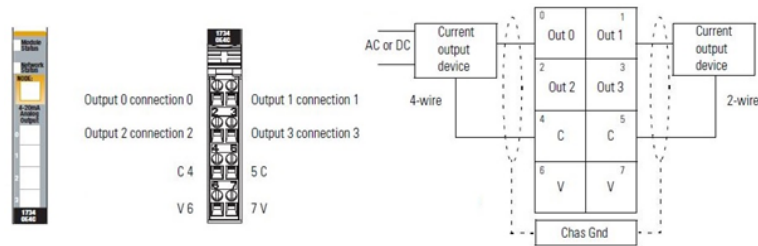


Figure 2.28 : Analog current output module.

2.12.2 1734-IV8 Digital input module

This module has 8 digital input. The minimum voltage to be in on-state is 10V DC and the maximum voltage is 28.8V DC where the 24V DC is the nominal voltage. The minimum current to be in on-state is 2mA and the maximum is 5mA where the 4mA at 24V DC is the nominal current. The nominal input impedance is $3.6\text{ k}\Omega$ and the maximum is $4.7\text{ k}\Omega$. The I/O module and wiring illustration can be seen in figure 2.29.

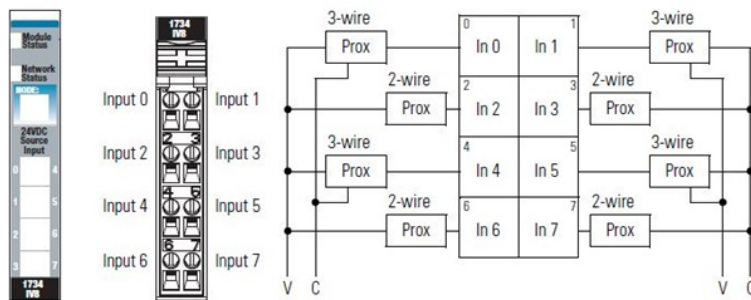


Figure 2.29 : Digital output module.

2.12.3 1734-OV8E Digital output module

This model has 8 digital sink output. There are two terms as sink and source output in digital output models. These terms are used to define the control current flow in a load. Sink digital I/O provides a common ground connection to the load where the source digital outputs provide voltage to the load. An example can be seen in figure 2.30.

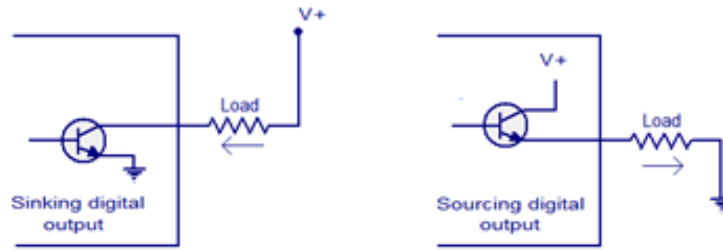


Figure 2.30 : Sink and source output diagram.

This module provides minimum 10V DC and maximum 28.8V DC at on-state where the 24V DC is the nominal output voltage of the device. The output current of the device is 1A per output and must not exceed the 3A per module. The I/O module and wiring illustration can be seen in figure 2.31.

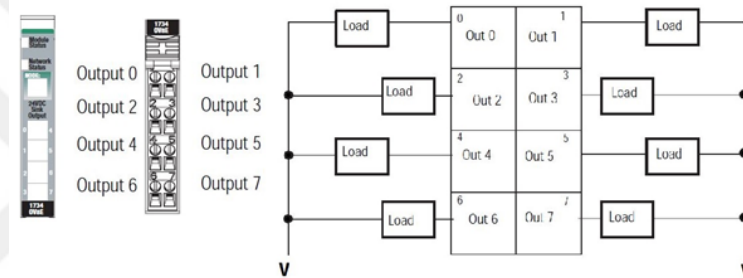


Figure 2.31 : Digital output module.

2.12.4 1734-IE8C Analog input module

This device has eight single ended, non-isolated current input. The current resolution is $0.32\mu\text{A}/\text{cnt}$ over 0-21mA. It is configurable to 4-20mA applications. The I/O module and wiring illustration can be seen in figure 2.32.

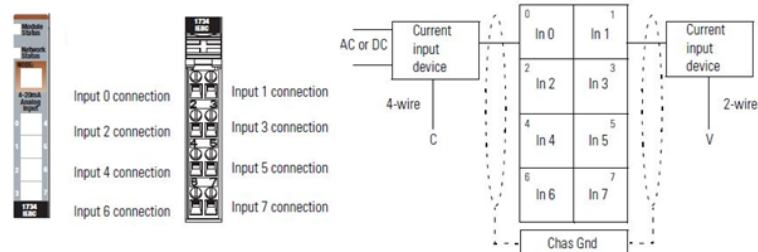


Figure 2.32 : Analog input module.

2.12.5 1734-IT2I Thermocouple input

This module has two differential, individually isolated inputs. The voltage resolution is $2.5\mu\text{V}/\text{cnt}$. B, C, E, J, K, N, R, S and T types of thermocouple can be connected

to the module. Also, it can be used as microvolt meter where the measurement range is μm 75mV. The module can measure with the absolute accuracy of 0.1%. the input impedance of the module is 100K Ω The module has a cold junction compensation range between 0 and 70C. The I/O module and wiring illustration can be seen in figure 2.33.

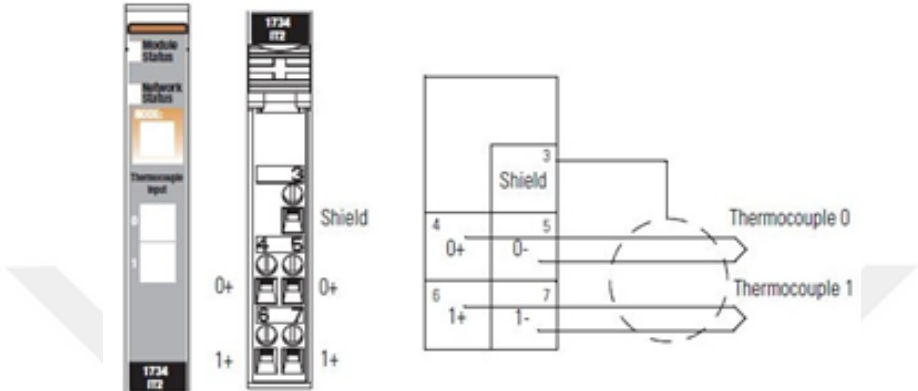


Figure 2.33 : Thermocouple input.

