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METU 2006

INVESTIGATION OF THE EFFECT OF OXIDATION FILTERS ON THE PARTICULATE EMISSIONS OF DIESEL ENGINES

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SEPTEMBER 2006

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A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

R.ERSEN CERİT

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
MECHANICAL ENGINEERING

SEPTEMBER 2006

Approval of the Graduate School of Natural and Applied Sciences

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This is to certify that we have read this thesis and that in our opinion it is fully adequate, in scope and quality, as a thesis for the degree of Master of Science.

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ABSTRACT

INVESTIGATION OF THE EFFECT OF OXIDATION FILTERS ON THE PARTICULATE EMISSIONS OF DIESEL ENGINES

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September 2006, 235 Pages

Oxidation filters are used to decrease particulate emissions commonly. In this study, design of a particulate trap to produce an alternative, low cost filter has been aimed. An experimental setup has been installed according to standards to carry out tests of these designed filters. Electronic measurement and control systems have been attached to this setup to increase efficiency of experiments.

Two filter designs have been used in the experiments. First design consists of aluminum wire cloth. Second design is sheet metal structure, which includes three longitudinal cells. Metal chip is used as filter material. Empty filter tests have been performed firstly, and then experiments have been repeated with aluminum, iron, and copper chip addition in filter.

Copper chip test results are better than other metal chip for first experiments. Afterwards, experiments have been repeated with varying copper chip amount.

Suitable copper chip amount was determined based on fuel consumption rate of the engine.

As a result, designed filter reduce the particulate emissions with high efficiency. Although, carbon monoxide, and carbon dioxide gaseous emissions increase with designed filter, hydro carbon emissions decrease.

Keywords: Particulate Trap, Diesel Catalyst Filter, Soot Oxidation.

ÖZ

OKSİDASYON FİLTRELERİNİN DİZEL MOTORLARIN PARTİKÜL EMİSYONLARINA ETKİLERİNİN ARAŞTIRILMASI

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Eylül 2006, 235 Sayfa

Oksidasyon filtreleri, partikül emisyonlarının azaltılması amacıyla sıklıkla kullanılmaktadır. Bu çalışmada, düşük maliyetli, başka filtrelere alternatif oluşturabilecek bir partikül tutucu filtle tasarımı amaçlanmıştır. Bu tasarımın testlerinin yapılabilmesi amacıyla, standartlara uygun bir deney düzeneği kurulmuştur. Elektronik ölçüm ve control sistemleri deneylerin verimliliğini arttırmak amacıyla bu düzeneğe eklenmiştir.

Deneylerde iki farklı filtre tasarımı kullanılmıştır. İlk tasarım alüminyum ızgara telinden oluşmaktadır. İkinci tasarım uzunlamasına üç hücre içeren sactan bir yapıdır. Filtre malzemesi olarak metal talaşları kullanılmıştır. Öncelikle boş filter testleri yapılmış, sonrasında alüminyum, demir ve bakır talaşları eklenerek testler tekrarlanmıştır.

İlk deneylerin sonunda bakır talaşı daha iyi sonuçlar vermiştir. Sonrasında bakır talaşı miktarı arttırılıp azaltılarak deneyler tekrarlanmış, yakıt tüketimini arttırmayacak şekilde uygun talaş miktarı belirlenmiştir.

Sonuç olarak tasarlanan filtre partikül emisyonlarını yüksek oranda azaltıcı etkiye sahiptir. Her ne kadar karbon monoksit ve karbon dioksit gazlarını arttırsa da hidrokarbon emisyonlarını azaltmaktadır.

Keywords: Partikül Tutucu Filtre, Dizel Catalizör Filtre, Kurum Oksidasyonu.

To My Beloved Family…

ACKNOWLEDGMENTS

I would like to specially thank my supervisor Prof. Dr. A. Demir Bayka for all his patience, and invaluable guidance in progressing through the satisfaction of this study.

I would like to thank workshop personal of Mechanical Engineering Department, technicians Mustafa Yalçın, Servet Seherli, Rahmi Ercan, and Internal Combustion Laboratory technician Cemalettin Gül for their help.

I would also like to thank Aytaç Çelik and Ufuk Penekli for all their encouragement and friendship.

Finally, I deeply thank to my family for their support and patience. It is difficult for me to put into words the sacrifices they have done for me.

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A/F	: Air / Fuel Ratio
$(A/F)_{stc}$	: Stoichiometric Air / Fuel Ratio
BP	: Brake Power, HP
$BSFC$	: Brake Specific Fuel Consumption, kg/HPh
D	: Cylinder Diameter, m
DR	: Dilution Ratio
G	: Go Power Reading, in-Water
$\dot{m}_{air}$	: Air Flow Rate, kg/h
$\dot{m}_{ath}$	: Theoretical Air Flow Rate, kg/h
$\dot{m}_{fuel}$	: Fuel Consumption rate, kg/h
M_p	: Particulate Emissions Amount, g/HPh
m_p	: Mass of Particulate Collected on the Filter, g
N_{speed}	: Engine Speed, rpm
P_{dt}	: Reading of Manometer on Dilution Tunnel, in-Water
Q_c	: Fuel Thermal Coefficient, kj/kg
Q_{dt}	: Dilution Tunnel Flow Rate, m^3/h
Q_{exd}	: Exhaust Flow Rate on Dry Basis, m^3/h
Q_{exh}	: Exhaust Flow Rate, m^3/h
Q_{se}	: Flow Rate of Sampled Exhaust, m^3/h
RH	: Relative Humidity, %
S	: Cylinder Stroke, m
T	: Engine Torque, Nm
t_f	: Consumption Time of 86 ml fuel, s
V_s	: Swept Volume, m^3

ρ_f	: Fuel Density, kg/l
ρ_{std}	: Standard Air Density, kg/m^3
η_{th}	: Thermal Efficiency, %
η_v	: Volumetric Efficiency, %
λ	: Excess Air Coefficient
Φ	: Equivalence Ratio

CHAPTER 1

INTRODUCTION

1.1. Historical Background

The diesel engine was developed by Rudolph Diesel in the late 19th century. In 1923 the first diesel vehicles were built and shown at Berlin Motor Fair. Caterpillar Company introduced the 1C1 Diesel engine tractor in 1931. Mercedes Benz Company built the first automobile with a diesel engine (Type 260D) in 1936. M.A.N. produced the first four stroke supercharged engine to reach 45% efficiency in 1950 (Ludec, 2006).

After the Second Word War, Peugeot 403 was introduced, and this accelerated the diesel sales in 1960s. Diesel technology developed during the following decades, and diesel equipped passenger car sales also increased during the 1970’s too (Ludec, 2006). Today, approximately 95 % of all transit buses and tractors on the road are diesel equipped vehicles (Kilcarr, 2001).

Reason for that increased popularity, especially in heavy duty vehicles, is some advantages of diesel engines compared to gasoline engines. These advantages are their durability, reliability, low greenhouse gas emissions and fuel economy. On the other hand, there are some disadvantages of diesels such as noise and low specific power output and their NO_x and particulate matter emissions and high cost. Although new technologies minimize noise and high cost problems, harmful emissions issue, the most important problem of diesel engines, still exists. These emissions are gaseous emissions, nitrogen oxides, hydrocarbons and carbon monoxide, and particulate matter (PM).

After 1970's, international agencies have started to regulate diesel exhaust emissions. European Union emission regulation for light duty vehicles were specified in 1970 (Directive 70/220/EEC). United States Tier 1 regulation were published in 1991. Today, different regulations are in use in different parts of the world, among them the one developed by Japan, Tier 2 regulation of the US, and EU's Euro IV limits can be encountered as examples (Ecopoint, 2006).

Automobile producers and researchers have started to investigate new emission control methods after the regulations mentioned above were introduced. Later on, standardization of experiment conditions for these newly developed emission control methods has become a necessity. The US, EU, and ISO standards have been introduced to control measurement techniques. Today, existing emission measurement techniques are European legislation (Directive 1999/96/EC), US 2007 Regulation, and ISO 16183 Standard.

In the next sections of this chapter, diesel engine burning process, emissions of diesels, and common control methods of diesel emissions are discussed. Also details of this study are mentioned in the last section of this chapter.

1.2. Burning in Diesel Engines

Liquid fuel is injected into cylinder in droplet form at the end of compression in diesel engines. These droplets evaporate and are mixed with the air. The air has a high pressure and temperature because of the compression. Therefore, at that high temperature burning starts by itself. During the injection, burning process continues and newly injected fuel firstly mixes with burned gases and then air. Engine continues to work with the repetition of the processes; atomization, evaporation, formation of fuel/air mixture, and combustion of mixture (Karel, 1996).

As it is explained in the previous paragraph, burning in diesel engines is a very complicated process. Combustion rate in diesel engines is related to physical and chemical preparation of the mixture before autoignition and injection speed following it. Because of these relations, diesel engines can not work as fast as gasoline engines. Formation of combustion in cylinder, and following flame growth are related to the fuel specifications, design of the engine burning chamber and fuel injection system, and engine working conditions.

Because of the burning process indicated previously, fuel distribution is not homogeneous in diesel engines. As a result, different temperatures, pressures and fuel/air mixtures take place in the cylinder. Therefore, non uniform burning process occurs in diesel engines.

Formation of harmful emissions is related to the fuel distribution and changes in situation during the mixing of air and burned gases with fuel. As an example, oxides of nitrogen formations are related to high temperatures. Temperature of burned gases affects the evaporated and unburned fuel and that causes formation of the soot at burning area. Hydrocarbon formation occurs at the cylinder walls and flame quenching areas where excess air prevents combustion.

Although most of the emissions are formed in the cylinder, some emitted matter is burned in the cylinder. Some emissions occur in exhaust system, and some part of them burn again in the same system. In addition, formation and reduction reactions of emissions in the cylinder and exhaust system are the function of oxygen concentration, mixture rate, mixture temperature and time. As a result, total emission amount formed in diesel engines during the injection, burning and following stages can be calculated as:

$$\text{Total Diesel Exhaust Emissions} = \text{Formed Emissions During the Injection} + \text{Formed Emissions In Cylinder} + \text{Formed Emissions In Exhaust system} - \text{Burned Emissions In Cylinder} - \text{Burned Emissions In Exhaust system}$$

1.3. Diesel Engine Emissions

Increased consumption, energy, and transportation necessities cause air and environmental pollution. These environmental problems should not be considered as a local matter. Because of the air movement, polluted air travels big distances as a result many countries are affected from air pollution produced in different geographical locations, which makes it a global problem since it affects human health, agricultural patterns and industry directly or indirectly in a negative way.

During the last two decades, diesel emission formation and its harmful effects are investigated seriously. After these investigations it's found that, diesel exhaust contains nitrogen, oxygen, water, and carbon dioxide. It also contains noxious, toxic, and potentially harmful substances: particulate matter which can be called as soot. Organic compounds such as lubricating oil and unburned or partially burned hydrocarbons (HC), which are primarily the source of the unpleasant odor. Oxides of nitrogen (NO and NO_2, collectively known as NO_x), carbon monoxide (CO) and sulfur oxides are important and harmful emissions of diesel engines too. Inorganic constituents of diesel exhaust, such as metals, acids, and salts, are also among the chemical constituents called as toxic.

As a result of these found data, public concern increased about the emissions effect on the air pollution. Therefore many countries have limited the emissions from diesel engine exhaust. These harmful emissions include gaseous emissions and a solid emission known as particulate matter (PM). US Environmental Protection Agency (EPA) defines the PM as, "all compounds collected on a preconditioned filter in dilute diesel exhaust gases at a maximum temperature of 325 K" (EPA, 2006). In environmental legislation emission of fine particles is referred to the total mass of particles collected with high volume samplers of particles < 10 µm or < 2,5 µm respectively, independently of chemical composition, thereby defining PM10 or PM2,5 respectively.

Although diesel engines exhaust includes many different types of emissions, mentioned previously, some gaseous emissions which are hydrocarbon, carbon monoxide and oxides of nitrogen emissions and particulate emissions are the most important emissions to be controlled. Amount of gaseous and particulate emissions is related to the fuel characteristics, engine oil, engine design, burning rate, high burning temperatures etc.

Table 1.3.1: Diesel Emission Limits for HDV's of EU (Ecopoint, 2006).

	Mass of carbon monoxide (CO) g/kWh	Mass of hydrocarbons (HC) g/kWh	Mass of nitrogen oxides (NO_x) g/kWh	Mass of particulates (PM) g/kWh
2000	2.1	0.66	5.0	0.10 0.13*
2005	1.5	0.46	3.5	0.02
2008	1.5	0.25	2.0	0.02
EEV	1.5	0.25	2.0	0.02

EEV: Environmentally enhanced vehicle.
* For engines having swept volume of less than 0.75 dm^3 per cylinder and a rated power speed of more than 3000 min^{-1}.

Since the emissions are dependent on the weight and duty of the vehicle, the legislations are determined for each of the classified groups of vehicles separately.

For example, the diesel exhaust emission limits for heavy duty vehicles (HDV) of European Union (EU) are given in Table 1.3.1.

Countries have determined different strategies and deadlines to reduce the exhaust emissions after many investigations. For example, US EPA has determined eight different emission bins through which the vehicle manufacturers chose to certificate their vehicles, resulting in a fleet-wide average NO_x value less than 0.07 g/mile. The current Tier-2 limits were issued in 2004 and also will be fully implemented in 2007 after three years of phase-in period (Johnson, 2003).

On the other hand Europe has issued straightforward strategy of reducing the emissions by defining direct limits for each group of vehicles putting emphasis on each emission separately. Even not issued currently a future EURO V legislation is planned to be implemented for 2008 timeframe targeting PM and NO_x emissions of 0.02 and 2.0 g/kWh, respectively (Table 1.3.1).

1.4. Emission Control of Diesel Engines

As mentioned previously hydrocarbons, carbon monoxide, oxide of nitrogen and particute matter are the most important emissions of diesel engines to be taken into consideration. Engine manufacturers and oil producers have embarked on a major effort to reduce vehicle emissions to acceptable levels. The use of aftertreatment devices has also gained momentum over the years as improvements are made to ensure effectiveness.

In this section, a summary of the literature survey on the generally accepted emission control methods is discussed. Engine design, fuel formulations, fuel additives, exhaust gas recirculation, water injection/emulsion, secondary air injection, charge cooling system and aftertreatment technologies; 3-way catalyst, oxidation catalyst, reduction catalyst, thermal reactor, particulate trap are the methods used commonly on diesel vehicles. These methods are applied separately or together to reduce engine emissions.

1.4.1. Emission Control in Cylinder

Engine design includes carburetion, ignition timing, compression ratio, and combustion chamber design. It is of course a very complicated research area in which every engine manufacturer indulges. Almost each year new and more efficient, cleaner engines enter the market.

Alternative fuel investigations were preceded about sulfur content, fuel density, cetane number, oxygen and aromatic content. As a result biodiesel, synthetic diesel, water-fuel emulsions are in progress. Synthetic diesel fuel investigations concentrate on the use of coal, natural gas, and biomass resources.

Biodiesel is defined as the mono alkali esters of long-chain fatty acids derived from renewable lipid sources. Pure biodiesel has extremely low sulfur content (maximum 50 ppm) and no aromatic content. The cetane number of biodiesel is comparable to that of regular diesel.

A number of researchers have shown that biodiesel has fuel properties and provides engine performance that is very similar to diesel fuel. Biodiesel has the advantage of being biodegradable, non-toxic, and a renewable fuel. The lubricity is superior to that of conventional diesel, thereby increasing the life of the engine. Biodiesel has a high flash point, or ignition temperature, of 149 C^o compared to petroleum diesel fuel that has a flash point of 52 C^o. This means it is safer to use in transportation. These are major advantages that surpass all other liquid fuels (Chang &Van Gerpen, 1998).

The use of biodiesel instead of regular diesel fuel in a conventional diesel engine may result in a substantial reduction of unburned HC, CO, and PM although a slight increase in the NO_x emissions occurs. Absence of sulfur also enables the use of catalytic oxidation technologies without the concern over catalyst poisoning or PM emission penalties from the catalytic creation of sulfates (Nyika, 2001).

Jankowski et al. (1994) investigated the effects of rape seed oil methyl ester (RME) (Canola oil in the U.S.) in a direct injection (DI) diesel engine and compared these results against those obtained with normal diesel fuel. All tests were conducted on a RABA MAN diesel engine that had a rated power of 141 kW at 2100 rpm. They found 15% reduction in NO_x emissions, 40 % reduction in PM, and 12 % reduction in HC emissions. Additionally, with the RME, the engine's energy efficiency was slightly higher, and no significant changes in engine performance were found.

McMillian & Gautam (1998) described the manufacture of Fischer-Tropsch (F-T) liquid fuels as a product of gas synthesis (a mixture of carbon monoxide and hydrogen) which is straight chain aliphatic hydrocarbons containing virtually no aromatic compounds or sulfur species. Ryan and Montalvo (1997) performed emissions tests on a Detroit Diesel Series 60 engine and reported that F-T fuels reduced NO_x by 85 %, PM by 30 %, HC by 30 %, and CO by 46 % compared to average diesel fuel.

The cetane number of Fischer-Tropsch diesel is well over 60, making it possess shorter ignition delays. The straight run F-T contains the lowest aromatic content of all known liquid fuels to date. This makes it easier to disintegrate the molecules during the combustion process because possessing low aromatic content, means having less of the ring-structured benzene ring which is very stable and therefore difficult to break due to the many resonance structures.

The ECD fuel, which is a reformulated diesel produced and marketed by ARCO Oil Company, has an ultra low sulfur content of 7.4 ppm, a tremendous reduction compared to 300 to 350 ppm of conventional diesel. The ECD was assessed together with a California specification diesel (CARB) as a control fuel to determine the benefits on regulated exhaust emissions.

Biodiesel, Fischer-Tropsch, and ECD are the most likely fuels to meet the new pending regulatory emission standards particularly because of their low sulfur content, which would be benefit in reducing air pollution and toxic emissions. An important advantage of the low sulfur content is that it will enable the use of aftertreatments to significantly reduce PM.

Fischer-Tropsch fuel reduced NO_x by 85 %, PM by 30 %, and CO by 46 % over diesel fuel according to tests conducted by Ryan and Montalvo (1997). These significant reductions are attributed to the excellent fuel properties. ECD reduced NO_x by about 15 % over, CARB diesel but showed no significant reductions in PM. The fact that ECD fairs well in fuel properties and the results showing benefits in regulated emissions over CARB diesel is indicative of its advantages over conventional diesel. This places ECD in a very important and competitive position as a diesel fuel that is very capable of reducing emissions.

Diesel Additives are used to reduce particulate emissions also. For example, detergent additives are used to clean fuel injector. They reduce combustion noise, emissions and black smoke. Other advantages are maintenance of the injector system in peak condition, prevention of deterioration in fuel economy and extension of vehicle life.

Antirust additives help to reduce rust formation in fuel storage and delivery systems resulting in reduced maintenance of pipes and tanks and reducing risk of filter blocking due to rust deposits. Antifoam additives help reduce the tendency of diesel to foam in fuel delivery systems. Increase combustion efficiency so reduce emissions.

Cetane number is a value which measures ignition quality of a diesel fuel. It can be defined as the percent volume of cetane (n-hexadecane, Cetane No = 100) in alpha methyl naphthalene (Cetane No = 0) and provides the specified standard of 13 degrees (crankshaft angle) ignition delay at the identical compression ratio to that of the fuel sample. Therefore, cetane number is important for engine performance and environmental pollution.

In other words, higher cetane number indicates greater fuel efficiency. Cetane number improvers are used to improve diesel fuel combustion characteristics in engine chamber. If these improvers are used in diesel engines, they yield reduced starting time in cold weather. As a result, reduced engine noise, reduced white smoke during warm up and reduced emissions in exhaust gases are achieved (Sharp, 1994).

Exhaust gas recirculation (EGR) technology recycles some part of exhaust gases back in to the exhaust intake system. Therefore, reducing oxygen concentrations during combustion, and lowering the peak combustion temperature by absorbing heat into the stream of recirculated gases are accomplish. If the EGR stream is cooled before recirculation, its absorptive capacity is increased and therefore much more NO_x formation reduction is archived. EGR method is used to reduce NO_x emission approximately 30-40 %. However this method increases fuel consumption, forms sulfur in the fuel to sulfur dioxide and also increases particulate matter, CO, and HC (Heywood, 1988 & Khair, 1997).

Another emission reduction method, used in diesel engines is water injection/emulsion. Injecting water into the combustion chamber reduces combustion temperature. Water can be mixed with the charge air (humidification), through direct injection into the cylinder or through water/fuel emulsion. Water/fuel emulsions can reduce smoke, while humidification can increase smoke. This method is used to reduce NO_x emissions, because at low temperatures NO_x formation decreases as mentioned previously.

Water/fuel emulsions and direct injection of water in the combustion region, are used to reduce NO_x production. Generally, water/fuel emulsions or direct water injection cause about 1 % NO_x reduction for every 1 % of water to fuel ratio. Humidification requires about twice as much as water for the same NO_x reduction (Goldsworthy, 2002). Not all the injected water will end up in the combustion zone; actually it depends on how the water is injected. Therefore it affects the reactions occur in the following stages. Other effects of these methods are the reduction of PM and an increase in CO and HC emissions. Disadvantages are potential for corrosion of engine parts, freezing, and reduced lubricity.

Secondary air injection is used to reduce diesel emissions also. In this method, air is injected into the exhaust manifold (secondary air). Therefore CO and HC emissions react with air, and oxidize through afterburning at temperatures over 600°C to form water and carbon dioxide. The exothermal reaction also increases the exhaust gas temperature, which warms the catalyst more quickly. With the help of that temperature, emitted gases are regenerated more easily.