3. WORKING PRINCIPLE OF THE TMF RIG

In the thermomechanical fatigue test rig, all parts of the engine unit except the engine block, the cylinder head and the parts located on it is removed. In this way, the possible failure of other components of the engine unit such as turbo, injectors or pistons is prevented.

Air ventilator supplies the air through the air pipeline as depicted in figure 3.1. The air flow is measured with the flow meter and controlled by the actuator. Natural gas from the grid is fed to the gas burner in the same manner. For heating the cylinder

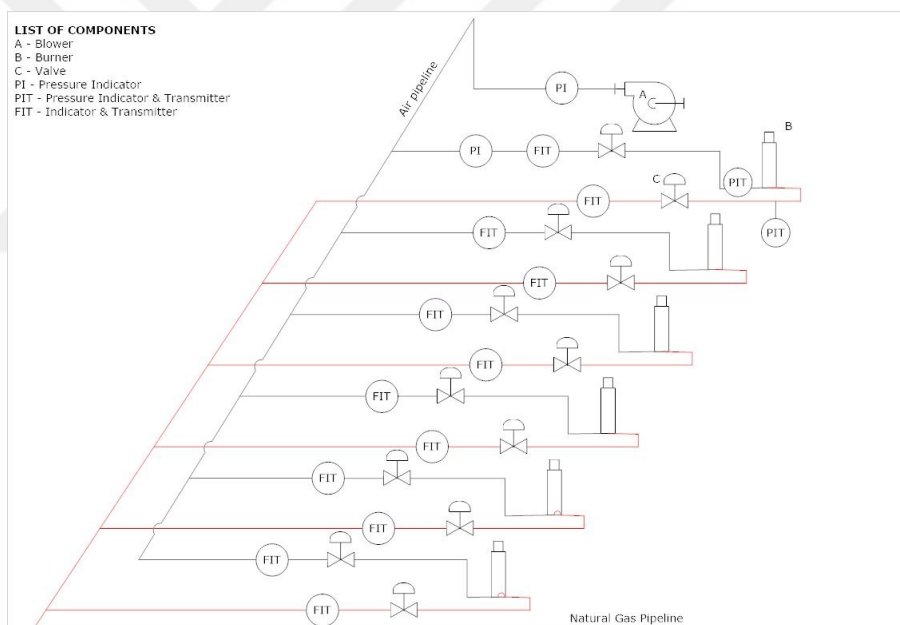


Figure 3.1 : Natural gas and air supply pipeline illustration.

head, natural gas and air are fed to the engine block from the bottom of the engine block. It is crucial to have enough air in the combustion chamber to have stoichiometric combustion. Therefore, the ratio of the air to the natural gas must be at least 10 times. The fuel mixture is burned up with gas burners and the flames start to heat the cylinder head. Various thermocouples are located on the cylinder head and the engine block for measuring the temperature.

Besides the heating, cooling the cylinder head and the engine block is demanded in order to prevent the objects from melting in the heating phase and cool down the

objects in the cooling phase to create thermomechanical fatigue. Ethylene Glycol is an odorless, colorless, sweet and medium toxic type of chemical. It is used in anti-freezing mixtures in the vehicle. In this test rig, ethylene glycol is diluted with water and stored in the 2000 liter tank as a coolant for the cylinder head and engine block. The coolant pass through the cylinder head with the help of the pump and the coolant pressure is measured in both the inlet and outlet of the block. There is a flow meter for measuring the coolant flow in the inlet. The flow of the coolant differs in the heating and cooling phases. The flow of the coolant changes with the help of AC driver which drive the coolant pump. By increasing or decreasing the frequency of the pump supply, the pump conducts the coolant faster or slower respectively.



3.1 Cases

There are four cases in the TMF test rig. These four cases can differ in the AFR of the combustion, coolant flow, set points or in the time interval of the profiles.

3.2 Phases

Each case of the test comprises heating and cooling phases. Heating profile in heating phase and cooling profile in the cooling phase can result in different cases and cycles. In this test rig, we have four cases that differ in attributes. Thus all of these cases are comprises two different heating/cooling profiles as a time-dependent or temperature dependent.

3.2.1 Time dependent

Heating phase with time-dependent profile, in any case, results in heating the cylinder head for a specific amount of time and afterward, in a cooling phase, the cylinder head is cooling down for the specific amount of time, regardless of the temperature of the cylinder head in both phases.

3.2.2 Temperature dependent

Heating phase with temperature dependent profile results in heating the cylinder head until it reaches the predefined value, afterward cooling down the cylinder head to the predefined value, regardless of the phase duration.

3.2.3 Automatic Operation

In automatic case, set points for the natural gas and air flow rates are continuously varied with tracking the predefined values in order to create random real driving conditions. The aim of this case is to expose the cylinder head to temperatures that can be reached in the real driving of the vehicle such as climbing hill and afterward, driving on flat road and finally pull away and engine stop conditions.

3.2.4 Manual Operation

In the manual case, there is no feedback control loop and the user only sets the angles of valves for both natural gas and air. The frequency of the coolant pump is also set by the user. Also, the selection of the specific burners to ignition is available.



4. CONTROL OF THE TMF TEST RIG

TMF test rig is a multi-input and multi-output system. The system needs to be controlled by a PLC to have proper expected behavior and able to data acquisition which is crucial to investigate the system behavior and for further studies.

Thus, the first thing that must be taken to account is to prevent any hazardous situation and equipment damage during the test.

For satisfying all the conditions mentioned above, Programmable Logic Controller (PLC) is used. There are several input and outputs that the PLC must handle. Inputs and outputs of the system can be seen in table 4.1 and 4.2 respectively.

Table 4.1 : Input table.

Inputs	Quantity
Natural gas flow transmitter	6
Air flow transmitter	6
Coolant flow transmitter	1
Thermocouple	1
Lambda sensor	6
Air pressure transmitter	1
Natural gas pressure transmitter	1
Coolant pressure transmitter	2

Table 4.2 : Output table.

Outputs	Quantity
Valve Actuator	6
AC Driver	6
Burner Ignition Relay	1

4.1 Inputs

Input devices are actually devices that measure the system variables and transmit to the PLC to have proper feedback control. Exact measurements of the system variable provide precise control of the related variable. Therefore the isolation of wiring of the inputs until the PLC is important and must have appropriate shielding.

Some of these sensors are transmitting the measured variable in the form of continuous electrical current. The electrical current is between 4mA and 20mA which correspond to the minimum and the maximum value that the sensor can measure. While the others are transmitting the measured variable in the form of the voltage difference.

The properties of the sensors can be seen in table 4.3.

Table 4.3 : Input devices specifications.

Input Device	Measuring interval	Unit	Output Unit	External supply
NG FT	0-170	m^3/h	mA	Yes
Air FT	0-720	m^3/h	mA	Yes
Coolant FT	10-600	L/min	mA	Yes
Thermocouple	(-270) - 1260	Celsius	mV	No
Lambda Sensor	0-950	AFR	mV	Yes
Air PT	0-100	mBar	mA	Yes
NG PT	0-3	Bar	mA	Yes
Coolant PT	0-3	Bar	mA	Yes

4.2 Outputs

These devices are processing the signal sent by PLC and take an action as an actuator or. PLC can send a signal in forms of electrical current or voltage depending on the actuator. Precise actuation is crucial to complete the control loop. Therefore, appropriate wiring with shielding is crucial.

The properties of the output devices can be seen in table 4.4.

Table 4.4 : Output devices specifications.

Output Device	Operation Range	Unit	Input Unit	External Supply
Valve Actuator	0-90	Degree	mA	Yes
AC Driver	0-400	Hertz	mA	Yes
Burner Ignition Relay	0-1	On-Off	V	Yes

4.3 Flow Control

Flow control in natural gas and the air is required for having control over the AFR in the combustion chamber. The flow control is simply made by the valve actuator and flow transmitter on each pipeline with PI controller. The block diagram of the control loop can be seen in figure 4.1.

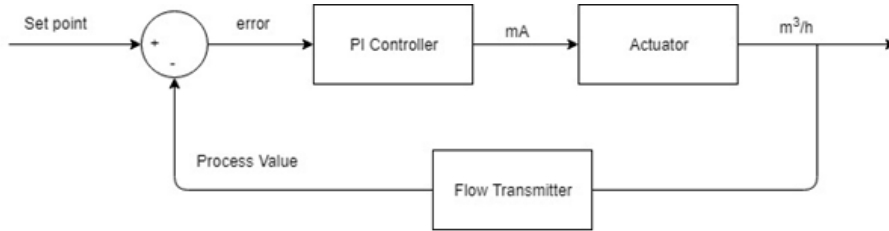


Figure 4.1 : Flow Control Block Diagram.

The important part of the flow control is in modeling the actuator. Since the actuator is sluggish to the step input, proper modeling of the actuator is not possible. Therefore by hand tuning of the PI controller, desired to settle time and steady-state error is required in multiple attempts. In figures 4.2, performances of the various tuned PI controllers can be seen.

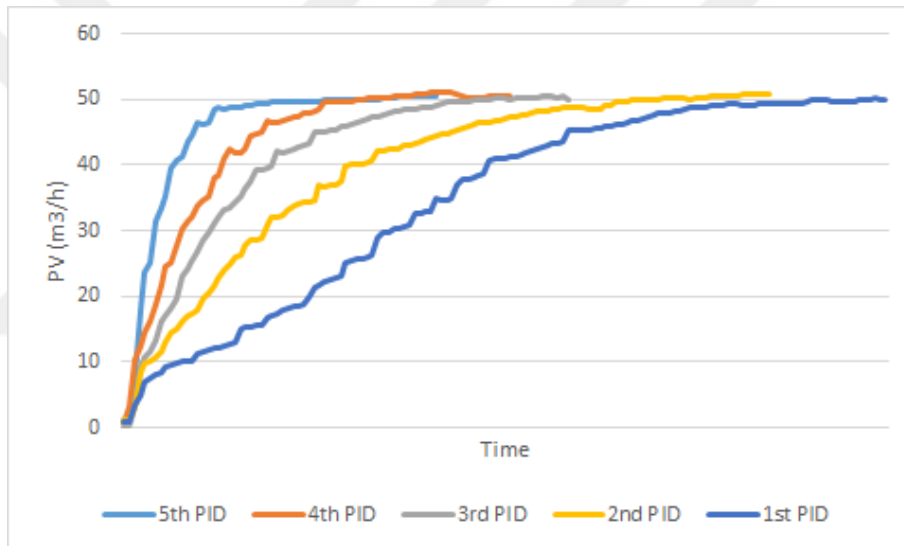


Figure 4.2 : PI controller performance.

Flow control of the coolant is also done by the PI controller, simply with the flow meter on the coolant pipeline and coolant pump which is connected to the AC driver. The block diagram of the flow control related to the coolant can be seen in fig 4.4.

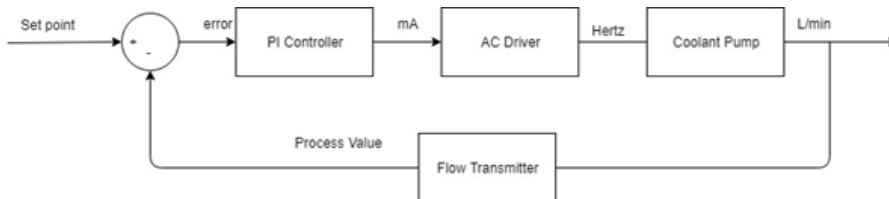


Figure 4.3 : Flow Control Block Diagram.