Charge Cooling, another emission reduction method, is related to cooling of the engine charge air. With that cooled air combustion chamber temperature is lowered. As mentioned previously, NO_x emissions formation is related to temperature, therefore amount of emissions is decreased. However the expected performance improvements from cooling the charge air are not realized due to the significant frictional losses in the charge pressure.

1.4.2. Aftertreatment Technologies

Reduction catalysts include platinum and rhodium materials, which are used to help reduction of NO_x emissions. When an NO or NO_2 molecule contacts the catalyst, the catalyst rips the nitrogen atom out of the molecule and holds on to it, freeing the oxygen in the form of O_2. The nitrogen atoms bond with other nitrogen atoms that are also stuck to the catalyst, forming N_2. As a result, amount of NO_x emissions in the exhaust reduces, and clean gases, O_2 and N_2 are formed.

Catalysts which can eliminate all the three pollutants, CO, HC, and NO_x simultaneously are termed as three-way catalyst (TWC). Usually, noble metals, such as, platinum (Pt), palladium (Pd), rhodium (Rh), iridium (Ir) and many combinations of these metals are used as TWCs. Metal ion-exchanged zeolites also have good potential for catalytic reduction of automotive pollutants. Ion-exchanged ZSM-5 zeolite has been most widely searched for this purpose, other zeolites like zeolite-X, zeolite-Y, mordenite, are also being searched extensively for the abatement of automotive pollution (Bhattacharyya and Das, 1998). The overall catalytic reactions which are important for controlling exhaust emissions are shown in Table 1.4.2.1 (Taylor, 1983).

TWCs containing noble metals such as Pt, Pd, Rh and Ir have been tested by Bhattacharyya and Das (1999) to explore the best performance from them. Pt and Pd are excellent oxidizing catalysts and are used as catalysts for their contribution to CO and HC conversions. However, they are poor NO_x reducing catalysts in lean automobile exhaust, and Pt exhibits the poorest NO_x conversion activity. However, both Pt and Pd are capable of reducing NO_x and oxidizing CO and HC simultaneously near stoichiometry. Rh is an excellent NO_x reducing catalyst even in presence of small quantities of oxygen (O_2). Ir, on the other hand, exhibits superior ability to convert NO under oxidizing conditions.

Table 1.4.2.1: The overall reactions in a catalyst bed (Taylor, 1983).

	$CO + 1/2O_2 \rightarrow CO_2$
	$HC + O_2 \rightarrow H_2O + CO_2$
	$H_2 + 1/2O_2 \rightarrow H_2O$
	$NO + CO \rightarrow 1/2N_2 + CO_2$
	$NO + H_2 \rightarrow 1/2N_2 + H_2O$
as well as	
	$HC + NO \rightarrow N_2 + H_2O + CO_2$
	$NO + 5/2H_2 \rightarrow NH_3 + H_2O$
	$CO + H_2O \rightarrow CO_2 + H_2$
	$HC + H_2O \rightarrow CO + CO_2 + H_2$
and possibly	
	$3NO + 2NH_3 \rightarrow 5/2N_2 + 3H_2O$
	$2NO + H_2 \rightarrow + H_2O$
	$2N_2O \rightarrow 2N_2 + O_2$
	$2NH_3 \rightarrow N_2 + 3H_2$

The low NO activity of Pt and Pd catalysts at the fuel rich mixtures is due to temporary CO poisoning. Addition of O_2 to the feed stream tends to clean CO by oxidizing it to CO_2. Therefore amount of CO decreases and efficiency of catalyst increases. However, adding O_2 to stream forms fuel lean mixture suddenly and that decreases catalyst activity (Summers and Baron, 1979).

Thermal reactors are used for oxidizing unburned hydrocarbons and carbon monoxide. The functions of a thermal reactor are to promote rapid mixing of the hot exhaust gases with secondary air injected into the exhaust manifold and to retain the gases at a high enough temperature for sufficient time to oxidize emitted HC and CO. The temperature levels typically required for bulk gas oxidation of HC and CO in a reactor are about 600-700 C^o, which are much higher than those required in a catalytic converter.

A practical limitation to reactor effectiveness with fuel-rich engine operation is mixing of secondary air and exhaust gases. Maximum reduction of CO and HC occurs with 10 – 20 % excess air in the mixture. However, even with very high reaction temperature, 100 % oxidation of CO and HC is not achieved due to incomplete mixing (Bhattacharyya & Das, 1999).

Diesel oxidation catalysts (DOC) are used for oxidation of HC, CO, and PM. They provide significant reductions in the CO and HC emissions. DOCs also catalyze the conversion of sulfates to sulfur dioxide. Effect of DOCs on PM emission is not clear. When the low sulfur fuel is used in the engine, DOCs have been reported to be active in PM reduction. In the presence of sulfur, catalyst activity decreases and the sulfates form a greater fraction of PM.

A typical oxidation catalyst consists of a stainless steel containing a honeycomb like structure called a substrate. The interior surfaces of the substrate are coated with catalytic precious metals, such as platinum or palladium. A disadvantage of the oxidation catalysts is that although they reduce the particle mass, number of particle may remain same (Ambrogio, Saracco and Specchia, 2001)

Carbon monoxide and hydro carbon emissions are generally reduced with oxidation catalysts. Function of these catalysts is the oxidation of carbon monoxide and hydro carbons to form carbon dioxide and water. Reduction of carbon monoxide and hydro carbons is easy with the rare metal coated mono block catalyst filters, because exhaust gases of diesel engines include high amount of oxygen (Neeft, Makkee and Moulijn 1998).

However, the sulfur content of the fuel should be concerned when considering the application of oxidation catalysts. Aftertreatment technologies can certainly increase the conversion of SO_2 to SO_3.

In figure 1.4.2.1, transformation of HC and CO emissions to other gases related to exhaust gas temperature can be seen. As it can be shown in the figure, even at low temperatures, their formation is possible. If rare metal combinations are compared, activity sequence is: Pd < Pt/Pd < Pt. Platinum is the best catalyst compared to other known catalysts. Catalyst filter coated with platinum give 78% HC and 95% CO formation efficiencies at 235 C^o (Koltsakis & Stamatelos, 1997).

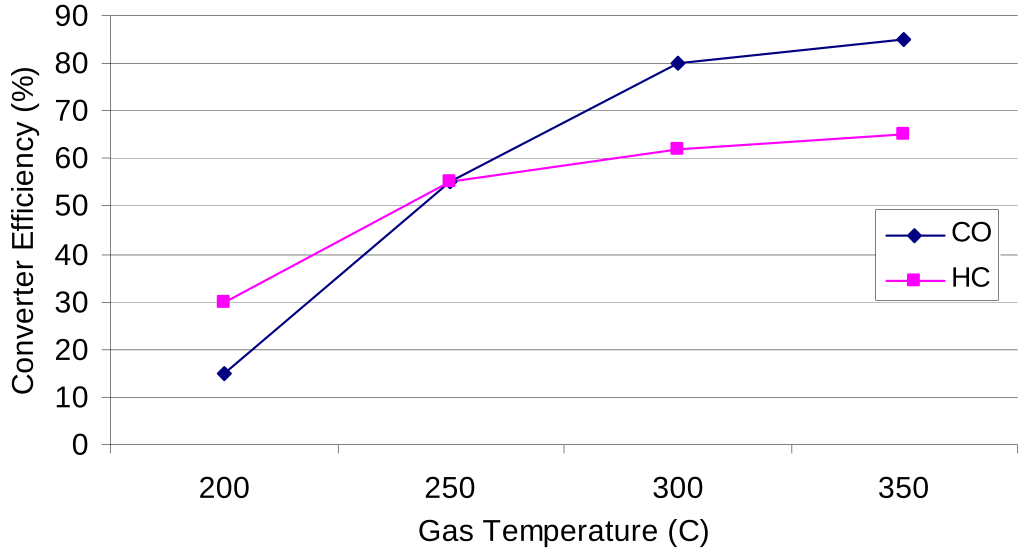

Figure 1.4.2.1: Transformation of CO and HC emissions as to exhaust gas temperature (Koltsakis & Stamatelos, 1997).

Diesel particulate filter (DPF) is the only method that presents desired reductions in particulate matter emissions. These filtering systems contain a particle trap placed in the exhaust pipe of the vehicle to hold the particles as the exhaust gas passes through. The particulate filters are a porous structure made of silicon carbide having channels with the adjacent inlet cells blocked and the alternative cell blocked at the outlet end in general.

New generation filters can trap about 95 % of the PM. In order to maintain maximum performance, the filter has to be regularly regenerated or cleansed from periodically burning the accumulated particles. Otherwise, collected particulate will prevent the passage of the exhaust gas, and increase the backpressure to the engine. Consequently, performance of engine decreases and fuel consumption increases.

In the presence of oxygen, combustion in particulate filter occurs naturally when the temperature of the exhaust exceeds 550 ^{o}C, which is usually higher than the engine’s exhaust gas temperature. Many techniques have been experienced to lower the combustion temperature by researchers. Fuel injection to the exhaust to increase the temperature or position oxidizing catalysts at the upstream of particulate trap to lower the temperature are some of the methods which increase regeneration rate of trap significantly.

An alternative method used with particulate filters is using fuel additives that lower the combustion temperature of the soot below 450 ^{o}C. In addition to the active passive regeneration methods mentioned above, methods classified as active regeneration also exist, which compromises the combustion of collected soot via external heat supply, whose most common examples are electrical heaters and microwave heating systems.

1.5. This Study

Objective of this study is to design of a low cost and efficient particulate filter, and to perform experiments on the filter to investigate: particulate holding performance, catalyst effect, effects on the exhaust gas concentration, and effects on the engine’s performance of the designed filter.

For the experiments, an experimental setup is designed applying European Union sampling and measurement procedure (Directive 1999/96/EC). Due to dimensional limits, partial flow dilution system with isokinetic probe and fractional sampling methods are selected for the setup. In addition, experiments are performed according to one of the European Union heavy duty diesel engines emission test cycles, European Stationary Cycle (ESC). A computer control system is installed to take measurements more clearly. Electronic measurement and control apparatus are used in the setup, and a computer program is written to manage that system.

Details of filter design parameters, designed particulate filters, sampling methods, dilution tunnel design, particle sampling system, air and fuel measurement systems, electronic equipments, computer program, and emission test cycles are explained in the following chapters.

CHAPTER 2

LITERATURE SURVEY

2.1. Sampling and Dilution Systems

These systems are very important for a representative measurement. Measured amounts are significantly related to designs of sampling and dilution systems. Sampling and dilution system serves to reduce the concentration in the raw exhaust gas to a concentration which can be handled by the measurement system, reduce the gases temperature to an adequate level, usually close to ambient temperature, and control the condensation and nucleation processes, related to temperature.

The system has to be designed such that no significant losses occur. Cooling the exhaust without dilution will cause a strong nucleation and condensation problem. Then, most volatile material will be found in the particle phase. On the other hand, a sufficient dilution at temperatures where the volatile components are still in the gas phase will prevent saturation and thereby nucleation. If preheated air is used at a high enough dilution ratio, the saturation ratio can be kept low enough, thus avoiding condensation and nucleation. Use of preheated air in the dilution process is called hot dilution. Only solid particles are measured in this technique (Kittelson, 1999).

Dilution methods are grouped as dynamic and static ones. Dynamic one is called dilution tunnel where a stable exhaust flow rate exists and where dilution air continuously mixes with the exhaust gas. Static dilution method is known as dilution room and a portion of exhaust gas or partially diluted exhaust gas mixes with air there.

2.1.1. Dilution Tunnels

Dilution tunnel is defined as channel system where the engine exhaust gas is diluted with air from the environment (EPA, 1977). In tunnel systems constant volume sampling (CVS) method is used and exhaust gas flow rate is stable. Dilution air is obtained from a blower. All or some portion of the exhaust gas is taken from the tail pipe and is given to the dilution tunnel. Also dilution air is given to the tunnel with another pipe. This air sucked by a blower, passes a filter and may be heated and than goes to the tunnel. Air and exhaust are mixed in the mixing chamber. If the distance, between the exhaust pipe and the tunnel, is long, all the passage that the gas passes through should be heated in case of condensation. Along the tunnel, temperature, pressure, and flow rate measurement devices are installed.

A homogeneous mixture of air and exhaust should be achieved in a short time. The most important point about that mixing process is avoiding of instantaneous temperature decreases where two gases come to the mixing chamber. If condensation occurs, the dilution ratio or the specifications of the dilution air should be adjusted.

There are different types of dilution tunnels used for dynamic dilution operations. Although equipment need in these tunnels are generally the same, design of the tunnel system and installations are different. Today, full exhaust flow dilution tunnels and partial exhaust flow dilution tunnels are the most frequently used dilution systems.

2.1.1.1. Full Flow Dilution System

As the full exhaust flow dilution tunnel systems (Figure 2.1.1.1.1) sample and dilute the entire engine exhaust flow, they have to be operated at very high flow rates, especially when large engines are tested. Therefore, full flow dilution tunnel systems are very large and installation of them is very expensive. Full flow systems are usually operated at low dilution ratios (< 10) with no provision of heating the dilution air. Because of that, to control the temperature and dilution ratio independently is impossible. Therefore, an uncontrolled temperature decrease causes condensation problem in tunnels as mentioned previously (Burtscher, 2005).

In full flow systems, calculation of the total particulate mass emitted during the sampling time is easy. Mass of collected particle on a filter times the ratio of tunnel flow rate to sampling system flow rate gives the total exhaust particle mass. Mass per distance (g/km) or energy (g/kWh) can be calculated directly depending upon the experiment conditions and time.

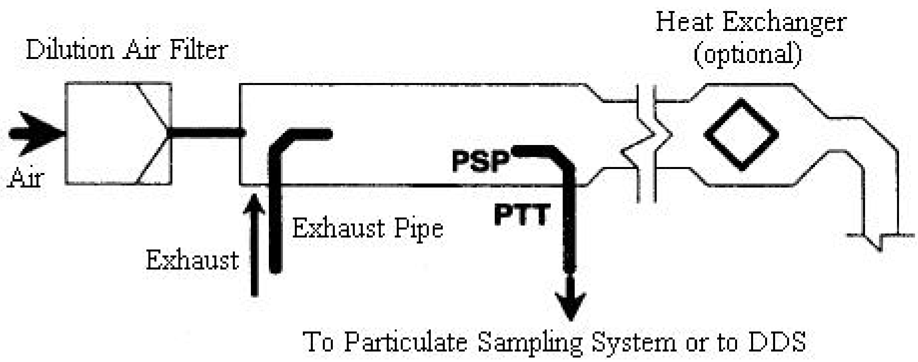

Figure 2.1.1.1.1: Full Flow Dilution System (Directive 1999/96/EC).

PSP: Particulate Sampling Probe.
PTT: Particulate Transfer Tube.
DDS: Double Dilution System.

2.1.1.2 Partial Flow Dilution System

Partial flow dilution tunnels sample only a portion of the exhaust gases. Therefore, these tunnels reduce system dimensions and installation cost. Sampling percentage of exhaust gas is the main factor which determines the tunnel flow conditions. Exhaust flow rate is calculated considering the fuel consumption and air intake rate of the engine. Partial flow systems have been accepted only for stationary tests, not for transient tests because transient conditions require accurate flow control systems (Kreft, 2002).

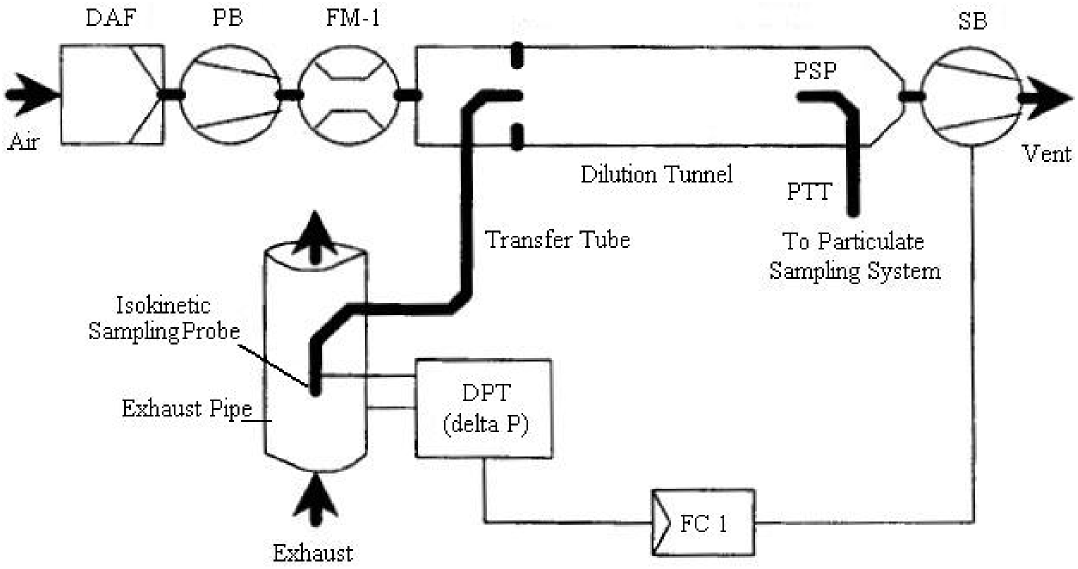

Figure 2.1.1.2.1: Partial flow dilution system with isokinetic probe and fractional sampling (SB control), (Directive 1999/96/EC).

Figure 2.1.1.2.1 shows the partial flow dilution system with isokinetic probe and fractional sampling. In that method, isokinetic sampling probe (ISP) is used to take samples, and these samples are transferred to the dilution tunnel (DT) from the exhaust pipe (EP) through the transfer tube (TT). Pressure difference of the exhaust gas between exhaust pipe and the probe inlet is measured by using the difference pressure transducer (DPT). Signal of transducer is transmitted to the flow controller (FC) that controls the suction (dilution) blower (SB). Suction blower speed determines the flow rates of dilution tunnel and transfer tube. Therefore, control system maintains zero pressure difference at the tip of the sampling probe.

When exhaust gas pressures in EP and ISP are equal, velocities are assumed to be identical. If that condition is realized, ratio between the flow rate through ISP and TT, and flow rate of exhaust gas become a constant amount. That amount, called as split ratio, can be determined from the cross sectional area of EP and ISP. Flow measurement device (FM1) measure the dilution air flow rate. Then, the dilution ratio is calculated from the dilution air flow rate and the split ratio.

Splitting of the exhaust gases and the following dilution process may be done by different dilution system types. For subsequent collection of the particulates, the entire or only a portion of the dilute exhaust gas is vacuumed by the particulate sampling system. If entire dilute exhaust gas is vacuumed, the method is named as total sampling type; otherwise it is labeled as fractional sampling type. Calculation of the dilution ratio depends upon the type of the system used. The following types are recommended methods of European Union in Directive 1999/96/EC.

When partial flow dilution systems are used, particulate loss in the transfer tube and following steps is an important problem which should be taken into account carefully. Taking a representative sample from the engine exhaust gases, and determining the split ratio are also important issues to be considered.

2.1.1.2.1. Isokinetic Systems

Function of isokinetic systems is to match the transfer tube flow to exhaust pipe flow in terms of volumetric flow rate or pressure. Thus an undisturbed and uniform exhaust flow is obtained at the sampling probe. This is usually achieved by using a difference pressure transducer between sampling probe inlet and upstream of the sampling point in the exhaust pipe. The split ratio is then calculated easily with tube diameters. Although isokinetic sampling method is used for matching the flow conditions, it is not used for matching the size distribution. If the particles in raw exhaust stream are small enough to follow the fluid streamlines, size distribution matching is not necessary.

2.1.1.2.2. Flow Controlled Systems with Concentration Measurement

In flow controlled systems with concentration measurement, a sample is taken from the bulk exhaust stream by adjusting the dilution air flow rate and the total dilute exhaust flow rate. The dilution ratio is determined from the concentrations of tracer gases such as CO_2 or NO_x naturally occurring in the engine exhaust. The concentrations of tracer gases in the dilute exhaust gas and in the dilution air are measured, whereas the concentration in the raw exhaust gas can be either measured directly or determined from fuel consumption amount and the carbon balance equation, if the fuel composition is known. The systems may be controlled by the calculated dilution ratio or by the flow into the transfer tube.

2.1.1.2.3. Flow Controlled Systems with Flow Measurement

In flow controlled systems with flow measurement, a sample is taken from the bulk exhaust stream by setting the dilution air flow and the total dilute exhaust flow. The dilution ratio is determined from the difference of these flow rates. Accurate calibration of the flow meters relative to one another is required, since the relative magnitude of the two flow rates can lead to significant errors at higher dilution ratios (<15). Flow control method is obtained simply by keeping the dilute exhaust flow rate constant and varying the dilution air flow rate.

2.1.2. Mini Dilution Sampling System

Diluted gases temperature should be below 52 ^{o}C according to standards of diesel exhaust gas test cycles (1999/96/EC). Reaching that condition requires high capacity machines and very large places, which increase system installation cost. To minimize this problem mini dilution tunnels are used.

The primary functions of the mini dilution system are to collect a known quantity of raw exhaust (partial flow) from the exhaust system of an engine and to mix this with a known quantity of ambient dilution air so that a particulate matter sample could be obtained. Diluting the raw exhaust with ambient air, while maintaining a constant temperature and flow velocity, obtain the sample condition and minimizes condensation that is a major obstacle to PM collection in the field. The dilution tunnel dilutes the air before drawing it through the PM filters.