5. PLC CODING

Allen Bradley PLC provides coding in four languages, Ladder (LD), Function Block Diagram (FBD), Sequential Function Chart (SFC), and Structured Text (ST). For the TMF test rig, the main coding is done in Structured Text and Function Block Diagram languages. Structured Text is a high-level language that is block structured and syntactically resembles Pascal, on which it is based. Function Block Diagram is a graphical language for PLC that can describe the function between input variables and output variables. A function is described as a set of elementary blocks. Input and output variables are connected to blocks by connection lines.

The state flow of the software is roughly illustrated in figure 5.1.

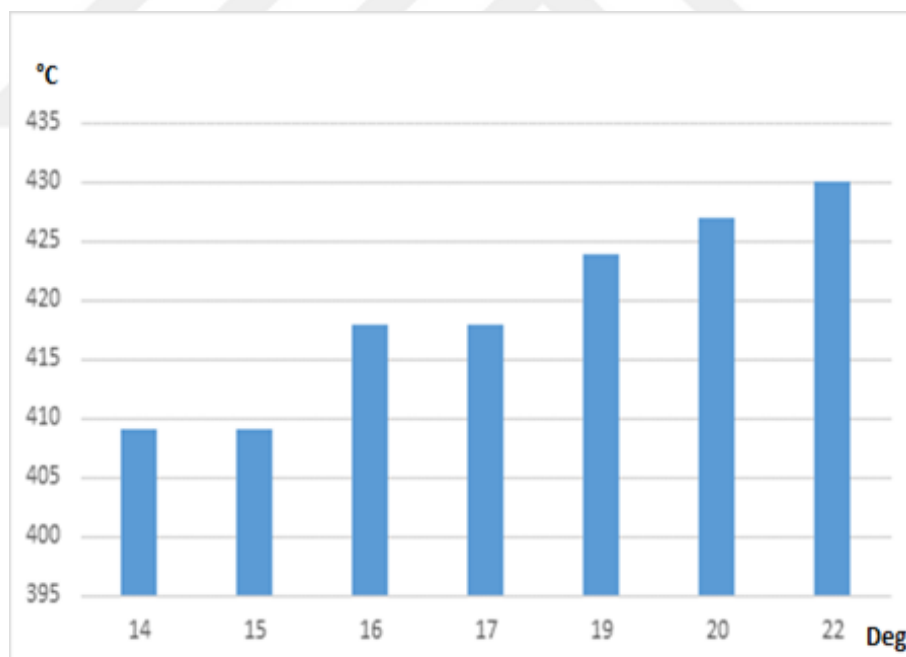


Figure 5.1 : State flow of main routine.

5.1 Main routine

The main routine is written in LD language. This routine runs in a periodic cycle of 100ms. The main routine is comprised of subroutines which shown in figure 5.1.

5.2 Input routine

In the input routine, the signals that come from the measurement devices are stored in the related tags. It is written in the ST language.

5.3 Core routine

In the core routine, system safety, cycle structure, manual and automatic test procedures, burner ignition permit and all the other crucial sections of the software is located. It is written in the ST language.

5.4 Setpoints routine

In the setpoints routine, the setpoints of the user or the setpoints that calculated in the core routine are validated and sent to PID routines.

5.5 Air PID routine (OXPID)

In Air PID routine, PID blocks are located for air flow rate control. It is written in the FBD language.

5.6 Natural Gas PID routine (NGPID)

In Natural Gas PID routine, PID blocks are located for natural gas flowrate control. It is written in the FBD language.

5.7 Coolant flowrate PID routine (CoolantPID))

In Coolant flowrate PID routine, PID block is located for coolant flowrate control. It is written in the FBD language.

5.8 Aggregate routine

In the aggregate routine, the input and output signals are scaled to proper and readable values for related devices and stored in the related tags. It is written in the ST language.

5.9 Output routine

In the output routine, the command signal is send to the related devices from the related tags. It is written in ST language.





6. SUPERVISORY CONTROL AND DATA ACQUISITION (SCADA)

SCADA is a system that provides industrial organization to control, monitor, and gather real-time data remotely. It is actually is a user-friendly interface that able the user to interact with PLC. In TMF test rig, the SCADA system is designed for the same purpose.

In figure 6.1, the flow diagram of the SCADA pages is roughly illustrated.

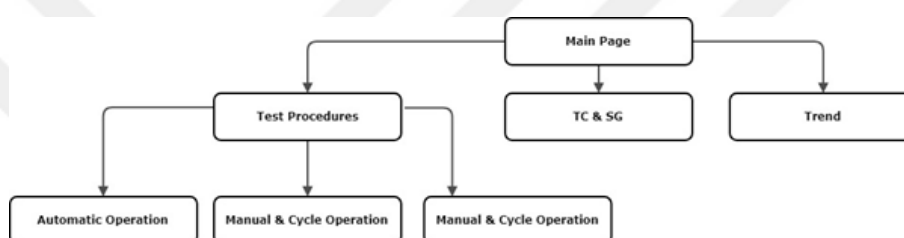


Figure 6.1 : SCADA pages flow diagram.

In the “Manual and Cycles” page, system operation is selectable as manual or one of the predefined cases.

In the manual operation, there is no active feedback control over the system, thus the angle of the valve actuators and the frequency of the coolant pump can be defined. Also, the flow rate of the natural gas, air, and the coolant liquid is observable. Burners that must be ignited during the test are selectable.

In the “Automatic Test Procedure” page, system operation is fully automatic and the system ignores case selection and manual operation.

In automatic operation, feedback control is commanding over the system. By defining the flow rate for the natural gas and air, the valve actuator’s angle for natural gas and air are set according to the PID controller. The control of coolant liquid flowrate is also done in the same manner.

In the “Cycle Profiles” page, the attributes of the cycles for each case is configurable. Cycle attributes are comprised of cycle type as a time-dependent or temperature dependent, heating time, cooling time, time offset, coolant flow rate in both heating

and cooling phases, and valve angles for both natural gas and air, the coolant flow rate in both heating and cooling phases.

In the “TC & SG” page, all the thermocouples and strain gauges values are observable.



7. Data Acquisition and Analysis

The system is able to record the values of the measurement devices and create datalogs. By investigating the datalogs, it can be seen how the cycles are applying on the cylinder head. It also makes possible to study AFR, the relationship between different actuators and outputs related to them. In figure 7.1 the valve actuator output can be observed.

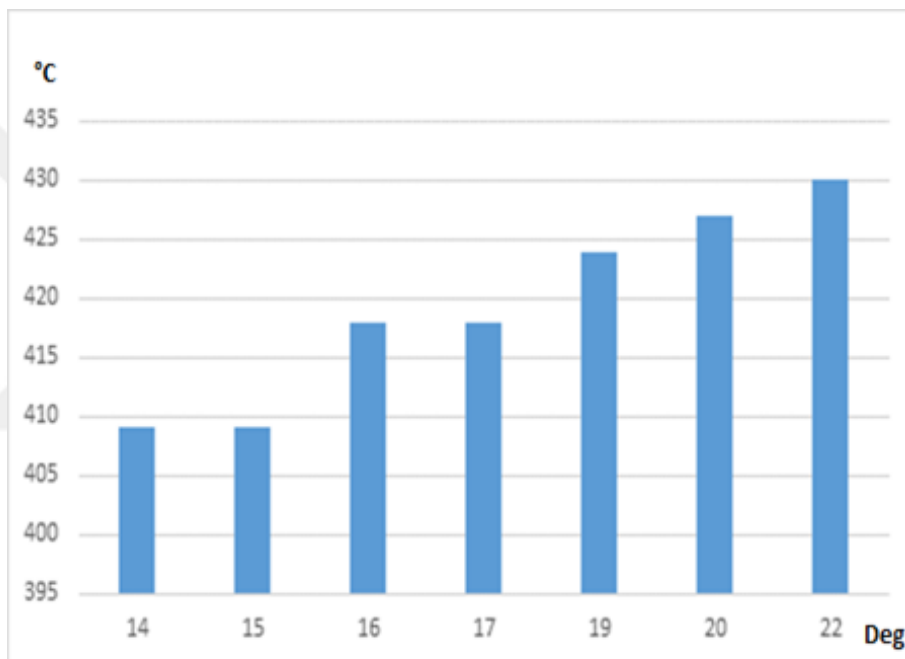


Figure 7.1 : Natural gas valve angle versus injector temperature.

In figure 7.1, the air flow is kept constant at $60 \text{ m}^3/\text{h}$. Therefore by changing the angle of the natural gas valve, the flow rate of the natural gas changes and affects the AFR directly. In figure 7.2, the relationship between AFR and natural gas valve can be seen. By comparing figure 7.1 and 7.2, the relationship between AFR and ejector temperature also can be obtained.

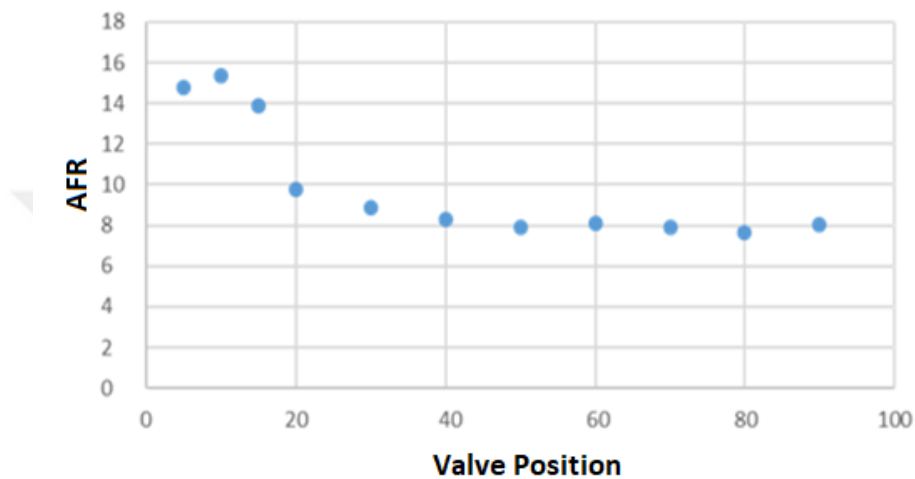


Figure 7.2 : Natural gas valve angle versus AFR.

In figure 7.3, the ejector temperature can be seen during cycles. Time-dependent cycle applied on the cylinder head and it results in temperature oscillation between in 50°C and 420°C in a controlled manner.

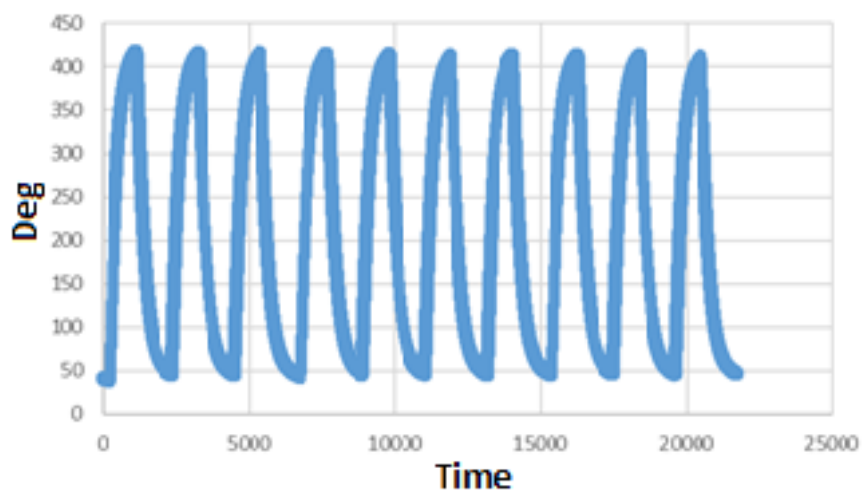


Figure 7.3 : Ejector temperature on the cylinder head during time dependant cycle.

Figure 7.4 shows a close look at a single cycle. Temperature profile, coolant, and ignition for heating phase can be seen.