2.1.3. Other Dilution Techniques

Although, mentioned dilution tunnel systems are used in common, some other dilution techniques also exist. Tunnel systems are based on constant volume sampling, so they measure the total amount of emitted particle. However, other techniques measure concentration of gases, and are based on constant dilution ratio. Other difference of these systems is flow rate amount, which can be a few liters per minute. Control of dilution air and system temperature is easy for these low flow rates. Some common examples of these systems are explained below.

2.1.3.1 Ejector Diluter

The ejector diluter includes a venturi nozzle (Figure 2.1.3.1.1). With the help of this nozzle, a finite amount of raw exhaust sample is mixed with a finite amount of dilution gas (usually air) homogeneously. Compressed dilution gas is accelerated and flows through nozzle, and draws the sample gas. As a result, self sucking occurs into the mixing chamber. Dilution gas can be heated, which enhances the process control. Ejector diluters operate at a dilution ratio (DR), which is approximately 10 and depends on nozzle design, composition of the sample and dilution gas, and pressures and temperatures of exhaust gas, dilution gas, and diluted sample (Giechaskiel, 2004).

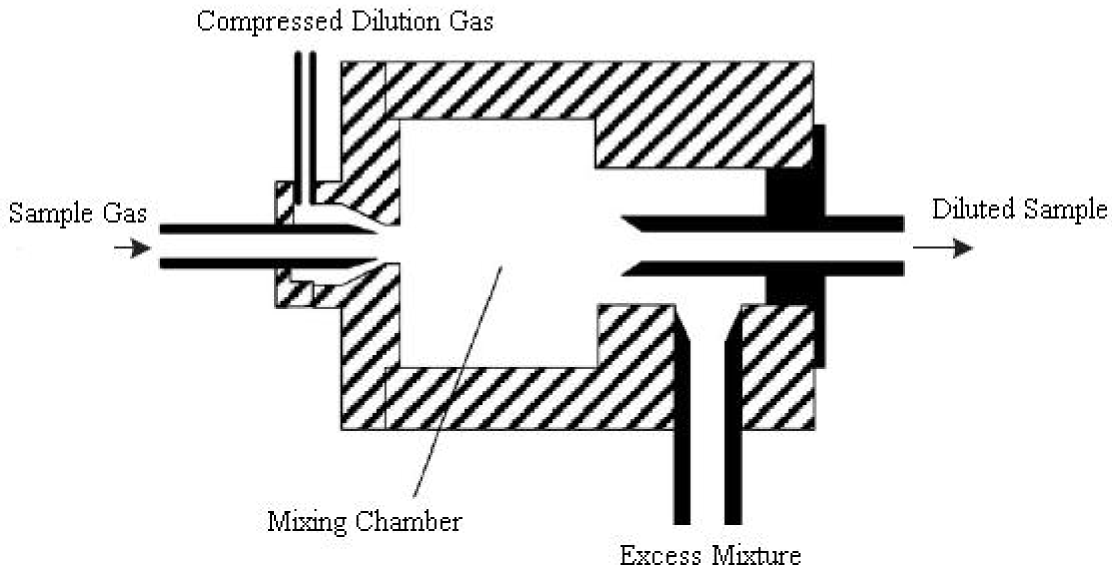

Figure 2.1.3.1.1: Ejector Diluter (Burtscher, 2005).

2.1.3.2. Rotating Disk Diluter

The first rotating disk diluter (Figure 2.1.3.2.1) was designed by Hüglin et al. (1997). This dilution system allows a large dilution ratio range (1:30 to 1:1000). The temperature of the dilution air and of the dilution system can be adjusted separately. Therefore, condensation problem of emissions can be prevented easily. Moreover, nucleation process can be studied by changing the temperature and dilution ratio. Unfortunately, rotating disk diluters work well only for particles below 1 μm. For larger particles, impact of particles decreases the efficiency of system. In addition, maximum diluted gas flow rate can be a few liters per minute.

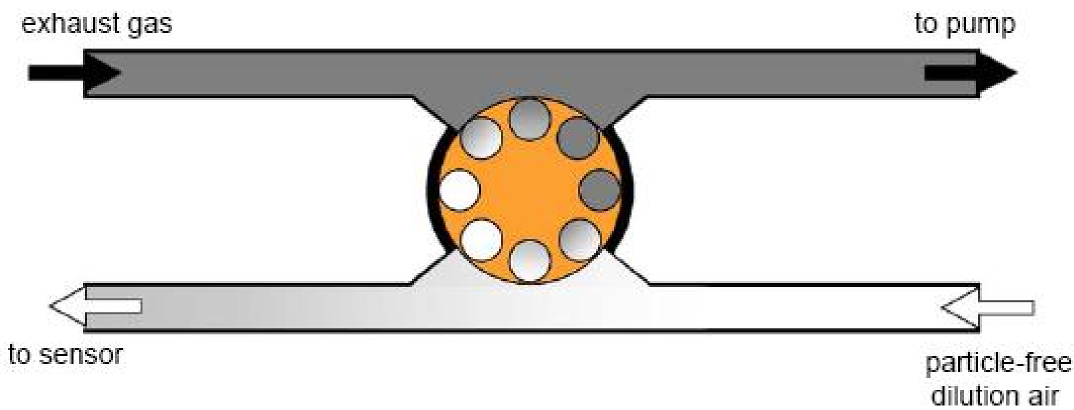

Figure 2.1.3.2.1: Rotating Disk Diluter (Burtscher, 2005)

2.1.4. Particle Losses and Reentrainment

The most important reasons of the particle losses in the sampling system are inertial impact, diffusion, thermophoresis, and electrostatic deposition (McAughey, 2000). With the adequate design of the sampling system, this particle loss problem can be minimized. Particle losses by diffusion and thermophoresis have been analyzed by Fissan (1988). In addition, it is found that losses in the sampling line of a typical light-duty chassis dynamometer are less than 5 % (Ahlvik et al. 1998). A summary of particle losses during the sampling and dilution processes mentioned by Burtscher (2005) is given below.

Inertial and gravitational deposition is mainly important for larger particle losses, because it‘s effect on small particles (<1 μm in diameter) is low. To prevent inertial and gravitational deposition, sharp bending and long horizontal tubing should be avoided.

Diffusional deposition is also important about particle losses. Diffusion affects mainly small particles, which affect directly the number concentration quantity. Therefore, diffusional deposition is important when number concentration is measured but not if total particulate mass is considered. To reduce this deposition problem residence time can be decreased.

Another deposition type is thermophoretic deposition. This effect occurs when the sampling system is much colder than the exhaust gases. In that condition, particles are driven towards the sampling tube walls. Avoiding high temperature differences through the system, and heating the sampling line prevent particle losses due to thermophoretic deposition.

Electrostatic deposition occurs because of the charged particles. Unfortunately, a significant fraction of particles is charged after the emission process. These particles are attracted by electro statically charged walls. Using electrically conductive tubing material can prevent this deposition type.

Reentrainment of particles, which is previously formed in the exhaust gases sampling and dilution system, is another process that causes measurement problems. These particles may be reentrained as larger agglomerates (Ambs et al., 1990). Usually reentrained particles are significantly larger. Although the effect of non-isokinetic sampling is low for the particles smaller than 100 nm, it may be significant for reentrained agglomerates.

Temperature changes during the operation causes reentrainment of particles. If a phase of operation at high load follows the operation of low load period, because of the temperature change, material deposited during the previous phases volatilize and mix with the exhaust gases (Hall and Dickens, 2000). An impactor or cyclone, which is used to remove large particles, can be installed in the system before the measurement devices to eliminate reentrainment problem.

2.2. Particulate Matter Sampling and Measurement Procedures

Standards for existing and proposed particulate matter (PM) sampling and mass measurement procedures are indicated by the European Union legislation (Directive 1999/96/EC), US 2007 Regulation and ISO 16183 Standard. Main points of sampling and measurement methods considered in these documents are transportation of exhaust gas to dilution tunnel, design of dilution tunnel, and tunnel operating conditions, such as temperature, dilution ratio, and humidity.

Condensation, vaporization, thermophoresis, and other physical processes are obviously dependent to temperature. Mixture temperature is related to exhaust gas temperature, dilution air temperature, and dilution ratio. Due to temperature limits dilution ratio reach high levels. Design of particulate sampling system also affects the collected amount of particulates directly.

As a result, there are many sources of variability in particulate matter measurements of heavy duty engines. These factors have been researched for many years, but unfortunately they are poorly understood. Therefore, three main regulations about sampling and measurement have some different limits and conditions. The most important provisions of these regulations are explained in the following parts.

2.2.1. European Union Legislation (Directive 1999/96/EC)

The European regulations for heavy duty diesel engines are referred as Euro I-V. Euro I and Euro II standards were introduced in 1992 and 1996 respectively. These standards have been applied to both heavy-duty highway diesel engines and urban busses. The European Parliament and the Council of Environment Ministers adopted the Euro III standard in 1999, and also adopted Euro IV and V standards for the years 2005 and 2008 respectively.

Samplings of European regulation are made by using the CVS (constant volume sampling) technique. Two types of sampling methods are considered in directives, full flow and partial flow dilution systems, whose details are explained in previous sections (Figures 2.1.1.2.1 and 2.1.1.1.1). Full flow dilution systems are used for transient and steady state tests but partial flow systems are used only for steady state tests.

With the directive, new emission test cycles, European stationary cycle (ESC), European transient cycle (ETC), and the European load response (ELR) are introduced in the year 2000. ESC accepts raw exhaust for gases pollutants, and partial dilution method for PM measurement. Optionally, full dilution for both gases and PM measurements with 191 ^{o}C maximum sample temperature for gases and secondary dilution for PM methods can be used with ESC. Full dilution for gases and PM (191 ^{o}C max. temp. for gases and secondary dilution for PM) measurements are used with ETC. ELR is used for smoke opacity measurement from heavy-duty diesel engines.

To prevent water condensation in the dilution and sampling system, directive recommends maintaining the temperature of diluted exhaust gas below 52 ^{o}C at filter holder. The temperature of the dilution air should be 25 ± 5 ^{o}C unless dilution air preheating is used.

A particulate sampling system, sampling filters, a microgram balance, and a temperature and humidity controlled weighing chamber are required to determine the mass of particulates. Details of these parts are explained in the directive separately.

Dilution and sampling systems must be designed to minimize deposition and alteration of the particulates, which cause measurement errors as mentioned previously, and all parts of them must be made of electrically conductive materials. Dilution tunnel and sampling tube walls may be heated up to 52 ^{o}C.

Particulate sampling filters diameter must be minimum 47 mm and filters must have minimum efficiency of 95% for particles 0.3 μm and above. In addition, stain diameter of filter is defined as the area in which the gases pass and its diameter is 10 mm smaller than that of the filter.

2.1.1.1. European Emission Test Cycles

European Union emission test cycles for heavy duty diesel engines, accepted since the year of 2000, are European stationary cycle (ESC), European transient cycle (ETC), and European load response (ELR) as mentioned previously. Transient cycle method uses full dilution, so it causes dimension and cost problems. Load response method measure smoke opacity as mentioned. Consequently, to measure efficiency of particulate filters designed in this study stationary cycle method is selected. Details of ESC are explained in next section.

2.1.1.1.1. European Stationary Cycle

In ESC method to measure the engine emissions, 13 experiment modes are used. Experiment modes are explained in Table 2.1. These experiments are performed for 3 engine speeds (A, B, C). To determine these experiment speeds, 2 engine speeds, the high speed $nh_{i,}$ and the low speed nl_o should be calculated.

The high speed nh_i is determined by calculating 70% of the declared maximum net power. The highest engine speed where this power value occurs on the power curve is defined as nh_i. The low speed nl_o is determined by calculating 50% of the declared maximum net power. The lowest engine speed where this power value occurs on the power curve is defined as nl_o.

The required engine speeds A, B, C are calculated as follow:

$$A = nl_o + 0.25(nh_i - nl_o)$$
$$B = nl_o + 0.50(nh_i - nl_o)$$
$$C = nl_o + 0.75(nh_i - nl_o)$$

Table 2.1: European Stationary Cycle (ESC) Test Modes (Directive 1999/96/EC)

Mode	Engine Speed	% Load	Weight Factor,%	Duration
1	Low idle	0	15	4 minutes
2	A	100	8	2 minutes
3	B	50	10	2 minutes
4	B	75	10	2 minutes
5	A	50	5	2 minutes
6	A	75	5	2 minutes
7	A	25	5	2 minutes
8	B	100	9	2 minutes
9	B	25	10	2 minutes
10	C	100	8	2 minutes
11	C	25	5	2 minutes
12	C	75	5	2 minutes
13	C	50	5	2 minutes

2.2.2. International Organization for Standardization Standard (ISO 16183)

ISO 16183 specifies the measurement and evaluation methods for gases and particulate exhaust emission from heavy duty engines under transient conditions. Directive 2001/27/EC has adopted the technical details of ISO 16183 for NO_x

emission measurements during the transient test cycles as an alternative to the requirements of EU directives.

ISO standards recommend employing transient tests with raw exhaust for gases pollutants and partial dilution for PM. Measurement setup of partial dilution system is shown in Figure 2.2.2.1. Dilution air temperature must be higher than 15 ^{o}C; however, diluted exhaust temperature shouldn't be higher than 52 ^{o}C at filter holder.

Particulate sampling filter diameter must be minimum 47 mm similar to EU limits, and filters must have minimum efficiency of 99% for particles 0.3 μm and above. In ISO standard stain diameter is not defined.

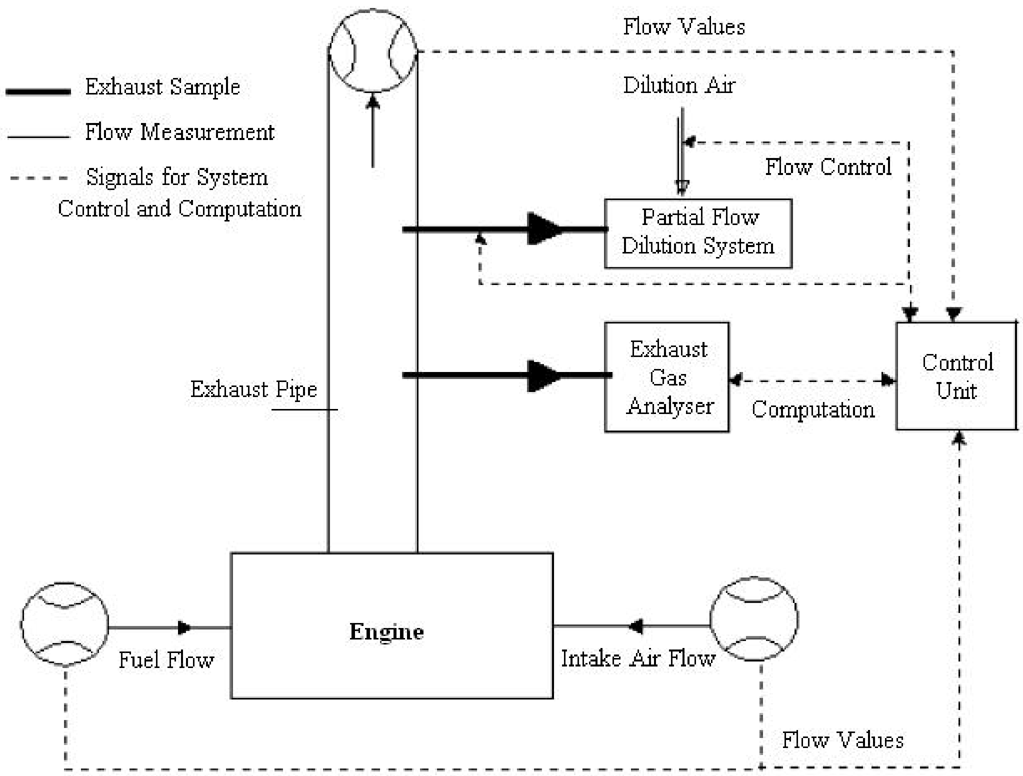

Figure 2.2.2.1: Partial flow dilution system according to ISO 16183.

2.2.3. US 2007 Federal Regulations

Dilution and sampling system of US regulation uses CVS concept. To prevent condensation in dilution tunnel, the flow capacity of CVS must be sufficient enough to maintain diluted exhaust stream in the primary dilution tunnel at a temperature of 191 ^oC or less at the sampling zone. Gases emission samples can be taken from this point, but particulate emission samples must be diluted in the secondary dilution system.

Primary and secondary dilution air temperatures must be higher than 15 ^oC. Air used for primary and secondary dilution processes must be filtered with minimum filtration efficiency of 98% and 99.97% respectively. Temperature of secondary diluted exhaust gas must be 47±5 ^oC at upstream of filter face. Sample must be taken at 30.5 cm maximum from secondary dilution tunnel exit. In addition, a particle pre-classifier must be installed upstream the filter holder, either inertia impactor or cyclonic separator, with 50% cut point between 2.5 and 10 μm. It should allow at least 99% of 1μm particles to pass through, in terms of mass.

Particulate sampling filters diameter must be minimum 46.5 mm, and filters must have minimum efficiency of 99% for particles 0.3 μm and above. Moreover in the US regulation minimum stain diameter is defined as 38 mm.

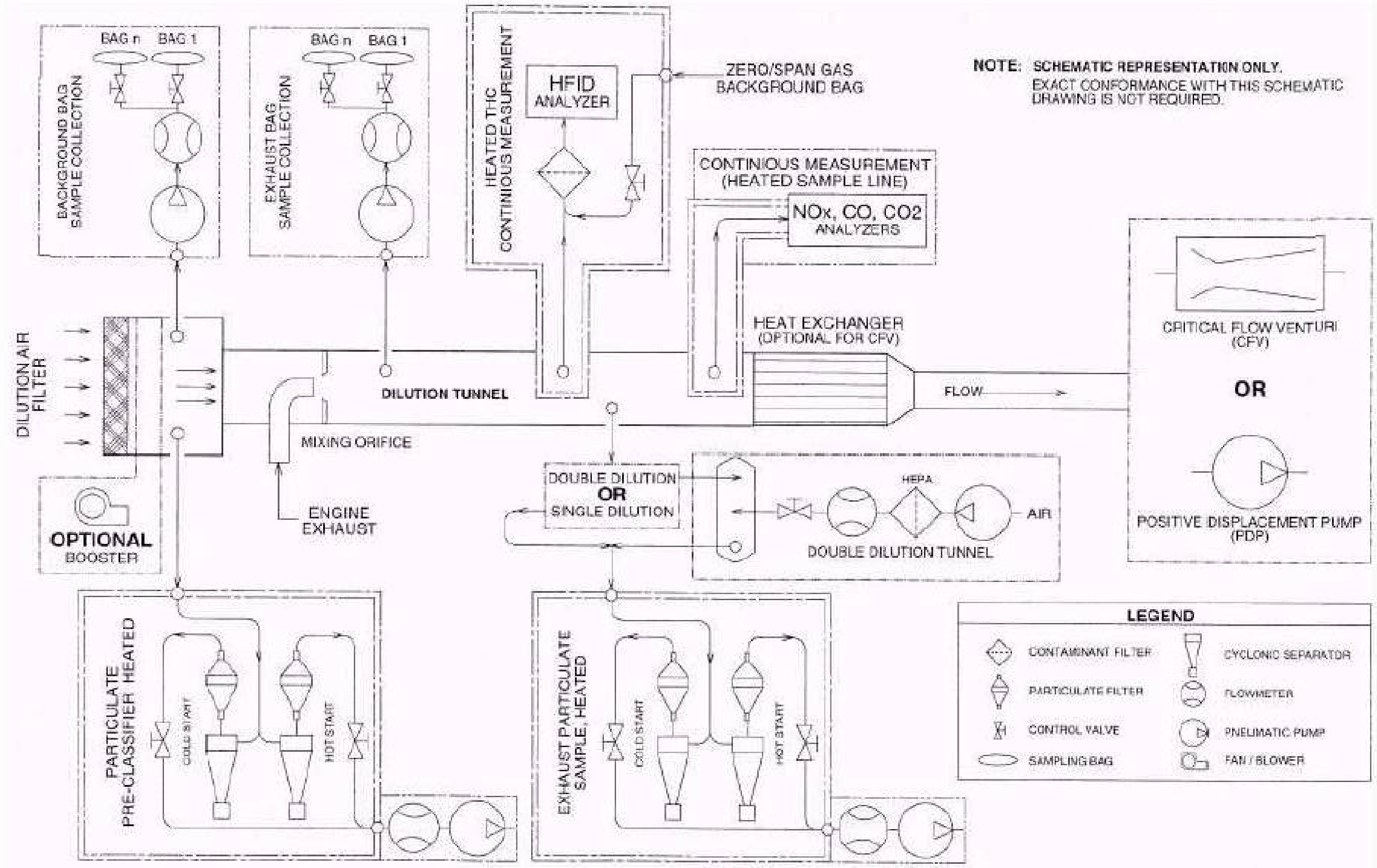

Figure 2.2.3.1: Measurement setup of US EPA 2007 Regulation.

2.3. Diesel Particulate Filters

Filtration of diesel exhaust gaseous is defined as separation of solid particles from the aerosol in general. Filtration comprises the separation of solid particles, and adhesion of them to the filter surface. Many conditions affect this separation and adhesion processes, such as flow rate, pressure and temperature. Efficiency of filtration is determined in different ways based on number of particles, mass of particles, or elementary carbon mass.