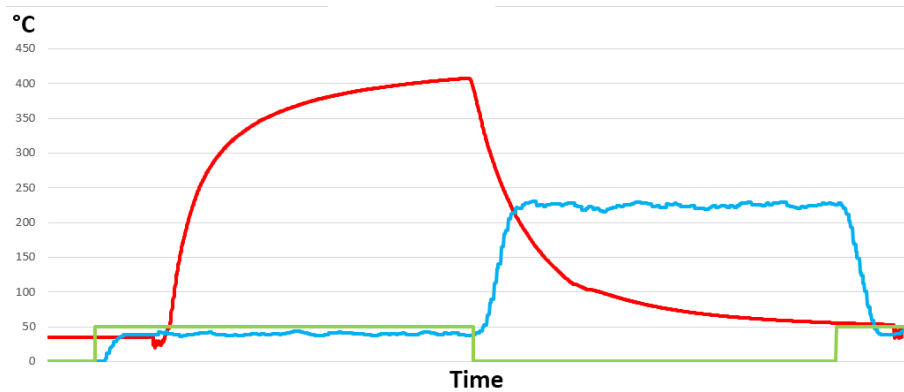


Figure 7.4 : Close look to single time dependant cycle.

The green line is ignition command, the red line is the temperature of the injector and the blue line is coolant flow rate. Heating and cooling time is 120 and 90 seconds respectively. The coolant flow in the cooling phase is 40L/min and in the heating phase is 220L/min.

7.1 Ignition dead time

As it can be seen in figure 7.4, the temperature of the injector starts to rise after while from ignition command. The reason is, it takes some time to metal for heat up and the most important is that the real ignition occurs after 17s of ignition command. In figure 7.5, the dead time of ignition is illustrated.

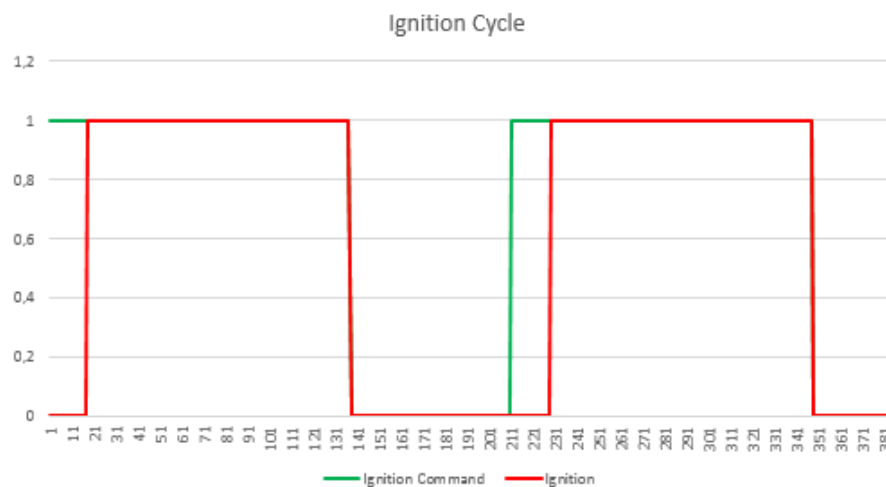


Figure 7.5 : Dead time of ignition.

The green line stands for ignition command and the red line stands for the actual ignition. The time interval that ignition has occurred is the heating phase and the time interval that ignition is not happening is the cooling phase (red line value is 1 for heating phase and 0 for cooling phase.)

This is an issue for implementing the cycles properly and takes a considerable time for actual ignition. Therefore, the dead time of ignition is included in the cooling phase for overcoming this issue.

7.2 Capability of the test rig

By investigating the outputs of the system, the capability of the test rig is written in below.

Exhaust temperature: 900-1000°C

Maximum Cylinder head Temperature: 425 °C

Minimum Cylinder head Temperature: 45 °C

Coolant maximum flow: 250 L/min

Coolant minimum flow: 10L/min

Cycle per day: 250

Total daily test duration: 10 hours

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APPENDICES

APPENDIX A : System View

APPENDIX B : Pipeline of natural gas and air

APPENDIX C : CAD draw

APPENDIX D : Electrical panels

APPENDIX E : User interface (SCADA)





APPENDIX A

Figures below are related to system setup.



Figure A.1 : TMF test rig.

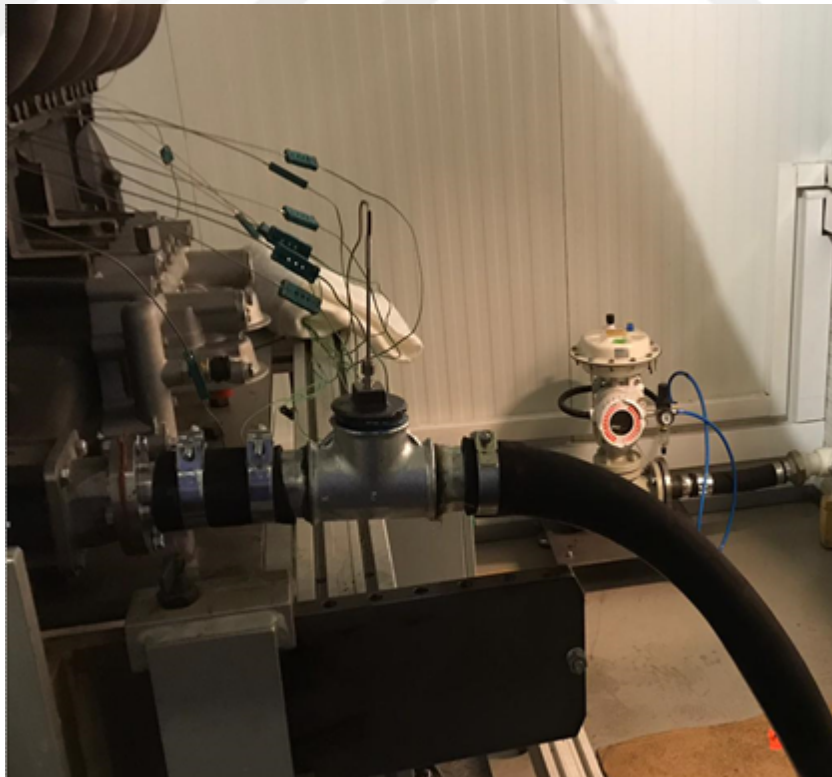


Figure A.2 : Coolant inlet.