2.3.1. Separation and Adhesion

There are three basic mechanisms of separation. These are impaction or inertial deposition, diffusion deposition, and flow line interception. Illustration of separation processes by flow around a single fiber is in Figure 2.3.1.2.

In impaction or inertial deposition, big particles are intercepted due to inertia forces. Diffusion deposition affects very small particles, which reach the walls only due to diffusion. In flow line interception, also called blockage, a particle in the flow line just touches the surface and stay there.

These separation processes depend on particle size and density mainly. Large particles are retained primarily by means of impaction, where inertia is the predominant force, and separation of ultra-fine particles whoes diameters are below 100 nm (Burtscher, 2005) is only based on diffusion (Figure 2.3.1.1). Furthermore, flow velocity has an influence on separation process, in other words, when velocity is higher impaction, otherwise, diffusion is effective.

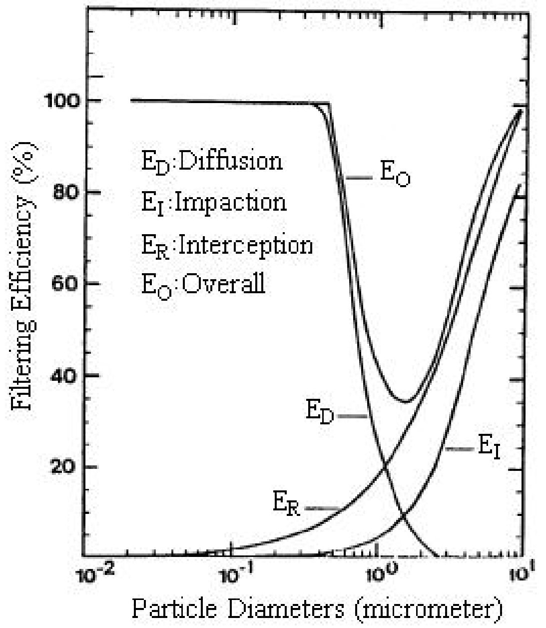

Figure 2.3.1.1: Separation effects based on particle size (Baraket, 1992).

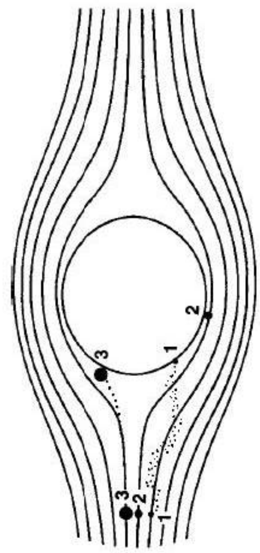

Figure 2.3.1.2: Illustration of separation processes by flow around a single fiber. 1.Diffusion 2.Interception 3.Impaction (Mayer, 2003)

Wall flow filters have porous structures, so they are described by a flow through model, whereas fiber structure filters are modeled by cylinders flowing around them (Figure 2.3.1.3). As shown in Figure 2.3.1.3, flow direction frequently changes in porous structures, hence velocity decrease and deposition rate by impaction and diffusion increases.

Besides, degree of separation, a second important criterion of filtration, is the adhesion of particles on the surfaces of filter structure. Adhesion is related to contact surface characteristics and flow forces. If particles are small, flow forces on them are also low. Hence, small particles' risk of being carried away by flow is low once they are adhered on surface.

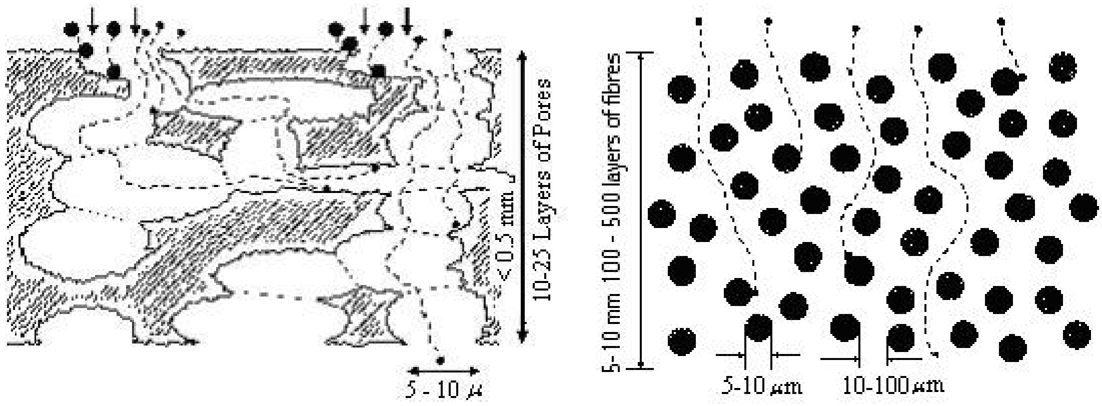

Figure 2.3.1.3: Wall flow filter (cell filter) flow illustration is at left. Right one shows fiber structure filter flow (Mayer, 203).

2.3.2. Regeneration and Cleansing of Diesel Particulate Filters

DPFs separate and retain the particles, so after thousand hours, ash starts to block the structure ways. In fact, blockage time depends on many conditions such as raw emission amount of the engine, oil consumption, qualities of fuel, and characteristics of the filter.

Soot collected in filter contains elementary carbon and hydrocarbons mainly. They are burned in filter, and CO, CO_2, and H_2O are formed. This burning process is called regeneration. Regeneration is based on temperature and amount of oxygen. If required temperature level and oxygen amount can not be obtained, some part of soot is accumulated. Moreover, much of the ash can not be burned and stay in filter structure even soot burning conditions are obtained.

Some methods are used to increase regeneration rate in filters. These methods are mainly categorized as passive and active methods. If regeneration is obtained by external energy supply that methods are named as active. If activation energy is reduced by the catalysts to a level where reaction starts even at lower operating temperature, these methods are named as passive. Some frequently used methods are explained below.

Electric heating, injection management, throttling of air flow or exhaust gas flow, and external regeneration (with burners) are mainly used as active regeneration methods. Active regeneration methods require to install control systems of filter. When maximum load is reached procedure of regeneration must be started either automatically or manually.

Different electric heating systems are used in filters. Heating of the exhaust flow, heating of the filter structure, and sequential heating of filter parts, in which only one filter candle or one filter channel is brought to regeneration temperature at a time, are some of the methods applied. Drawback of these electric heating methods is their using limited electric supply on vehicles.

Using energy of engine combustion for regeneration is a general method. Delayed injection, post injection, and exhaust gas recirculation are frequently used methods taking the required energy for regeneration from the engine. With these methods exhaust temperature is increased up to 200 ^{0}C. On the other hand, all these methods increase fuel consumption.

Continuously regeneration trap by NO_2, catalytic coatings, and using fuel additives are passive regeneration methods used in general. For small engines, soot loaded filters are exchanged with clean ones. Passive regeneration methods are less complex than active methods because, they do not require any control system or other auxiliary equipment.

Continuously regenerating trap (CRT) system makes use of a coated precious metal oxidation catalyst to generate NO_2 from NO. CRTs consist of two parts, coated structure, and conventional particulate trap. Coated part is positioned in front of the particulate trap. NO_2 is unstable at high temperatures (higher than 250 ^{0}C); therefore, in the particle trap the reaction is reversed, than the free oxygen molecule oxidizes the carbon. The CRT System requires sulphur free fuel, in order to avoid the formation of sulphate which otherwise interfere with the NO_2 conversion. Reactions of CRT can be summarized as follow.

$$2NO + O_2 \rightarrow 2NO_2$$
$$C + 2NO_2 \rightarrow CO_2 + 2NO$$
$$C + O_2 \rightarrow CO_2$$

Another method used to decrease the ignition temperature of soot is catalytic coating of filter. Coating is used in both cell and fiber filters as layers of transition metals on filter surfaces. Unlike precious metals, transition metals do not need NO_2 generation; however, they require higher temperature.

Fuel additives are used to catalyze soot combustion in filters. They reduce both, burning temperature (about 300-400 ^{0}C) and reaction time. Such elements as cerium, copper, iron, and strontium can be enumerated the examples of as fuel. With these additives better regeneration, even with old engines is obtained; however, they may cause extra ash formation, and faster pressure increase in filters.

2.3.3. Back Pressure of Particulate Filters

Filter systems installed in exhaust pipe cause pressure increase, called back pressure. Pressure loss of new filters at nominal load of the engine is usually around 50 mbar. 200 mbar at nominal load become generally accepted maximum pressure loss. That pressure loss increases the fuel consumption.

In cell filters, at first, when the filter is clean, the amount of pressure loss increase faster when compared to the soot retained. However, while the amount of soot retained increased in the filter the amount of pressure loss starts to change proportional to the amount of soot retained. If soot cake is formed then back pressure increase sharply, this may cause clogging. At the same time, degree of separation continuously increases due to formation of soot cake.

For fiber filters, pressure loss also increases sharply at the beginning. Then slope becomes proportional to amount of soot retained, and clogging does not occur. However, degree of separation is then decrease.

Increase of fuel consumption related to back pressure is proportional to the average engine pressure. If this working pressure of a high duty engine is in the range of 8-10 bars, then increase of fuel consumption due to pressure loss of 200 mbar is at most near 2%. For passenger cars operating at lower working pressure and at higher back pressure that increases near 5%.

It was found by VERT for engines of the power range of 50-500 kW, pressure loss of 200 mbar at maximum is acceptable. Smaller engines tolerate higher pressure loss; for instance, 400 mbar is usual for passenger cars. Pressure loss for bigger engines has to be smaller, due to overlapping of valves and high supercharging in these engines.

2.3.4. Diesel Particulate Filter Types

Technical requirements on Diesel particulate filters, according to VERT ("Verminderung der Emissionen Realer Dieselmotoren im Tunnelbau" / Reduction of Diesel Emissions in Tunneling), a research program sponsored by Swiss, German, and Austrian occupational health authorities, are listed below.

Exhaust temperatures reach 750 ^{o}C normally, may reach 1400 ^{o}C during regeneration. Extreme temperatures and rapid temperature changes cause high thermal loads. Therefore, material used in particulate filter should have high strength. Also material used in filters should have resistance to damage due to ash of oil and additives.

Particulate filter should have high capability up to 20g/l to store soot and ash. Filter should cause low pressure loss. It requires low thermal inertia (rapid start up). It should obtain filtration efficiency higher than 99 % for particles larger than 20 nm. Filter structure should tolerate vehicle vibrations, especially if it is assembled close to the engine. It should be cleaned from ashes easily (Mayer, 2004).

Of course there is another aspect to be considered about cost. For example, Mayer (2003) indicates cost should be lower than the 10 US $ per kW. Filter volume, and functional life time should also be considered with respect to engine capacity.

Due to the mentioned requirements, some types of materials are used in DPFs in general. Monolithic-porous ceramic cell structures (wall-flow) or foams, porous sintered metals or metal-foams, and filament structures like fleeces, winded yarn or webbing of ceramic or metallic fibers are used in DPFs. Pore size or fiber diameter required for particulate filtration is about 10µm or less (Mayer, 2002). These filter structures and materials are explained in the following sections.

2.3.4.1 Ceramic Monolithic Cell Filters

Ceramic monolithic cell filters have long cells, being closed at alternating ends (Figure 2.3.4.1.1). Therefore, flow is forced through porous walls. By this method, large filtering areas are obtained even in small total volume (up to $2m^2/l$). Low back pressure and high rates of separation due to low velocities when crossing the walls are other advantages of these filters. Cordierite and silicon-carbide are materials used in monolithic filters frequently. Cordierite as filter material has been used for more than 20 years. Silicon-carbide is a novel material, with higher strength, good heat conductivity, high temperature resistance and chemical stability. However, it has a higher cost 40 times to cordierite.

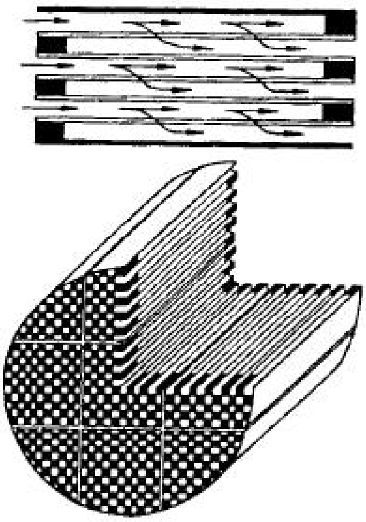

Figure 2.3.4.1.1: Ceramic monolithic cell filter, (Mayer, 2003).

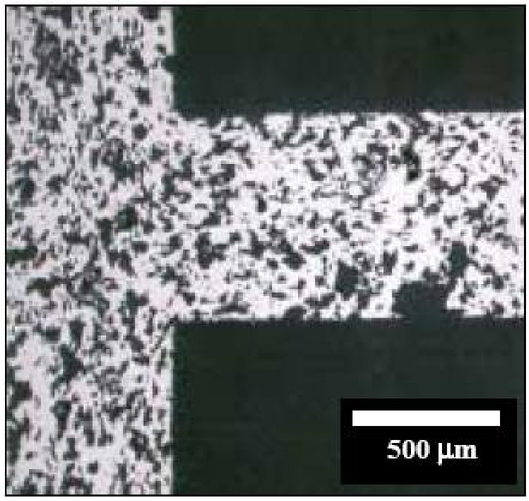

Figure 2.3.4.1.2: Ceramic cell pore wall, (Mayer, 2003).

In Figure 2.3.4.1.2 a photograph of a cell wall is shown. Wall thickness of filter is about 0.5 mm, average pore size is about 10-20µm. Filtration occurs at both surfaces of wall and within the holes of the ceramic walls.

Ceramic foams, which have porous structure, are also used as filter material (Figure 2.3.4.1.4). Large surface area is obtained with porous structure (Figure 2.3.4.1.3). Same materials are used in these filters compared to monolithic cell filters but their structure and flow of exhaust gas inside them is different. Ceramic foams can have 85-90 % pore volume, however cell size is larger than 100 μm (Adler, 2005).

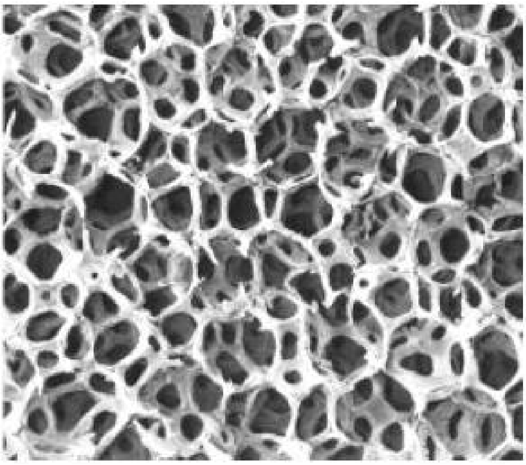

Figure 2.3.4.1.3: Structure of a ceramic foam filter, (Adler, 2005).

Figure 2.3.4.1.4: Ceramic foam filter (Guangdong, 2006)

2.3.4.2. Porous Sintered Metal Filters

Porous sintered metals are frequently used in DPFs. In Figure 2.3.4.2.1, one porous sintered metal filter produced by HJS Co. is shown. A thin sintered metal plate with exactly defined pore structure obtains high degrees of separation like ceramic cell filters. These filters have some advantages compared to ceramic cell filters, such as easy processing, better heat conduction, and high endurance to thermal stresses; however, they are rather heavy.

2.3.4.3. Filter of Wound Fiber

High temperature resistant fibers are rolled on a perforated tube by means of a special winding method, so a filter cartridge is formed in rhombic structures of channels. In Figure 2.3.4.3.1 a wound fiber filter produced by 3M is shown. These filters have high separation capacity; however, they are sensitive to mechanical forces, and have high cost.

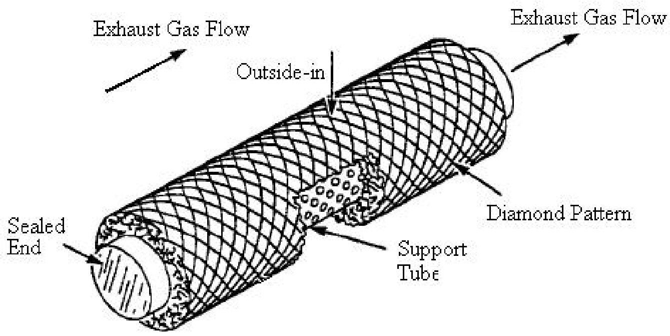

Figure 2.3.4.3.1: Filter of wound fiber (Mayer, 2003)

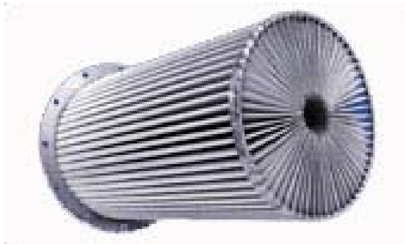

Figure 2.3.4.2.1: Sintered metal filter (HJS Co., 2006)

2.3.4.4. Knitted Fiber Filters

Knitted fiber or knitwear filters are made from ceramic yarn in form of a cylinder, called candle (diameter of fiber about 10µm). Gas flow through this cylinder is in radial direction. This type of filters is more durable compared to monolithic ceramic structures with respect to thermal loads. Due to their small diameter, these fibers retain their elasticity (Figure 2.3.4.4.1).

2.3.4.5. Filters of Braided Fibers

High temperature fibers are on the market in form of webs, possibly fixed on a metallic support. Such systems have been developed by Oberland-Mangold, HUG and by 3M. In Figure 2.3.4.5.1 a filter produced by Oberland-Mangold is shown.

Figure 2.3.4.5.1: Filters of Braided Fibers (Oberland Mangold, 2006).

Figure 2.3.4.4.1: Knitted Fiber Filter (Mayer, 2003).

2.3.4.6. Filter Papers / Filter Fleeces

In Figure 2.3.4.6.1, a paper filter produced by Auto Finish Systems (AFS), which can be used at reliable low exhaust temperatures, is shown. Paper filters can be used for temperatures up to 300 ^{0}C (Donaldson, 2006).

Fiber filters consisting of short fibers, randomly structured, fixed by some suitable glue, and fleeces of electric welded metal micro-fibers (Bekaert, 2006) are similar to paper filters regarding temperature.

Figure 2.3.4.6.1: Paper filter (AFS, 2006)

CHAPTER 3

EXPERIMENTAL SETUP

Experimental setup includes six main systems. These are: Engine-dynamometer system, air-fuel consumption measurement system, dilution system, particulate and gaseous measurement systems, and electronic control and measurement system. General view of the experimental setup is shown in the Figures 3.1 and 3.2. Parts of the setup are explained in following sections.

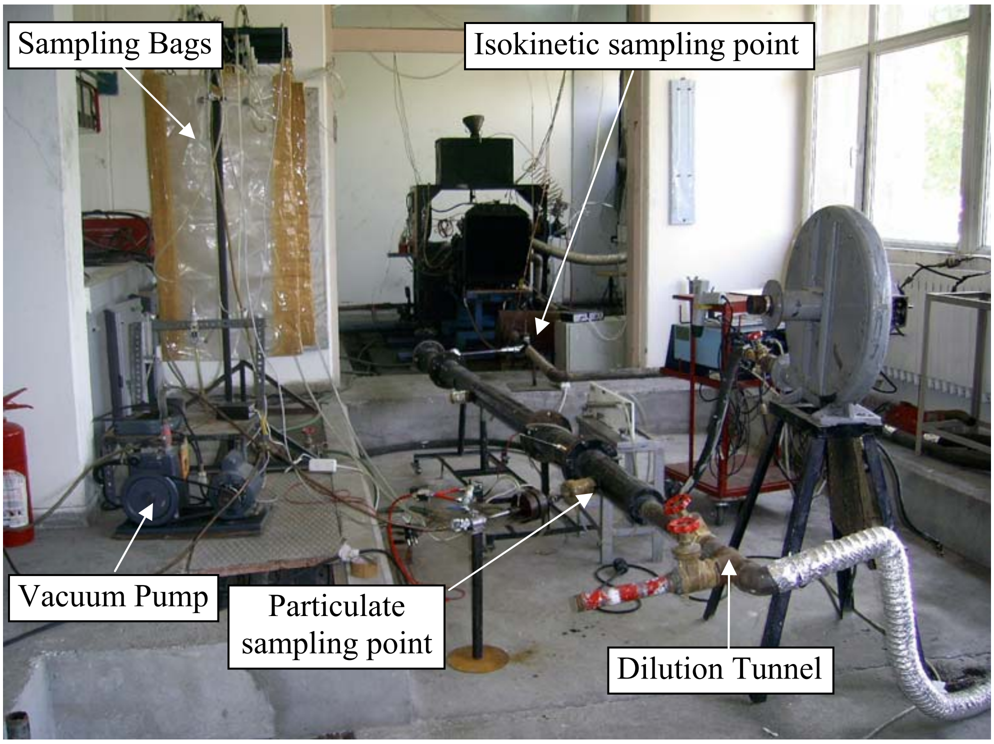

Figure 3.1: General view of the experimental setup

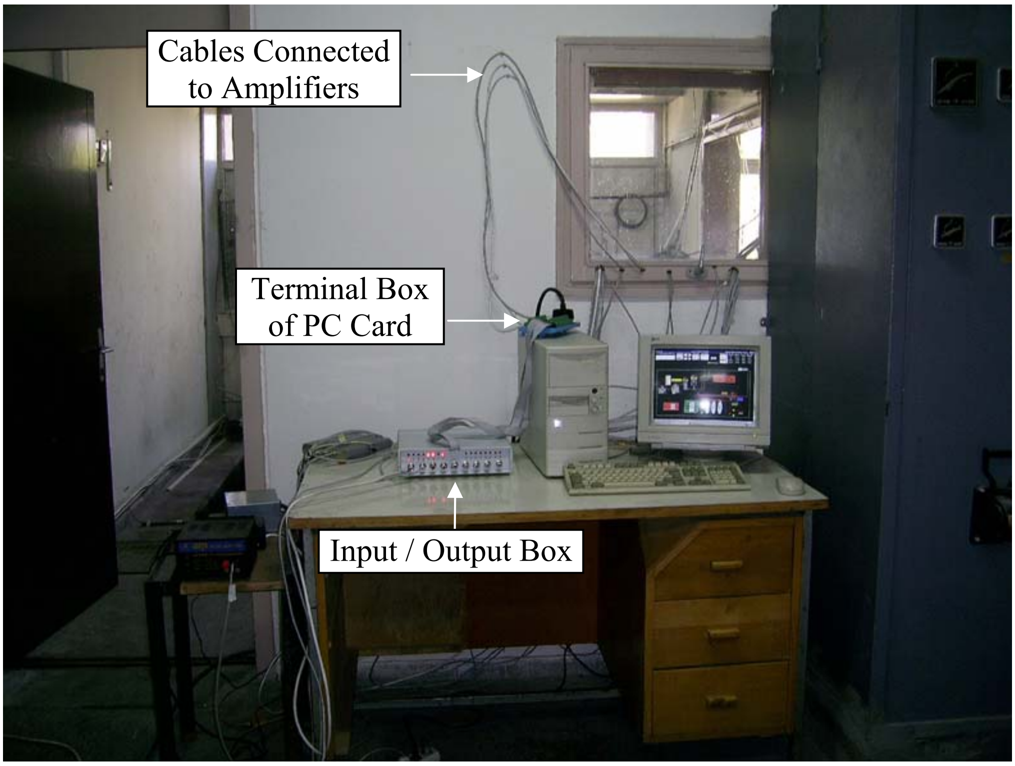

Figure 3.2: Control table of the experiments.