Figure A.3 : Coolant Outlet.



Figure A.4 : Ethylene glycol and AC driver.

APPENDIX B

Figures below are related to pipeline of natural gas and air.



Figure B.1 : Fan for air supply.



Figure B.2 : Air and natural gas pipeline.



APPENDIX C

Figure below are related to CAD draw of the system.

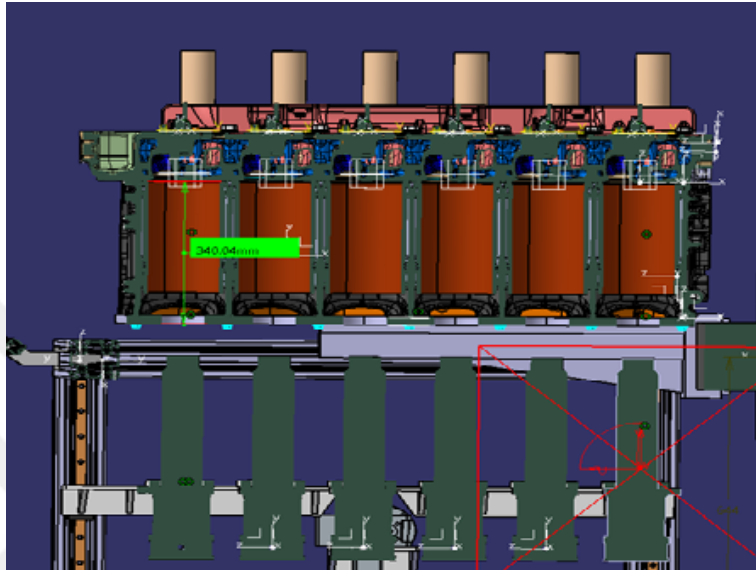


Figure C.1 : Internal view of test rig.

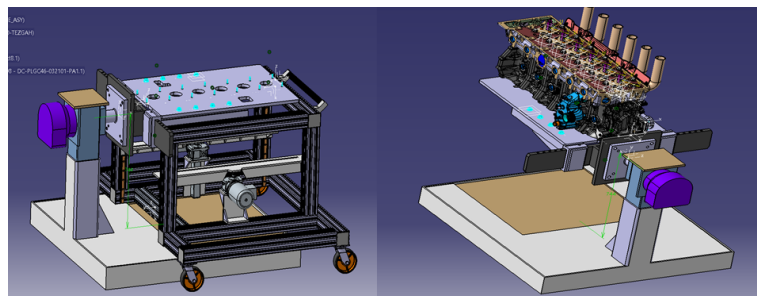


Figure C.2 : CAD draw of counter for engine block.

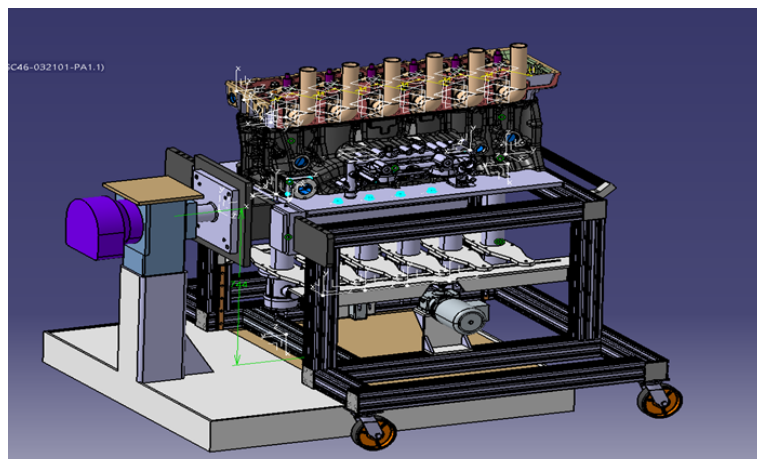


Figure C.3 : CAD draw of TMF test rig.



APPENDIX D

Figures below are related to the required electrical panels (From left to right, I/O, gas burner and PLC panel).

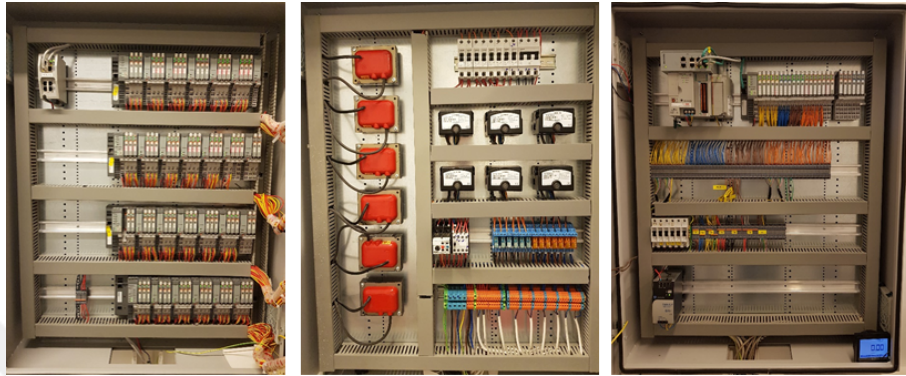


Figure D.1 : Electrical Panels.