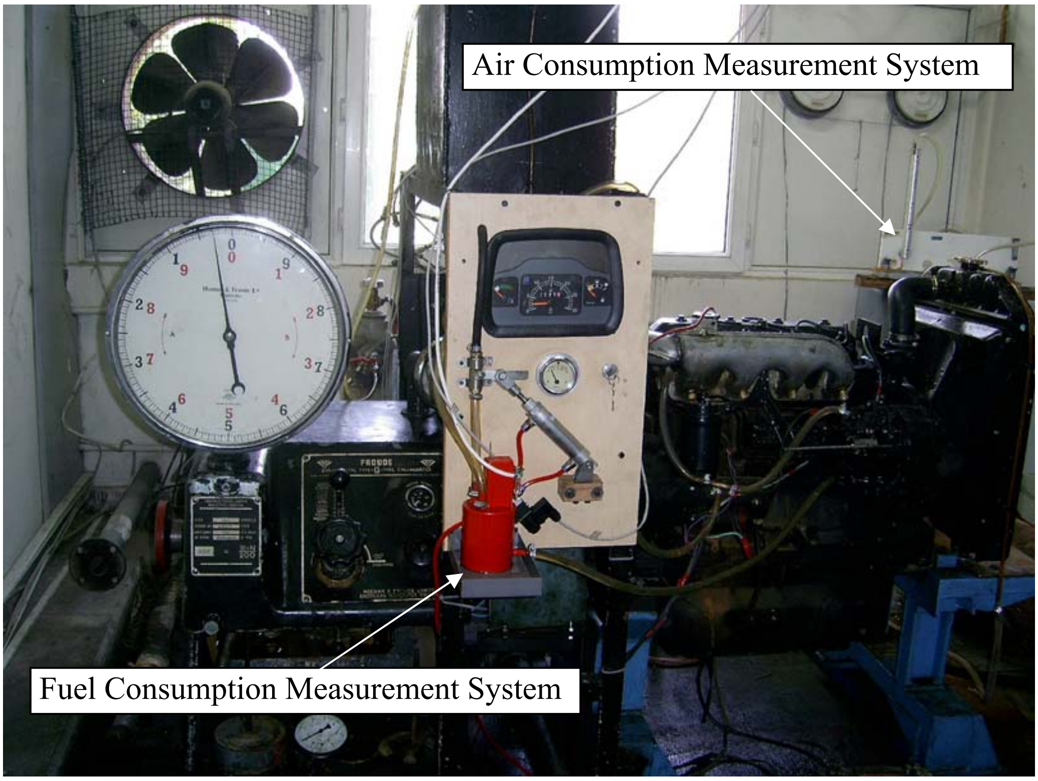

Figure 3.1.1: Engine, Dynamometer and fuel system.

3.1. Engine-Dynamometer System

Engine-dynamometer system is shown in the previous Figure 3.1.1. Engine is coupled to Froude Hydraulic Dynamometer. In the Figure, fuel tank and fuel consumption measurement system are shown also. These systems are explained in following sections.

3.1.1. Engine of Experiments'

Diesel engine used in the experiments is a four cylinder, four stroke engine and produced by Türk Traktör Co. Specifications of the engine are listed in the following Table 3.1.

Table 3.1: Specifications of the engine.

Make:	Türk Traktör Co.
Maximum Torque:	260 Nm at 1500 rpm
Maximum Power:	70 Hp at 2500 rpm
Swept Volume:	3908 cc
Compression Ratio:	1:17
Cylinder Diameter:	104 mm
Stroke:	115 mm
Low Idle Speed:	750 $\mp$ 25 rpm

3.1.2. Dynamometer

A dynamometer is a device used to measure speed and torque from which power produced by an engine can be calculated. There are two types of dynamometers: one that is bolted directly to the engine, known as an engine dynamometer, and the other that can measure power and torque without removing the engine from the frame of the vehicle, known as a chassis dynamometer.

In the experiments Froude Hydraulic Dynamometer, which is a sample of the first type, is used. A flywheel connected to engine shaft rotate in pump body where water passes in hydraulic dynamometer. Pressure of the water is changed to obtain a resistance which is used to measure engine power. Hydraulic dynamometer used in experiments has a capacity of 350 HP (Figure 3.1.1).

3.2. Air-Fuel Consumption Measurement Systems

3.2.1. Fuel Consumption Measurement System

Fuel consumption measurement system shown in Figures 3.2.1 and 3.2.2 includes optic sensors, valve and piston, 3-way solenoid, glass-buoy in the bulb structure, and flag. Flag, black colored plastic thin sheet, is glued on the glass-buoy, which floats on fuel in container.

Figure 3.2.1: Control panel of the engine.

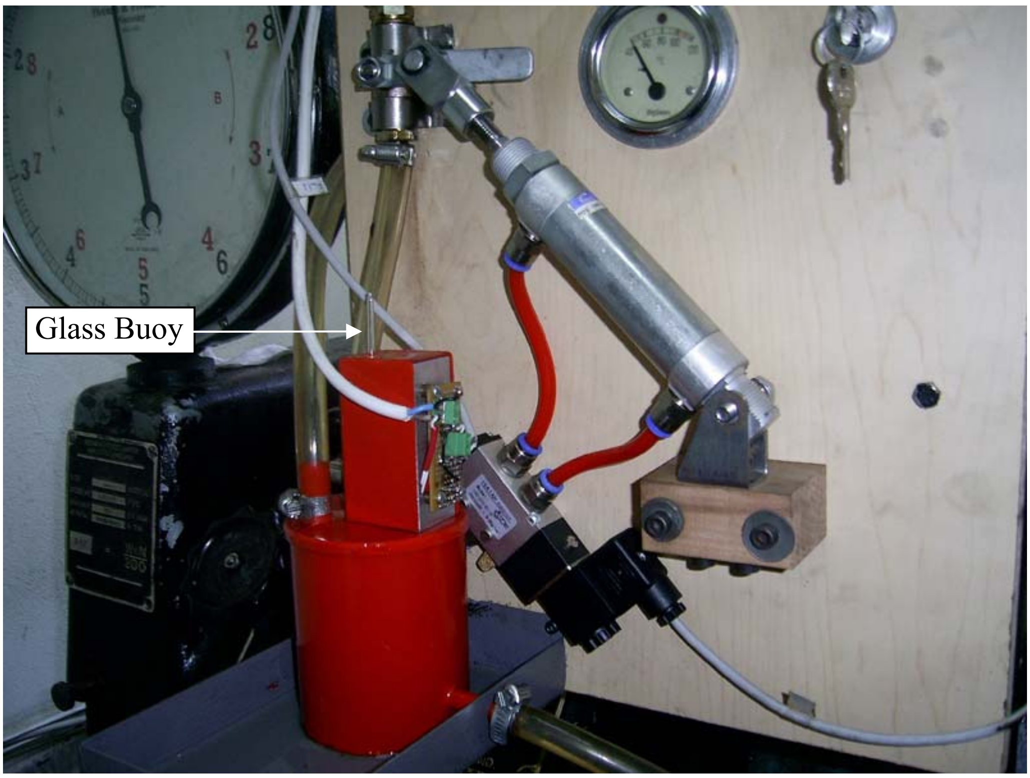

Figure 3.2.2: Fuel Consumption measurement system.

When fuel amount increases buoy and flag on it ascends. Two optic sensors are installed in such a way that flag pass inside them. With the ascending motion of flag, the sensor installed above sends a signal to the computer, and then the computer program written for the experiments sends a signal to activate the solenoid valve in which fuel comes, automatically. Computer signal is sent to solenoid, which directs the pressurized air, which in turn cause the piston open to close the valve.

3.2.2. Air Consumption Measurement System

Air consumption of the engine is measured by the system called Go-Power air flow meter (Figure 3.2.3). This system includes a pulse damping drum, used to amortize oscillations during the suction period of engine, a nozzle, and a manometer. Air enters the pulse damping drum by passing the high sensitive nozzle then pass a flexible hose to enter intake manifold. Air flow rate is calculated as to pressure difference, measured by a manometer, through nozzle.

Pressure reading device is a manometer in inches of water. Reading of pressure difference through nozzle by a manometer converted to air flow rate into the engine according to the calibration curve and equation in Figure C.5 (Appendix C).

Figure 3.2.3: Go Power, air flow measurement system.

3.3. Mini Dilution Tunnel

Mini dilution tunnel, used for the experiments in this study, was firstly designed and produced for PhD study of Karel (1996) (Figure 3.3.1). In dilution tunnel exhaust gas and dilute air should be mixed properly. Flow condition is the most important factor to obtain homogeneous mixture. In the first part of the tunnel, where two gaseous come in contact, flow is not laminar. This flow condition increases the mixing rate.

Through the tunnel, laminar flow condition is reached. According to BS 1042 (British Standard, 1992) to take accurate samples, minimum distance between the orifice (Figure 3.3.2), used to measure flow rate, and sampling point should be at least 10 times of the tunnel diameter. In designed dilution tunnel, pipe length between mixing area and sampling point is 16 times of the pipe diameter. Besides, orifice increases the mixing rate of the flow, because it causes narrowing and expansion in flow.

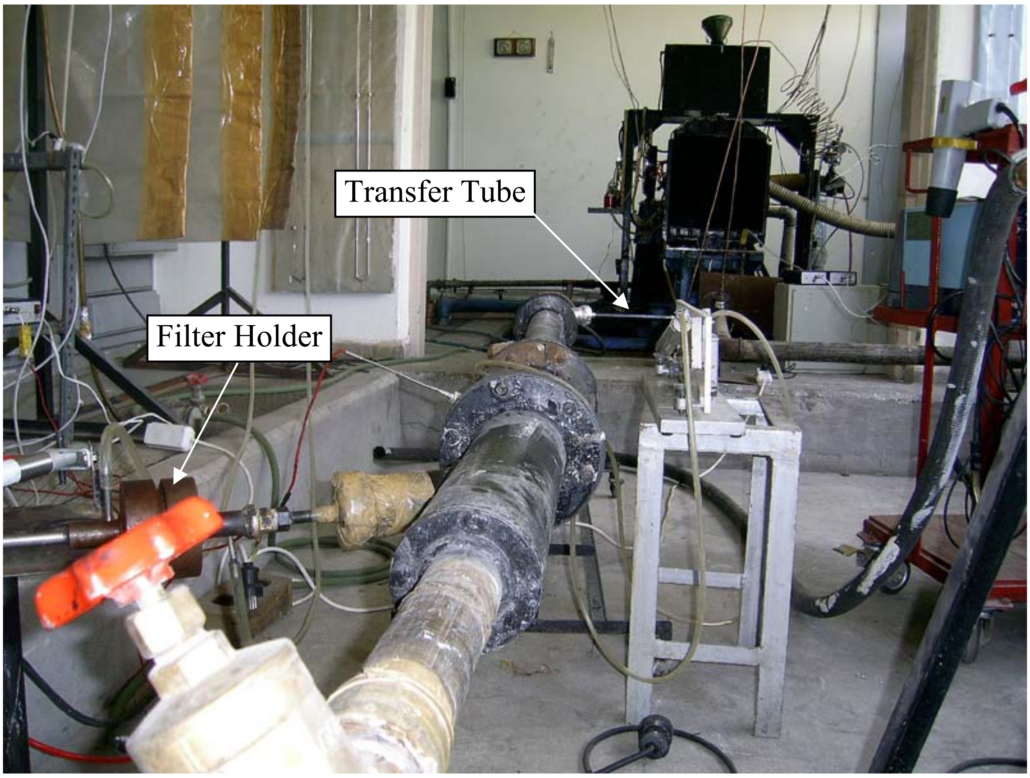

Figure 3.3.1: General view of the dilution tunnel.

Maximum mixture temperature should be 52 ^{0}C at the sampling point in tunnel (Directive 1999/96/EC). For dilution tunnel used in the experiments, that mixture temperature stays below the 52 ^{0}C when dilute air temperature is 22 ^{0}C, and temperature of sampled exhaust gaseous at full load is around 160 ^{0}C. When temperature of air taken from the environment reaches 35 ^{0}C, and when dilution ratio is decreased below 5, mixture temperature at sampling point passes the limit of 52 ^{0}C (Karel, 1996).

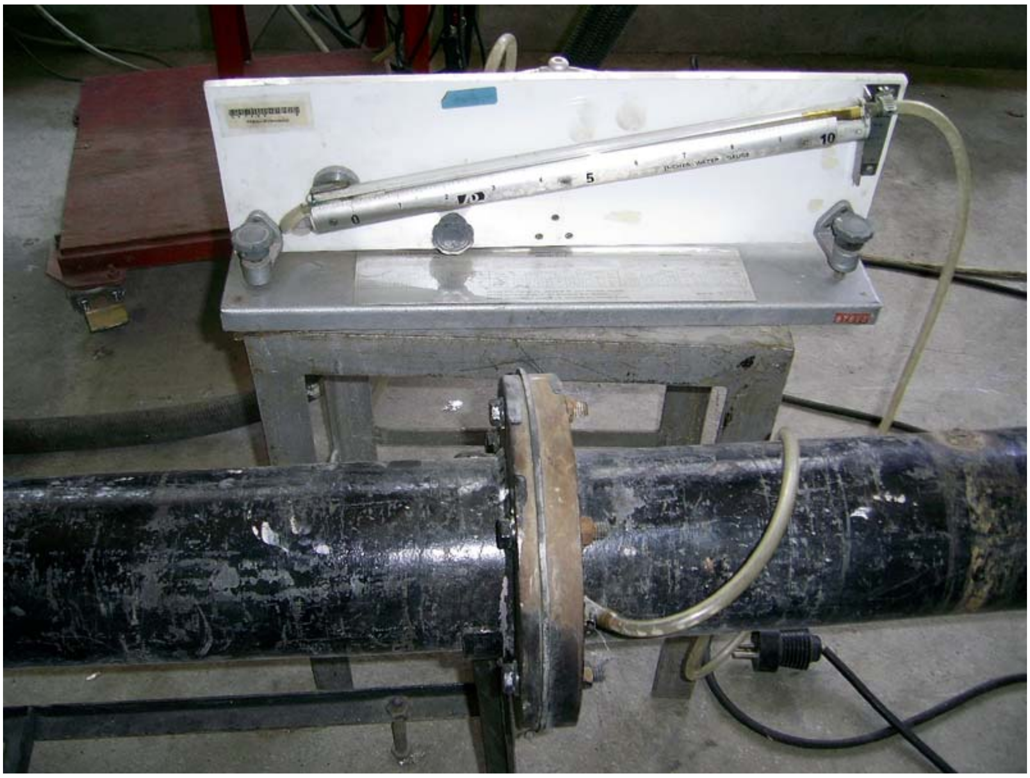

Figure 3.3.2: Manometer connected to orifice on dilution tunnel (DT).

Dilution tunnel was installed with pipes, whose inside surfaces are smooth, to prevent soot collection of the pipe inside. To measure soot amount adhered inside of the pipes, a section of pipe was cleaned before the experiment, and soot adhered was wiped with linen fabric and solvent material. Then total soot adhered inside of the pipes was calculated. The calculated ratio of adhered soot was 1.12 % of total soot of sampled exhaust gas according to this test (Karel, 1996).

3.3.1 Exhaust Gaseous Sampling System

To draw exhaust sample into the transfer tube, air blower is used (Figure 3.3.3). Blower supply dilute air and velocity of that air in the tunnel causes vacuum in the transfer tube. Sampling probe in transfer tube has an open tube facing upstream on the exhaust pipe centerline. A portion of exhaust gas is drawn from sampling probe to transfer tube with that vacuum.

Figure 3.3.3: Air blower connected to dilution tunnel (DT).

Reason of that vacuum is velocity and pressure difference between dilution tunnel and transfer tube (Figure 4.2.3). Hence the amount of sampled exhaust gas is related directly to dilution tunnel velocity and pressure. To control the amount of exhaust sample taken, tunnel flow rate is adjusted by a valve at the end of the tunnel (Figure 3.3.1). When the valve is turned to reduce passing gas amount, pressure inside the tunnel is increased, hence transfer tube velocity is decreased, and amount of sample taken is decreased. Obviously if valve is opened amount of sample taken is increased.

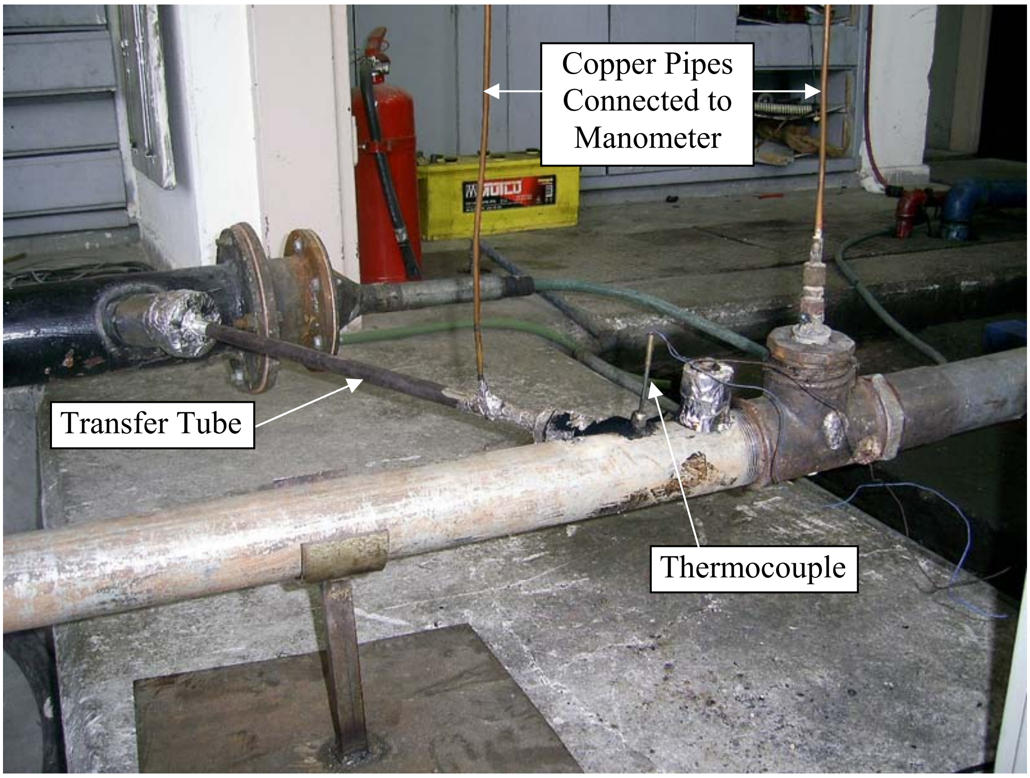

Figure 3.3.4: Isokinetic sampling point (ISP) and transfer tube (TT).

In order to get sample of gaseous with same concentration as exhaust pipe, iso kinetic sampling method is used. As mentioned in the Chapter 2, iso kinetic sampling requires pressure equalization between pipes. To make exhaust pipe and transfer tube pressures equal, pressures at sampling probe tip and at exhaust pipe near the sampling probe are measured (Figure 3.3.4), and dilution tunnel flow rate is adjusted considering that difference. Dilution tunnel flow rate is adjusted by the valve at the end of tunnel.

Design of the sampling system is based on Directive 96/EC/1999, which indicates that diameter of sampling probe should be minimum 12 mm and that ratio of sampling probe diameter to exhaust pipe should be 4. Due to these requirements, a sampling probe whose inside diameter was 13 mm, and an exhaust pipe whose inside diameter was 60 mm were used.

Another requirement is that maximum length of pipes from engine to dilution tunnel should be 10 m. In the system used, between the engine and dilution tunnel there are particulate filter, sampling probe and transfer tube, and pipes exhaust gaseous flow through. Total length of these parts was about 2 m. In addition, bends were minimized between engine and dilution tunnel to reduce inertial deposition.

For an iso kinetic system, the exhaust pipe must be free of elbows, bends and sudden diameter changes for at least 6 pipe diameters upstream and 3 pipe diameters downstream of the tip of the probe. The system used had a pipe whose inside diameter at the sampling point was 60 mm, hence distance from filter exit to the tip of the probe was 430 mm, greater than 360 mm, and pipe at downstream of the probe was longer.

Temperature of exhaust gaseous sampled is higher than temperature of pipe walls at the beginning. That temperature difference causes condensation, so soot is collected in pipe surfaces. Before the sampling, engine should be run for a while and engine regime should be waited. Moreover, exhaust gas temperature of at least 70 ^{0}C should be maintained at the probe, hence temperature at that point is measured, and flow conditions are adjusted if necessary.

Transfer tube used to pass samples to dilution tunnel should be as short as possible, not more than 5 m in length. Diameter of it should be equal to or greater than the probe diameter, but not more than 25 mm. It should exit from the centerline of the dilution tunnel and point downstream. Transfer tube used in the system had 13mm inside diameter, without any diameter change from tip of the probe to exit of the tube, and exited on the centerline of the tunnel.

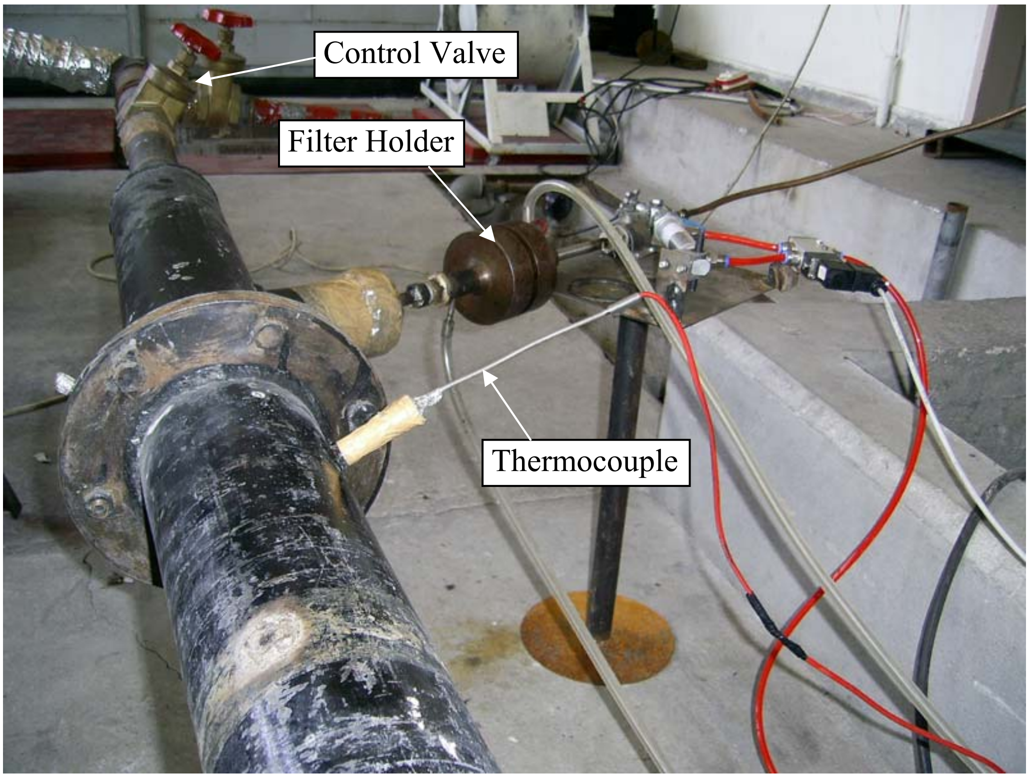

Figure 3.4.1: Particulate sampling point.

3.4. Particulate Sampling System

Particulate sampling probe should be installed facing upstream at a point where the dilution air and exhaust gas are well mixed, on the dilution tunnel centerline approximately 10 tunnel diameters downstream of the point where the exhaust enters the dilution tunnel. In the system used, particulate sampling probe was installed at the distance 16 times of pipe inside diameter from exhaust entrance in dilution tunnel.

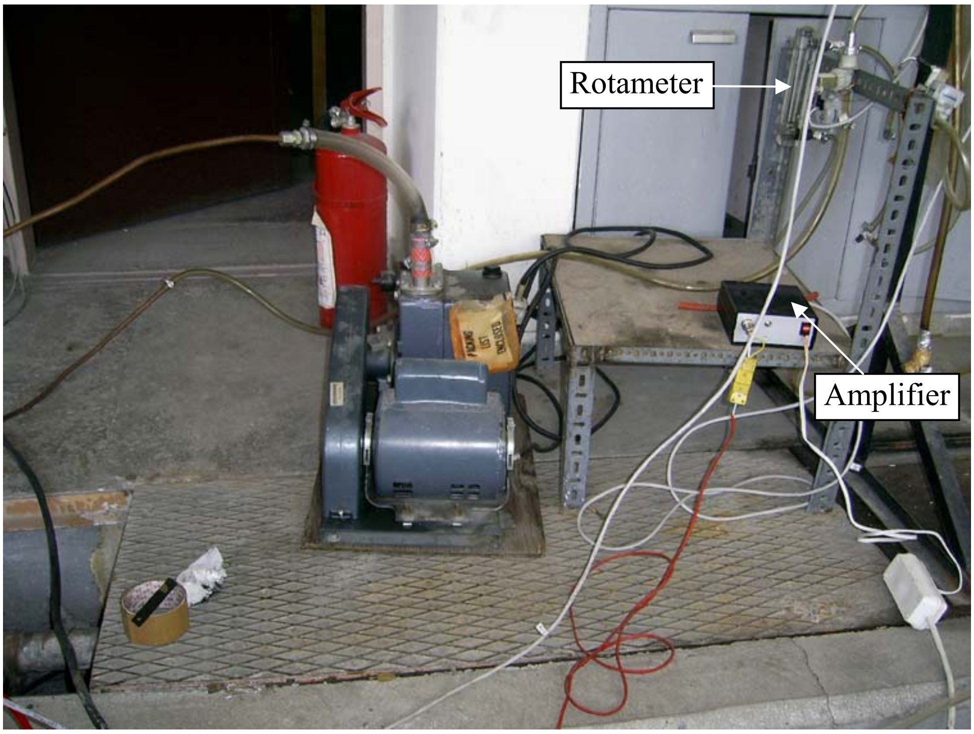

Figure 3.4.2: Particulate sampling line with vacuum pump and rotameter.

Sampling probe should have 12 mm minimum inside diameter. Opening of probe should have sharp edges, and wall thickness less than 1 mm. Therefore, opening of probe was machined to make it thinner, and a pipe whose inside diameter was 12 mm was used.

Particulate transfer tube of sampling line was connected to a filter holder, which had a fine particle filter, made of fiberglass, in it (Figure 3.4.1). Filter holder was connected to vacuum pump, used to take samples and draw them to bags (Figure 3.4.2). Particulate transfer tube from the tip of the probe to the filter holder must not exceed 1020 mm in length, and must be minimized in length whenever possible. Therefore, length of particulate transfer tube used in the system from probe tip to filter holder was designed as 430 mm.

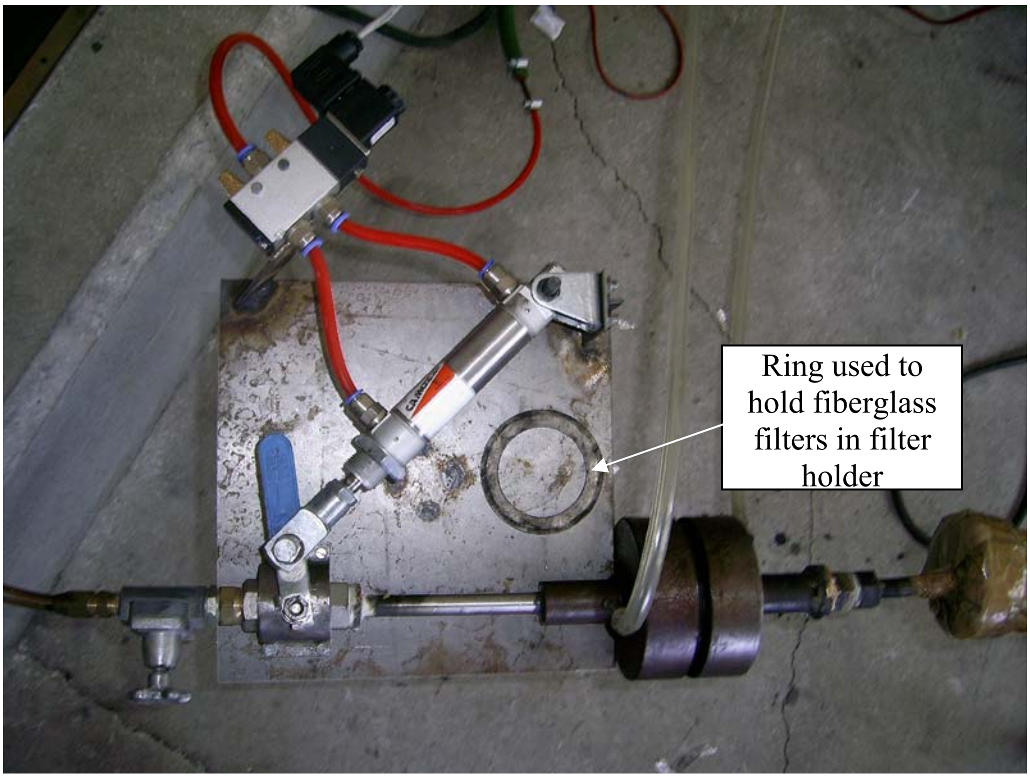

Figure 3.4.3: Filter holder and solenoid-piston-valve system on particulate sampling line.

Gas temperature at the sampling point must not greater than 52 ^{0}C. For this reason, temperature at the sampling point is measured with a thermocouple (Figure 3.4.1), and flow conditions are adjusted if necessary.

3.4.1 Filter Holder and Filters

Filter holder used in experiments are produced with a kind of material, which does not have any reaction with exhaust gaseous (Figure 3.4.3). Filters are positioned in such a way that sampled gaseous do not pass from outside of these filters. In the experiments fiberglass filters are used.

Figure 3.4.4: Balance with 1/10000 g sensitivity.

A preparation process in harmony with the standards mentioned above is necessary to make these filters ready. The preparation process applied includes keeping the filters for 3 hours in an oven at 60 ^{0}C, and then leaving them in a desiccator for 24 hour (Figure 3.4.4 and 3.4.5). Afterwards, filters are weighted. During this process filters should not be touched by hands. After the experiments, these filters are weighted again by a balance with 1/10000 g sensitivity.

An important risk factor that should be considered during experiments is the possibility of the blockage of filters. Blockage may cause a cut open in filters. A manometer parallel to filter holder is connected to measure pressure difference thought filter.

Figure 3.4.5: Oven and desiccator with filters in it.

3.5. Sampling of Gaseous Emissions

Sampling of gaseous emissions is performed by using nylon bags (Figure 3.5.1). Those bags are placed in particulate sampling system line after vacuum pipe. Sampled gaseous pass through filter holder next to the vacuum pump, hence purified gaseous are collected in the bags. Gaseous are canalized by using solenoid valves. There are 10 solenoid valves connected to the computer used in the experiments. Sampled gaseous in bags are vacuumed by the AVL Gas Analyzer device (Figure 3.5.2) to measure concentrations of CO, hydrocarbons, and nitrogen oxides.

Figure 3.5.1: Nylon bags and solenoid valves on them

AVL gas analyzer device has two probes, one for measurements of opacity, and other for measurements of gaseous emissions (Figure 3.5.3). For the measurements of opacity an auxiliary device is used with AVL gas analyzer (Figure 3.5.2).

Figure 3.5.2: AVL gas analyzer and opacity measurement devices.

Figure 3.5.3: AVL gas analyzer's gaseous emissions measurement probe and filter holder on it.

Figure 3.6.1: General view of control table.

3.6. Electronic Control and Measurement System

For the control of experiments and taking measurements different apparatus were used during experiments. Thermocouples, amplifiers, optic sensors, solenoid valves, pistons, input-output box, data acquisition card and a personal computer were used for the temperature measurements, fuel flow rate measurement and gaseous flow control. General view of the control table is shown in Figure 3.6.1.

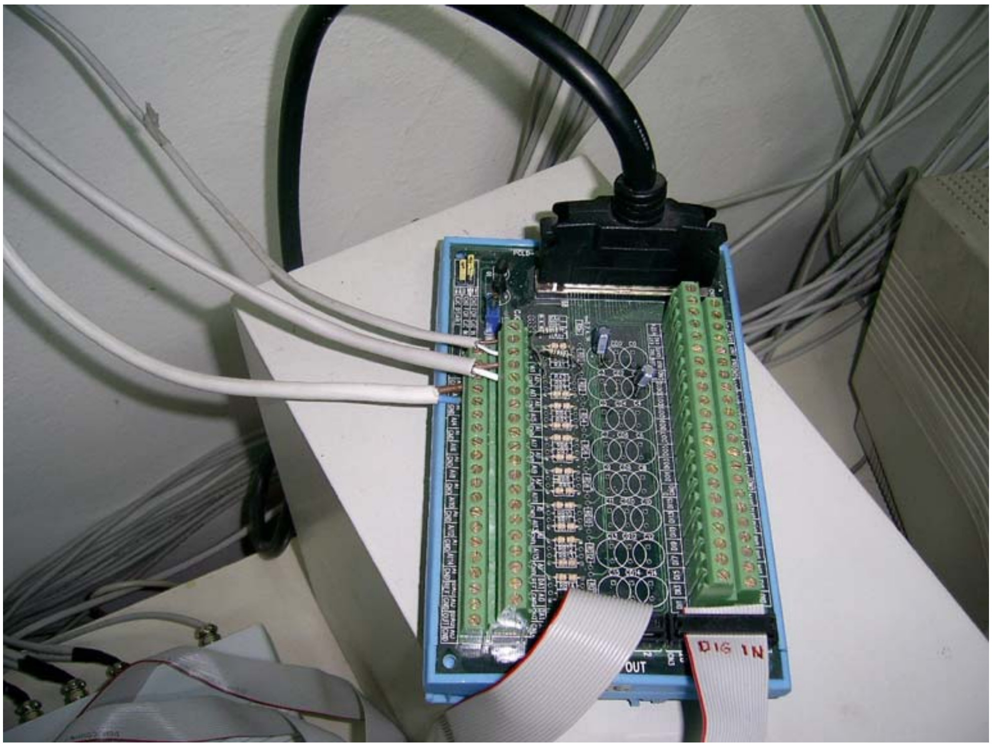

Figure 3.6.2: Data acquisition card terminal box.

3.6.1. Data Acquisition

A data acquisition card that was placed internally and installed to a personal computer was used for the collection of data, and sending necessary signals to control devices with the help of software. The collected data was low voltage outputs of temperature measurement devices. These low voltages have been amplified with the help of amplifiers, which were produced for this thesis study, and then supplied to the analog inputs of the terminal of the data acquisition card.

To measure the fuel consumption rate two optic sensors were used as mentioned in the Fuel Consumption Measurement System section. Connection of these sensors is made to send signal with two output cables. Optic sensor signals were converted to digital signals with the help of input-output control box produced for this study and then supplied to the digital inputs of the terminal of the data acquisition card (Figure 3.6.2).

Figure 3.6.3: Front of the input-output control box.

Solenoid valve controls were made with the help of this card also. Signals came from Delphi program software, transferred to input-output box and necessary voltages were send to solenoids. Two kinds of solenoid valves were used. One type needs 220 volt for opening, and other needs 24 volts. Also optic sensors need 5 volt and relays in the input-output box need 12 volt. These voltages were supplied with adapters with the help of input-output box.

3.6.2 Input / Output Control Box

Digital signals between the PC card and optic sensors, and solenoid valves are controlled by the input / output control device, which is designed by Utku Avgan and produced for this thesis study based on experiment's equipments requirements.

Solenoids at the entrance of the plastic bags work with 220 volt. On the other hand solenoids direct the pressurized air, which controls the piston motion, work with 24 volt. Therefore input / output device includes relays, which work with 12 volt, can control 220 volt. Three voltage sources, 12, 24 and 220 volts are connected to the device (Figure 3.6.5).

Input-output box have eight input sockets, on the front of the box, and eight output sockets, on the back of the box, shown in Figures 3.6.3 and 3.6.4. However one socket can be used for two signal cables. Also input-output control box has one socket on the front for 12 and 24 volt cables, and one socket on the back for 220 volt cable.

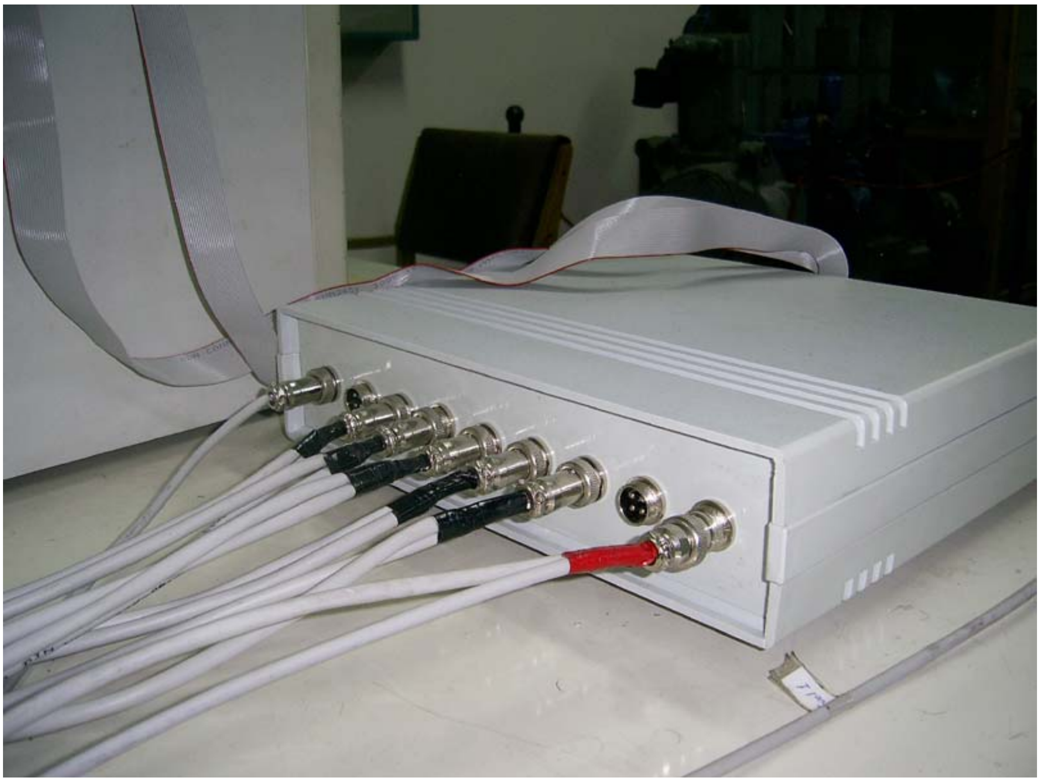

Figure 3.6.4: Back of the input-output control box.

3.6.3. Temperature Measurement

K type thermocouples were used to measure temperatures. Amplifiers necessary for the experiments are produced by using the design developed by Prof. Dr Demir Bayka. By using these amplifiers, signals of thermocouples are amplified to -10/+10 V range. Calibrations of these amplifiers were made with the help of thermometer, and calibration curves are in Figure C.1, C.2, and C.3 at Appendix C. Amplifiers (Figure 3.6.6) are connected to analog input ports of the data acquisition card. In the designed particulate filters and at the sampling points of exhaust gas, and diluted mixture, this temperature measurement procedure is used.

Figure 3.6.5: Adopters connected to input-output control box

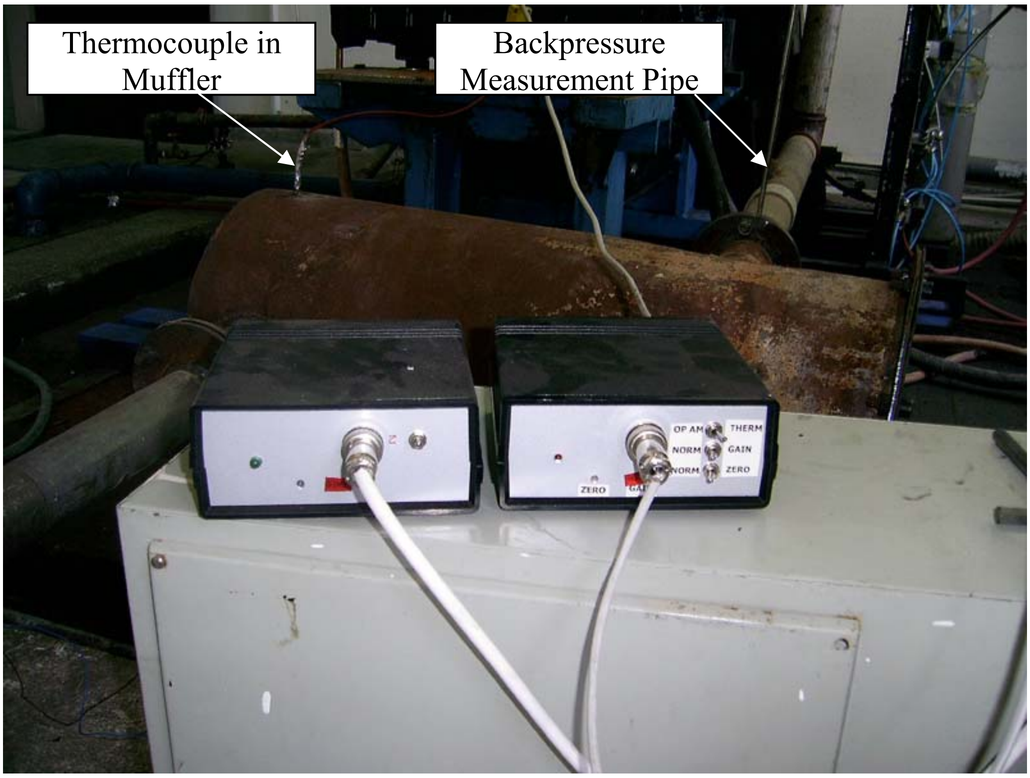

Figure 3.6.6: Two amplifiers used for temperature measurement.