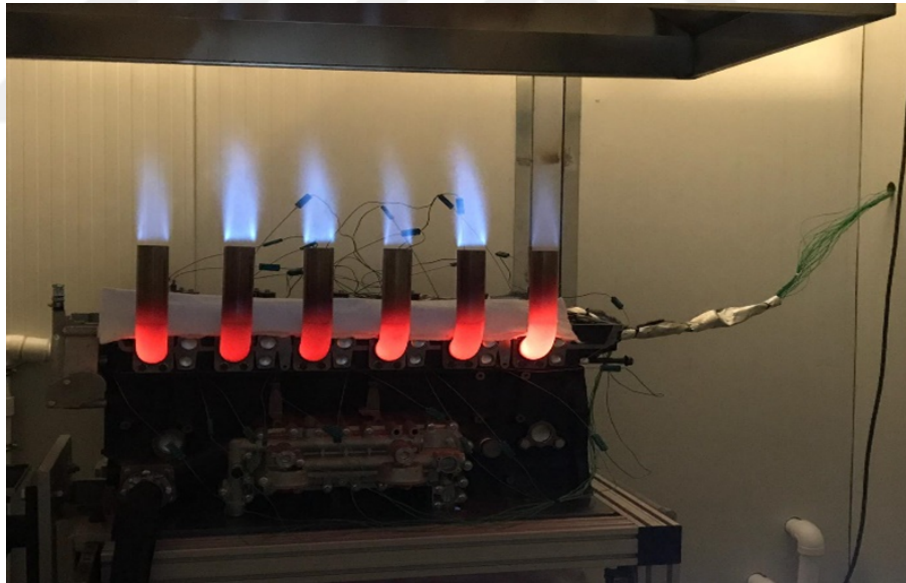


Figure D.2 : Test rig while working.



APPENDIX E

Figure below are related to user interface of test rig (SCADA).



TMF Test Rig Control Panel

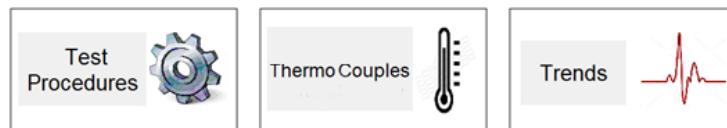
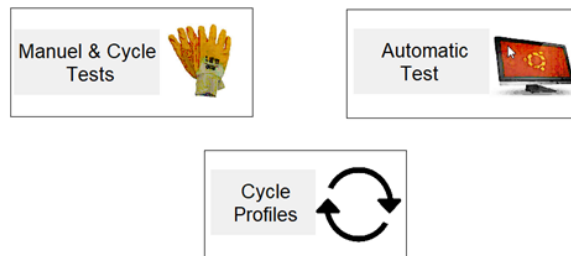


Figure E.1 : Main page.



Main

Figure E.2 : Test procedures.

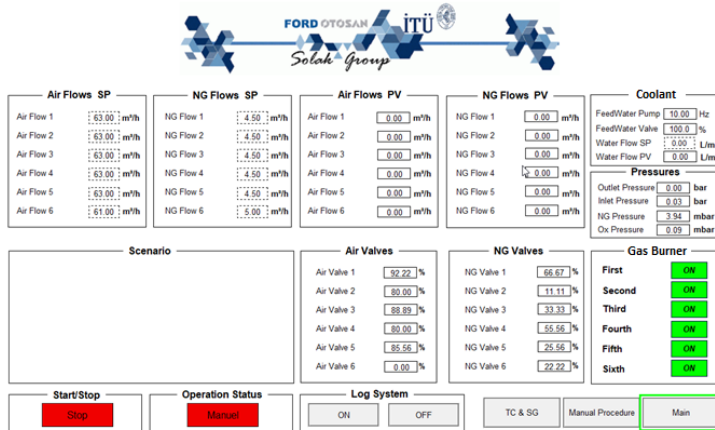


Figure E.3 : Automatic test

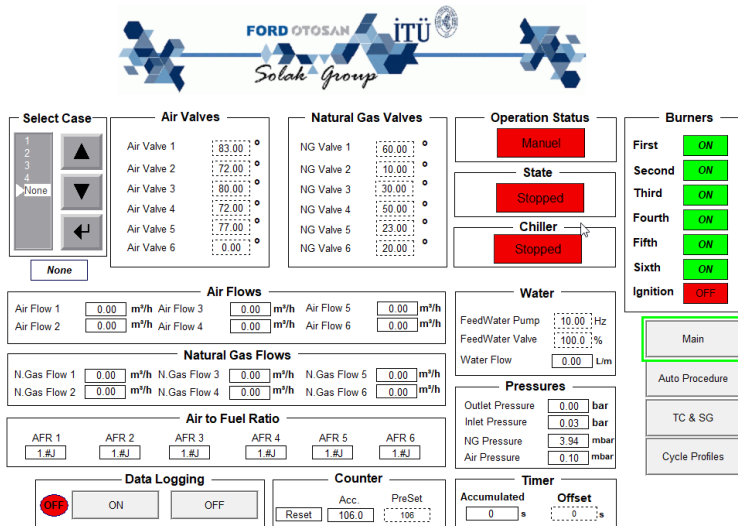


Figure E.4 : Manual test.

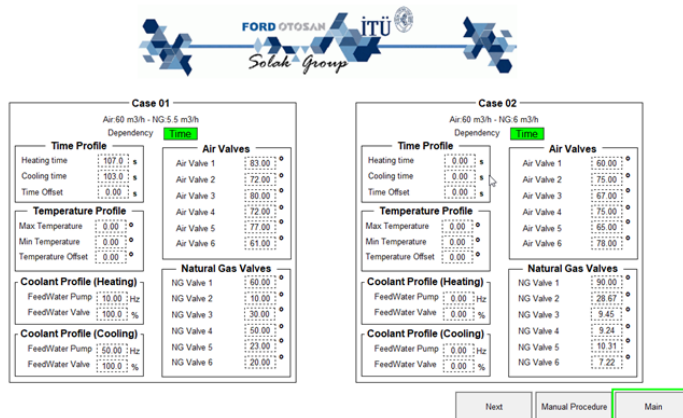


Figure E.5 : Cycle profiles.

CURRICULUM VITAE



Name Surname: Armin Mahpour

Place and Date of Birth: Oroumieh 29.03.1993

E-Mail: armin.mahpour@gmail.com

EDUCATION:

- **B.Sc.:** 2019, Istanbul Technical University, Faculty of Electrical and Electronics Engineering, Department of Mechatronics Engineering
- **M.Sc.:** 2016, Istanbul Technical University, Faculty of Electrical and Electronics Engineering, Department of Mechatronics Engineering

PROFESSIONAL EXPERIENCE AND REWARDS:

- 2019-Present Control and Calibration Engineer at Ford Otosan.
- 2018 Control and Automation Engineer at KupFer.
- 2016-2018 Control and Automation Engineer at Greenway CSP.