3.6.4 Computer Program

Computer program used during experiments was written in Delphi 4.0. Program has a data acquisition card selection window. After the card selection, user should select channels where input signals come. For this experimental setup, there are three analog input come to terminal box. Also channel-0 is used to measure atmospheric temperature. Therefore, channel-0 and channel-2 were selected for all experiments. Afterwards voltage ranges for input data are selected. For this experiments, -10/+10 voltage range were used.

When start button is clicked, data is collected in every second for temperature measurement of three points. For the fuel consumption measurement, data is collected in every 50 msec. As mentioned previously in data acquisition section, optic sensor output voltages come to input-output device, and then converted to digital signals come in terminal box as input data. Program check these digital inputs and when signal comes from lower optic sensor, send digital output to solenoid valve and open the fuel flow control valve. When signal comes from upper optic sensor, program send digital output and close the fuel valve. Based on these digital inputs program calculate the fuel consumption rate, and show position of fuel valve.

Computer program calculate temperatures at filter, iso kinetic sampling point and particulate sampling point based on analog signals comes from amplifiers. Moreover, solenoid valves on plastic bags and particulate sampling system next to filter holder are controlled with the help of computer program.

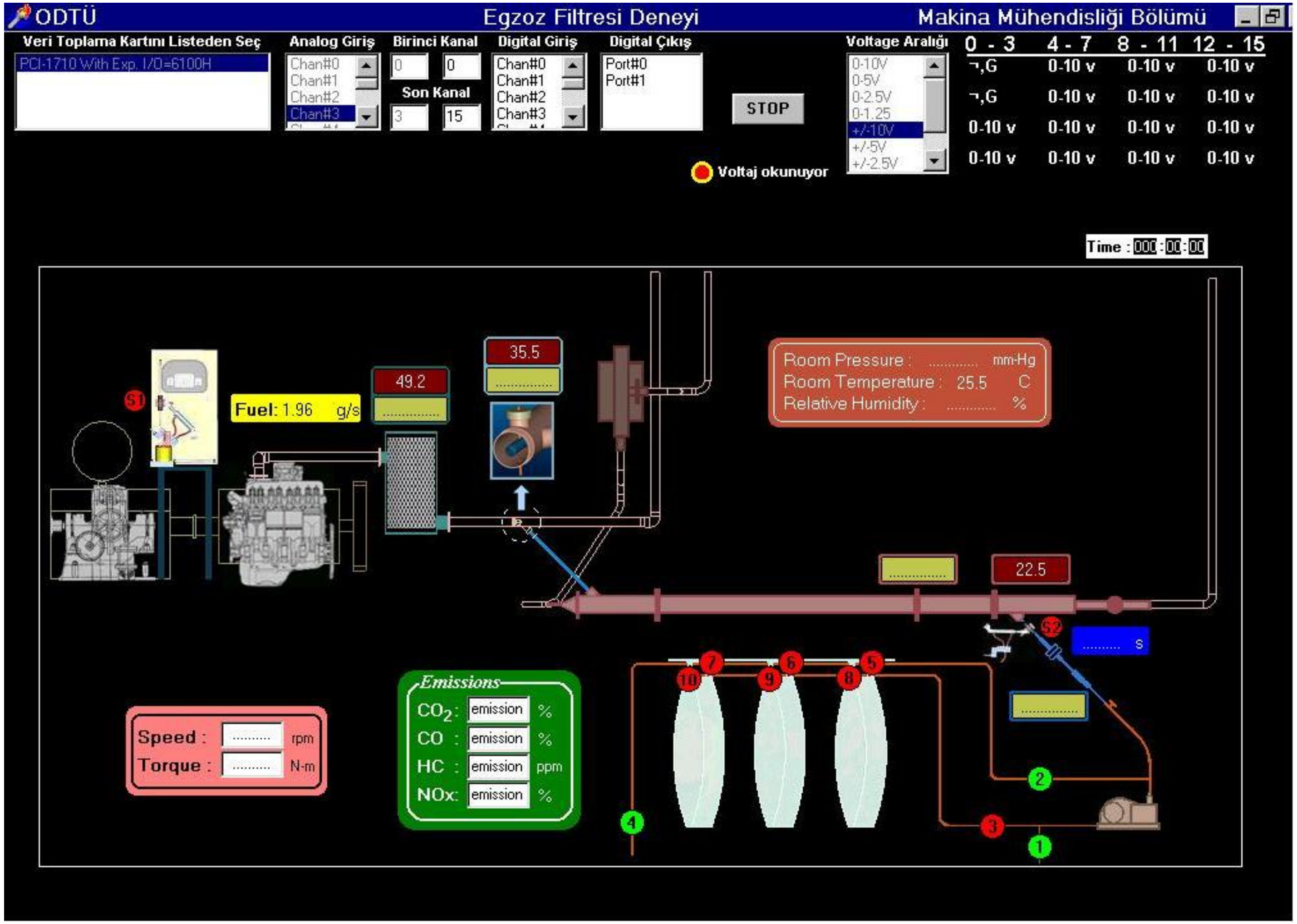

Figure 3.6.7: Screen shot of computer program

Computer program automatically open the solenoid valve next to the vacuum pump, and close the other solenoid valves opened previously when particulate sampling is started by user. Program measure the particulate sampling time, and after the 2 minutes close the solenoid valve on particulate sampling line and open necessary solenoid valves connected to vacuum pump.

CHAPTER 4

FILTER DESIGN

4.1 Filter Design Parameters

Soot which is particulate emissions is a problem sourced from diesel engine exhaust, and as previously mentioned, it should be prevented. Different studies performed to prevent these emissions or reduce them to harmless limits. Among them particulate trap applications supplied positive results.

However these applications have some problems as well. Most important one is material corrosion because of the high thermal stresses which occurs during the regeneration process. Second important problem is high pressure. If filter is blocked, back pressure increases and this affects the engine efficiency and fuel consumption rate negatively. If filter efficiency is low, necessary amount of soot can't be burned. Another important problem is high production cost. Filter design parameters considered in this study are listed below.

- Continuous regeneration of soot which is collected in particulate trap depending upon different weather and road conditions.

- Reduction of particulate emissions to minimum levels. These levels mentioned previously are determined according to the limits existing which are specified by standards and values. Some limits according to different years are illustrated in the Table 1.3.1 (Diesel Emission Limits for HDV's of EU). As can be seen in the table, emission limits are reduced to lower values in time. Therefore it is not wrong to claim that limits may decrease to smaller amounts in the long run.

- Minimization of the fuel consumption of engine which increases because of the high temperatures and high back pressure caused by particulate trap. This back pressure increases depending upon the traversed road or time. At starting conditions, it approximately 20 mmHg, and can increase 4-8 times to 150 mmHg levels.

- Prevention of material's deformations, cracks, or melting; leading to the increase in the system working time. These material problems are the result of thermal stresses. During the regeneration, high temperatures occur, and high thermal stresses are formed in the equipment.

Use of electrical or fuel-burn heaters or exhaust gaseous heat to reach oxidation temperature during the regeneration of collected soot, are methods increasing the process efficiency. Durable filter material selection is important to increase working time or lifetime of system as long as such high temperatures are necessary to reach efficient regeneration operation.

- Prevention of engine from stopping when particulate filter is blocked because of the emission of unexpected amount of particulate matter or insufficient regeneration.

- Design of filter to obtain easy installation, maintenance and repair conditions.

- Reduction of filter system cost.

4.2 Designed Particulate Filters

A silencer used in a bus previously was selected for this study. Some machining operations, cutting, grinding, welding were performed on it. Then designed filters were placed in this silencer, and the mechanism was installed in the exhaust system (Figures 4.2.1, 4.2.2, 4.2.3).

In this study, metal chip is used as main filtering material. Chip has a large surface area, and its surface is not smooth due to machining operation, increasing the rate of separation and adhesion, main processes of filtration. With the collected soot, backpressure in the filter increases, so temperature in the filter increases. At high loads, continuous regeneration is expected because 375-400 ^{0}C is enough to burn soot particles.

Figure 4.2.1: Silencer used in the experiments.

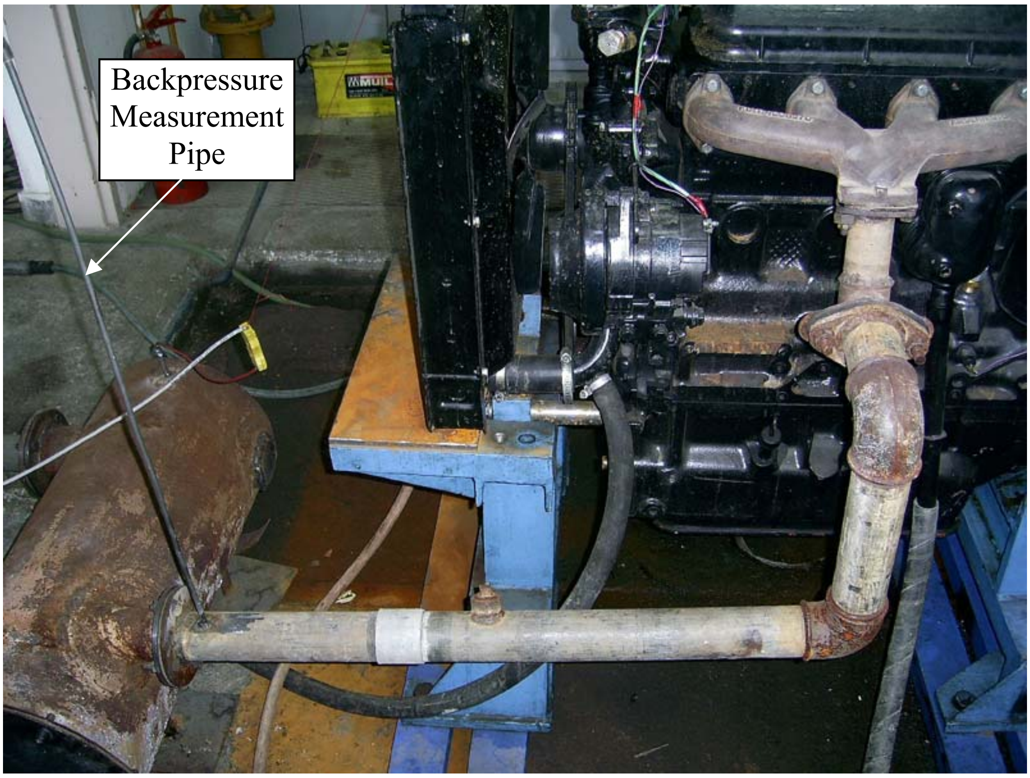

Figure 4.2.2: Silencer position in the exhaust line.

Aluminum alloys and copper are used as catalyst material commonly in particulate filters. Also these materials are used as fuel additive to reduce diesel engine emissions. Therefore, aluminum and copper chip is used in designed filters besides iron chip to investigate catalyst effect.

Figure 4.2.3: Silencer position and ISP in the exhaust line.

First design consists of aluminum wire clothe in cylindrical form and metal chip (Figure 4.2.4). Second filter has sheet metal structure, which have three cells in longitudinal direction. Entrance and exit of the filter are covered with aluminum wire cloth (Figure 4.2.5). With these cells, exhaust stream passing distance was increased; hence metal chip-gaseous contact time is increased. With the much contact time, separation and adhesion chance of particles is higher.

On the other hand, if filter passing distance is increased with cells and metal chip in them, velocity of stream decreases, back pressure on engine increases. As mentioned previously, back pressure affects fuel consumption in a negative way.

Figure 4.2.4: Aluminum wire cloth and metal chips.

All metal chip volumes used in first design were 500 cm^3. Therefore weight of aluminum, iron and copper chips in filter were 1350, 3940, 4460 grams. Total weights of filters were 2 kg, 4.6 kg and 5.2 kg respectively with aluminum wire cloth of 715 g.

According to the results of experiments with these three metal chips, copper that has better results was selected and other two experiments performed with copper chip.

Second filter design, which has long cells, contains 6.75 kg copper chip, and 13.25 kg sheet metal structure. Total weight of this filter is approximately 21 kg.

Figure 4.2.5: Second filter structure and entrance.

First filter, which has aluminum wire cloth structure, with less amount of copper chip is tested in the last experiment. Therefore filter particulate holding performance at minimum backpressure and fuel consumption amounts was checked. Therefore, 2.7 kg copper chip is used in the last filter.

These filters, designed and produced, have some advantages listed below:

- ✓ Large surface area.
- ✓ Easy to produce.
- ✓ No need to continuous maintenance.
- ✓ Low weight.
- ✓ Low cost.
- ✓ No need to an auxiliary system for regeneration.
- ✓ Continuous burning in filter.
- ✓ Low backpressure.
- ✓ Silencer effect.
- ✓ Catalyst effect.

4.3 Experimental Test Procedure

Experiments have been performed by setting a throttle position and varying the load on the engine with the help of the dynamometer according to following step by step test procedure. This procedure was used for all experiments performed with empty silencer, and aluminum, iron and cupper metal chips. Test modes used in experiments are calculated according to ESC test procedure (Directive 1999/96/EC). These test modes are listed in following Table 4.1.

1. Start AVL Gas Analyzer 15 minutes prior to tests to heat it self up and for automatic self calibration.

2. Make AVL Gas Analyzer leakage test.

3. Check fuel level in the fuel tank and open the fuel valve.

4. Check water level in the water tank of dynamometer, and start the water pump.

5. Start the pressurized air pump (which is used for piston-solenoid system).

6. Place the clean fiberglass filter (preparation process applied and weighted) in filter holder and take the number written on filter.

7. Check the bags and discharge the gaseous if necessary.

8. Turn on the water vane of dynamometer, then discharge the air left in the dynamometer until the water comes out having pressure value little more than atmospheric pressure.

9. Open the radiator water valve.

10. Turn the PC on and run the computer program.

11. Turn the adapters on (5, 12, and 24 volts).

12. Check the water levels of the manometers on dilution tunnel and Go Power system.

13. Start the engine and let it run at 750 rpm and zero load.

14. Start the air blower.

15. Start the vacuum pump.

16. Adjust the valve position to make ISP manometer difference to zero.

17. Take manometer readings of Go Power system and exhaust line for backpressure.

18. Start the particulate sampling from computer program.

19. Take rotameter reading.

20. Check the manometer on filter holder for blockage.

21. Take manometer reading of dilution tunnel.

22. Take the fuel flow rate and temperatures of silencer, ISP and particulate sampling point from computer program.

23. Place the probe of AVL Gas Analyzer device in exhaust pipe, and take emission data.

24. Place the opacity apparatus's probe of AVL Gas Analyzer device in exhaust pipe, and take opacity data.

25. Stop the engine, air blower and vacuum pump.

26. Change the fiberglass filter, and take the filter number.

27. Place the dirty fiberglass filters in glass containers.

28. Repeat steps 13 to 26 for engine speeds 1600, 2100 and 2600, and dynamometer readings 1.2, 2.4, 3.6 and 4.8 according to ESC test modes in Table 4.1.

29. After the 13 test modes performed, put the fiberglass filters in an oven, and keep them for 3 hours at 60 ^{0}C and then leave them in a desiccator for 24 hours. Afterwards, weight the filters.

30. Repeat these steps for empty silencer and all metal chips used as filter material.

Table 4.1: Experimental test modes.

Mode	Engine Speed	Load	Weight Factor,%	Duration
1	Low idle	0	15	4 minutes
2	1600	4.8	8	2 minutes
3	2100	2.4	10	2 minutes
4	2100	3.6	10	2 minutes
5	1600	2.4	5	2 minutes
6	1600	3.6	5	2 minutes
7	1600	1.2	5	2 minutes
8	2100	4.8	9	2 minutes
9	2100	1.2	10	2 minutes
10	2600	4.8	8	2 minutes
11	2600	1.2	5	2 minutes
12	2600	3.6	5	2 minutes
13	2600	2.4	5	2 minutes

CHAPTER 5

CALCULATION PROCEDURE

In this chapter, the engine performance and the exhaust emission's calculations have been determined. A computer program was written in Microsoft Excel to perform following equations.

5.1 Brake Power (HP)

The brake power at measured speed is evaluated as follows. The brake power is measured generally in terms of horsepower.

$$BP = \frac{Torque\ Reading\ x\ N_{speed}}{200}\ xK_d$$

$$K_d = \left(\frac{742.56}{P_d}\right)^{0.65} x \left(\frac{T_{atmK}}{298}\right)^{0.5}$$

$$P_d = P_{atm} - RH\ x\ P_v$$

Where RH is relative humidity, and K_d is the power correction factor. K_d is used to calculate engine power under the reference atmospheric condition of 25 ^{0}C and 99 kPa dry pressure.

5.2 Engine Torque (Nm)

The engine torque at measured speed is evaluated as follows. BP is brake power of the engine.

$$T = \frac{BP\ x\ 60000}{2\ x\ \pi\ x\ N_{speed}\ x\ 1.36}$$

5.3 Fuel Consumption (kg / h)

Fuel consumption of the engine at measured speed is calculated automatically by the computer program by using the following equation.

$$\dot{m}_{fuel} = \frac{86\ x\ \rho_f\ x\ 3.6}{t_f}$$

Where t_f is the consumption time of 86 ml fuel in s. ρ_f is the fuel density which is given between 0.82-0.85 (kg/l). It is accepted as 0.83 (kg/l).

5.4 Brake Specific Fuel Consumption (kg / HP h)

The brake specific fuel consumption is used to compare how efficiently the engine converts fuel to work. It is calculated as follows.

$$BSFC = \frac{\dot{m}_{fuel}\ x\ 3.6}{BP}$$

5.5 Air Flow Rate (kg / h)

Air flow rate of the engine is measured by using Go-Power air flow meter device. The manometer readings indicate the pressure difference through the nozzle. These manometer readings are converted into volume flow rate by using the calibration curve and equation.

$$\dot{m}_{air} = -11.549G^6 + 114.6G^5 - 450.38G^4 + 903.24G^3 - 1009G^2 + 755.31G + 0.4288$$

Where G (in-Water) is Go Power reading and $\dot{m}_{air}$ is calculated in Ibs/hr.

5.6 Air / Fuel Ratio

Air / Fuel ratio is calculated as follows.

$$A/F = \frac{\dot{m}_{air}}{\dot{m}_{fuel}}$$

5.7 Excess Air Coefficient

Excess air coefficient is calculated by the following way.

$$\lambda = \frac{(A/F)}{(A/F)_{stc}}$$

$(A/F)_{stc}$ is stoichiometric air-fuel ratio and accepted as 14,389 (kg-a/kg-fuel) for diesel fuel. Equivalence ratio related to this coefficient is calculated as follow.

$$\Phi = 1/\lambda$$

5.8 Volumetric Efficiency (%)

The volumetric efficiency of an engine is defined as the ratio of the mass charge induced at the atmospheric conditions to the total charge that would have been induced under standard atmospheric conditions. The volumetric efficiency is calculated by the following formulas.

$$\eta_v = \frac{\dot{m}_{air}}{\dot{m}_{ath}}$$

Theoretical air-mass flow rate:

$$\dot{m}_{ath} = \frac{\rho_{std}\ x\ V_s\ x\ N_{speed}\ x\ i\ x\ 2}{jx60}$$

$$\mathrm{V_s} = \frac{\pi\ x\ D^2\ x\ S}{4}$$

$$\rho_{std} = \frac{P_{std}}{R_{std}\ x\ T_{std}}$$

5.9 Thermal Efficiency (%)

Thermal efficiency of an engine is calculated as following way.

$$\eta_{th} = \frac{BPx1000}{Q_c\ x\ \dot{m}_{fuel}\ x\ 1.36}$$

Where Q_c (kj/kg) is fuel thermal coefficient (or heat of combustion) which is 42000 kj/kg for fuel which is used for experiments.

5.10 Dilution Ratio

Dilution ratio is the ratio of the exhaust gas drawn into the tunnel to total gas flow through the tunnel.

$$DR = (Q_{se} / Q_{dt}) x 100$$

Where Q_{se} is flow rate of sampled exhaust and Q_{dt} is dilution tunnel flow rate.

$$Q_{se} = Q_{exh} \left(\frac{D_{se}}{D_{exh}} \right)^2$$

$$Q_{dt} = 639,784 + 84,8454 P_{dt} - 0,802568 P_{dt}{}^2$$

Where D_{exh} is diameter of exhaust pipe, D_{se} is diameter of sampled exhaust transfer tube, P_{dt} (inW) is reading of manometer on dilution tunnel. Q_{dt} is calculated in lt/min with this equation.

$$Q_{exh} = Q_{air} + 770 Q_{fuel}$$

$$Q_{exd} = Q_{air} - 750 Q_{fuel}$$

Where Q_{exh} (m^3/h) is exhaust flow rate, Q_{exd} (m^3/h) exhaust flow rate on dry basis, Q_{air} (m^3/h) is air flow rate and Q_{fuel} (kg/s) fuel flow rate.

5.11 Particulate Emissions (g/HPh)

Particulate emissions amount evaluated as follows.

$$M_p = \frac{m_p \text{ x } \mathrm{Q_{exh}} \text{ x } \mathrm{DR}}{Q_{vp} \text{ x } \mathrm{t_s} \text{ x } \mathrm{BP}}$$

Where m_p (g) is mass of particulate collected on the filter, Q_{vp} (m^3/h) is vacuum pump flow rate, t_s (h) is particulate sampling time.

5.12 Gas Emissions (g/HPh)

Total hydrocarbon emissions are evaluated as follows.

$$M_{THC} = \frac{Q_{exd} \text{ x } \rho_{\mathrm{HC}} \text{ x } \mathrm{C_{HC}} \text{ x } 10^{-3}}{BP}$$

Where ρ_{HC} is density of hydrocarbons (0,619 kg/m^3), C_{HC} (ppm) is concentration of T-HC's.

All these calculated amounts are averaged by using the weight factors defined in the ESC test procedure.

CHAPTER 6

EXPERIMENTAL RESULTS

Experimental data and results have been presented in this chapter. With the help of figures results of experiments and analyses have been explained in detail. The measured and calculated data have been written in Appendix A.

Particulate emissions, fuel consumption, brake specific fuel consumption, brake power and torque, volumetric and thermal efficiencies, gaseous emissions, temperature in the filter, and backpressure on the engine are discussed in following sections.

6.1 Particulate Emissions

Particulate emission rates are listed in Table 6.1. As seen in the table, emission rates decrease with metal chip addition. For the empty filter, particulate emission rate was 5.49 g/HPh. With the metal chip addition, emission rates decreased to 1.32, 1.07 and 0.98 g/HPh for the filters with aluminum, iron and copper metal chip

Table 6.1: Results of experiments.

		Empty	Al	Fe	Cu	Cu 2	Cu 3
Particulate	g/HPh	5,49	1,32	1,07	0,98	0,46	1,36
Particulate-2	g/h	25,27	22,79	17,65	7,46	4,79	10,33
Brake Sp. Fuel Consumption	kg/HPh	0,497	0,558	0,571	0,581	0,603	0,498
Fuel Cons.	kg/h	7,04	7,55	7,94	7,77	7,96	7,05
Opacity	%/HP	0,489	0,505	1,043	0,802	1,047	0,639
HC	g/h	11,39	9,64	7,81	7,63	6,97	9,08
CO2	%	6,78	7,57	7,47	7,80	7,61	7,00
CO	%	0,083	0,141	0,145	0,197	0,195	0,12
O2	%	11,08	9,93	10,08	9,79	10,06	10,54
Volumetric Eff.	%	63,50	64,72	63,75	64,28	64,10	63,24
Thermal Eff.	%	21,48	19,99	19,00	19,19	18,64	21,28
Backpressure	mmHg	17,94	18,37	19,05	18,69	20,11	18,00
Brake Power	HP	28,40	28,40	28,10	28,00	27,80	28,00
Engine Torque	Nm	96,00	97,80	95,60	95,40	94,20	94,4

Table 6.2: Comparison of experimental results with empty filter.

		Al	Fe	Cu	Cu 2	Cu 3
Particulate	%	-75,96	-80,51	-82,15	-91,62	-75,23
Particulate-2	%	-9,81	-30,15	-70,48	-81,04	-59,12
Brake Sp. Fuel Cons.	%	12,27	14,89	16,90	21,33	0,20
Fuel Cons.	%	7,24	12,78	10,37	13,07	0,14
Opacity	%	3,27	113,29	64,01	114,11	30,67
HC	%	-15,36	-31,43	-33,01	-38,81	-20,28
CO2	%	11,65	10,18	15,04	12,24	3,24
CO	%	69,88	74,70	137,35	134,94	44,58
O2	%	-10,38	-9,03	-11,64	-9,21	-4,87
Volumetric Eff.	%	1,92	0,39	1,23	0,94	-0,41
Thermal Eff.	%	-6,94	-11,55	-10,66	-13,22	-0,93
Backpressure	%	2,40	6,19	4,18	12,10	0,33
Brake Power	%	0,00	-1,06	-1,41	-2,11	-1,41
Engine Torque	%	1,88	-0,42	-0,62	-1,88	-1,67

respectively. Emission rates were 0.46 and 1.36 g/HPh for the filters with 7 kg, and 2.7 copper chips. Particulate-2 amounts in Table 6.1, list the particulate emission rates in g/h, these were 25.27, 22.79, 17.65, 7.46, 4.79, 10.33 g/h for aluminum, iron, and three copper filters respectively.

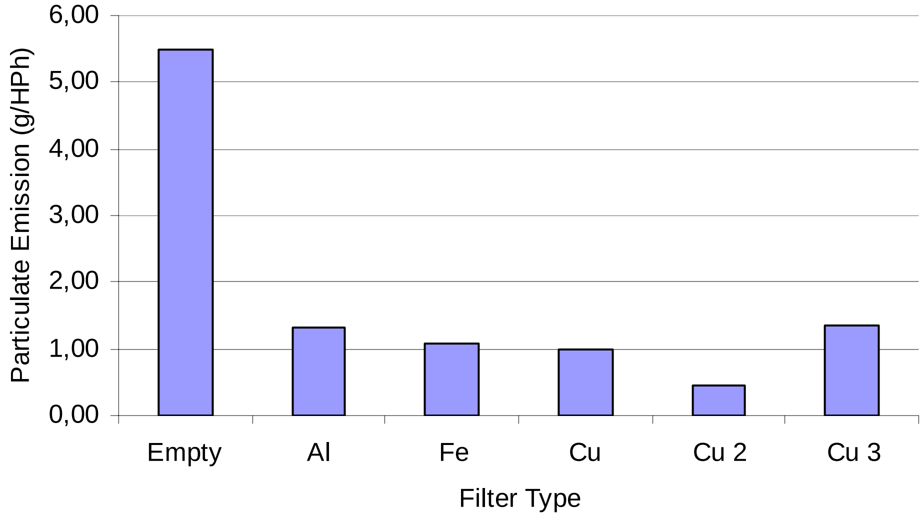

Figure 6.1: Average specific particulate emission for filters (g/HPh).

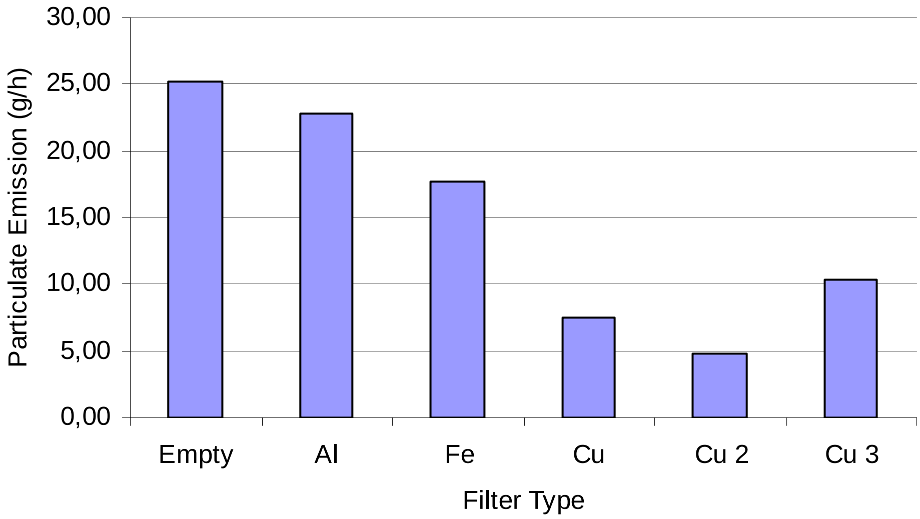

Figure 6.2: Average particulate emission for filters (g/h).

Particulate emission rates of test modes are presented in three graphs. Figure 6.1 shows emission rate with respect to brake power for each filter type. As seen in the figure, for the filter type Cu-2, which has 7 kg copper in it, emission rate decreased to minimum level. Figure 6.2 shows emission rate in gram per hour for each filter type. In Figure 6.3, particulate emission rates at each test mode are plotted. Although, at the high loads and speeds particulate emission rates are higher than 30 g/h, emission rates are below the 10 g/s generally. At the modes of 8 and 10, two results are higher than the expected amounts. These results may related with particles, which adhered on filter surfaces previously, being carried away by flow.

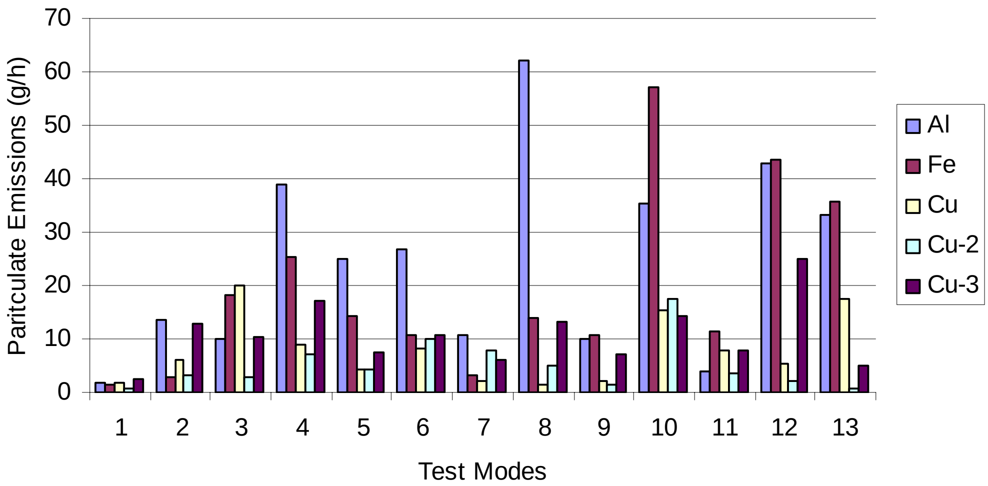

Figure 6.3: Particulate emission rates for filters at 13 modes.

6.2 Brake Power and Torque

Brake power and torque are the most important parameters shows engine performance. These parameters calculated approximately same for all filters as shown in Table 6.1. Also in Figures 6.4 and 6.5 these calculated engine parameters are plotted. As seen in these figures, brake powers for all filter types are approximately 28 HP, and torques are around 95 Nm.

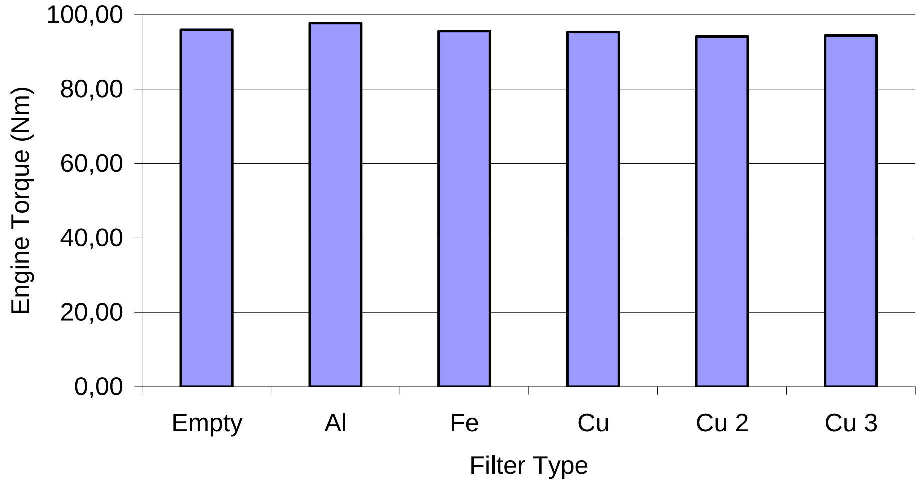

Figure 6.4: Average engine torque for filters.

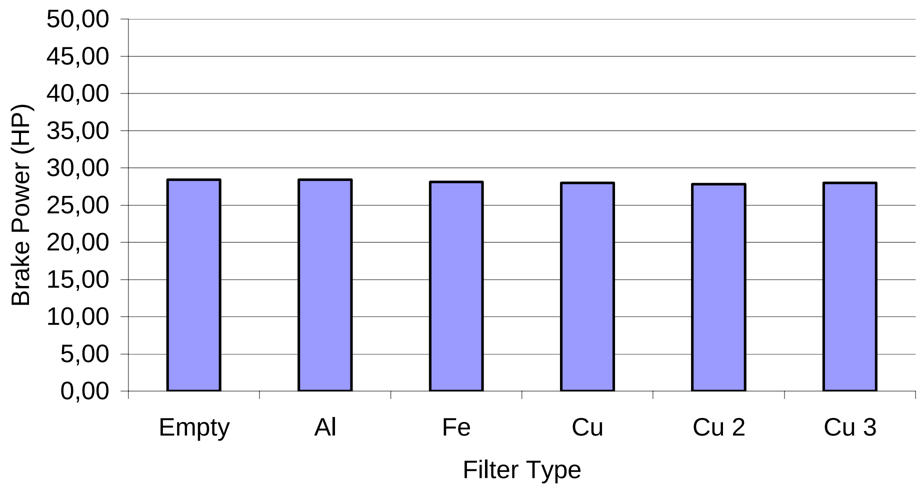

Figure 6.5: Average brake power for filters.

Figure 6.6 shows the brake power at different test modes of filters. Brake power is related to engine speed and load basically. Therefore, low amounts are at test modes of 1, 7, 9 and 11, where engine loads were 0 % and 25 % respectively. Highest brake power occurs at 10. test mode, where engine speed is 2600 rpm, and load is 100 %.

Engine Torque is related to brake power and engine speed. Highest torque occurs at test modes of 2, where load is 100 %, and speed is 1600 rpm, as seen in Figure 6.7. Also lowest levels occur at test modes of 7, 9 and 11, where load is 25 %.

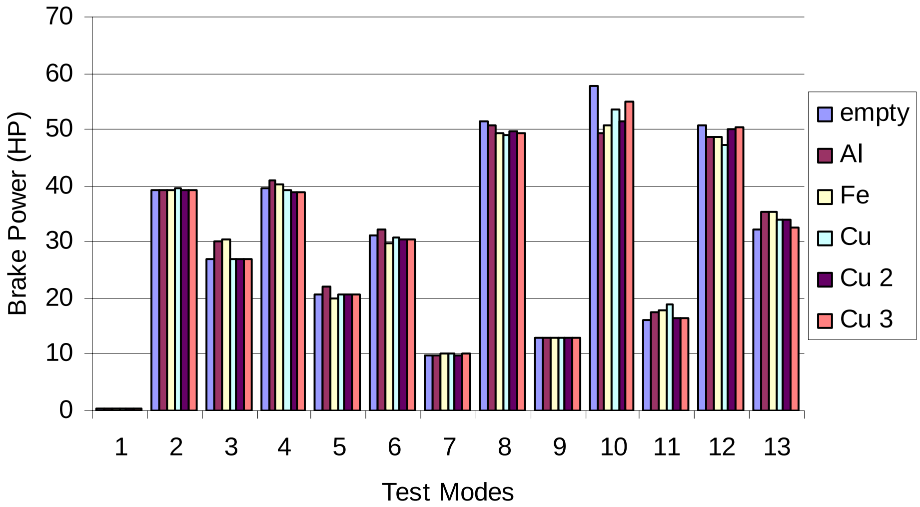

Figure 6.6: Brake powers for filters at 13 modes.

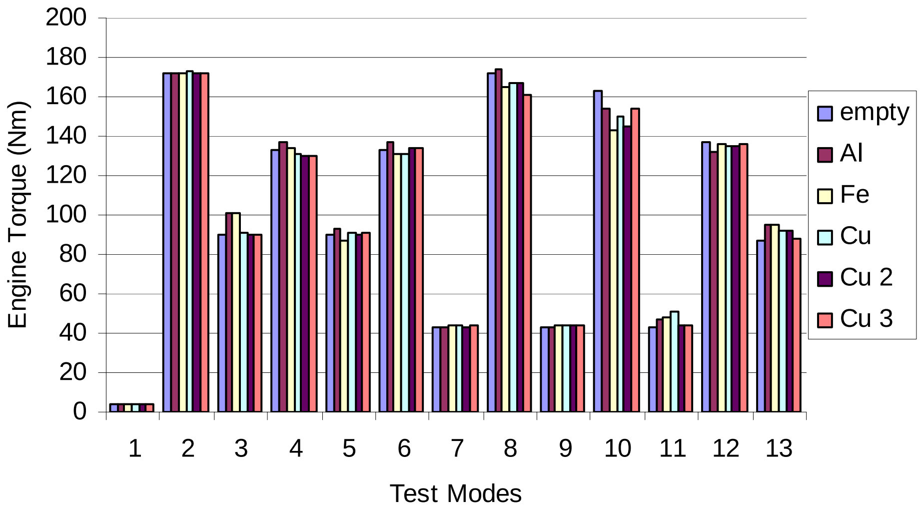

Figure 6.7: Engine torques for filters at 13 modes.

6.3 Brake Specific Fuel Consumption

Brake specific fuel consumption (BSFC) gives the rate of fuel consumed by the test engine to produce unit power per unit time. Results of test modes with different filters are supplied in following figures. As seen in Table 6.1, BSFC has increased related to the amount of metal chip in the filter. For the filter, which had 7 kg copper chip in it (Cu-2), BSFC rate increased up to 20 %. Last filter's copper chip amount was adjusted as to fuel consumption rate, so average BSFC of last filter approximately same to empty filter, as seen in Figure 6.8.

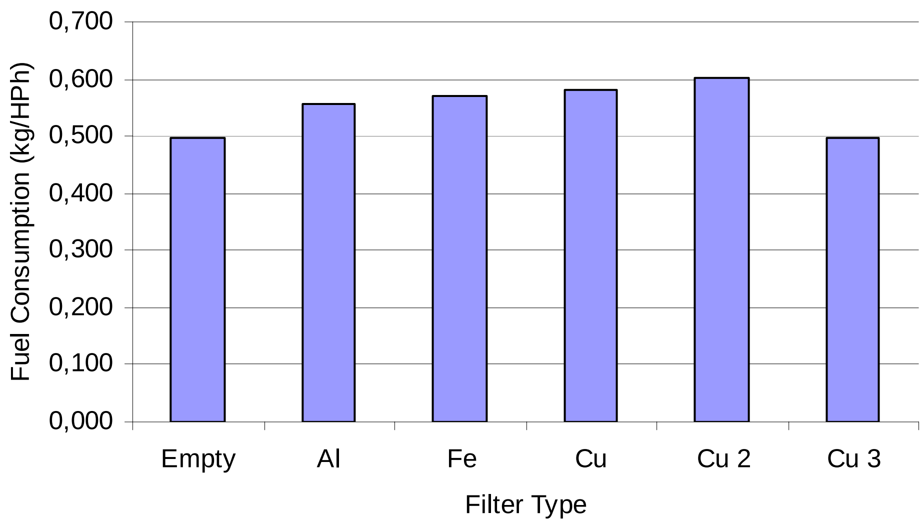

Figure 6.8: Average fuel consumption for filters at 13 modes.

Because of the low brake power, results at first mode, at low idle, and zero load, are higher than other results (Figure 6.9). Also BSFC's at the test modes of 7, 9 and 11, where engine load are 25 %, are higher than others.

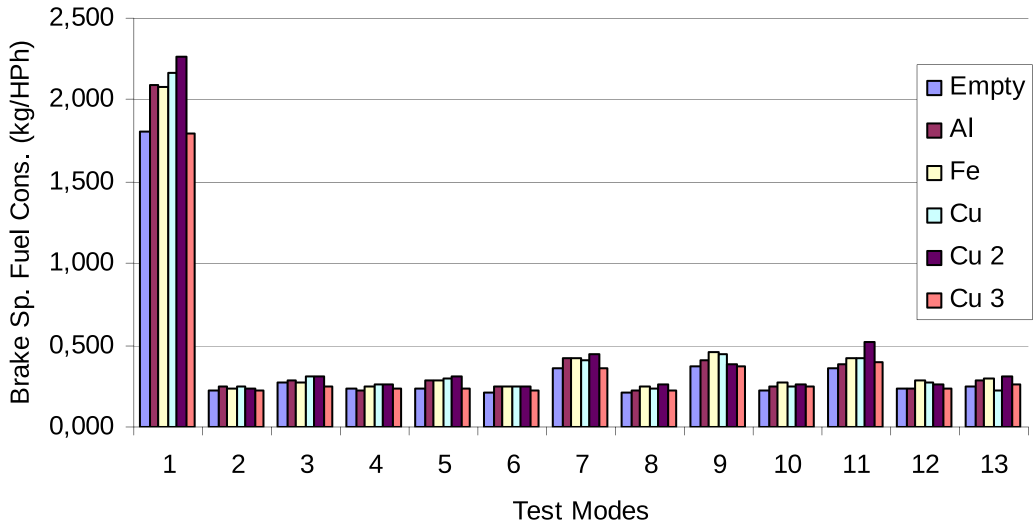

Figure 6.9: Brake specific fuel consumption rates for filters at 13 modes.

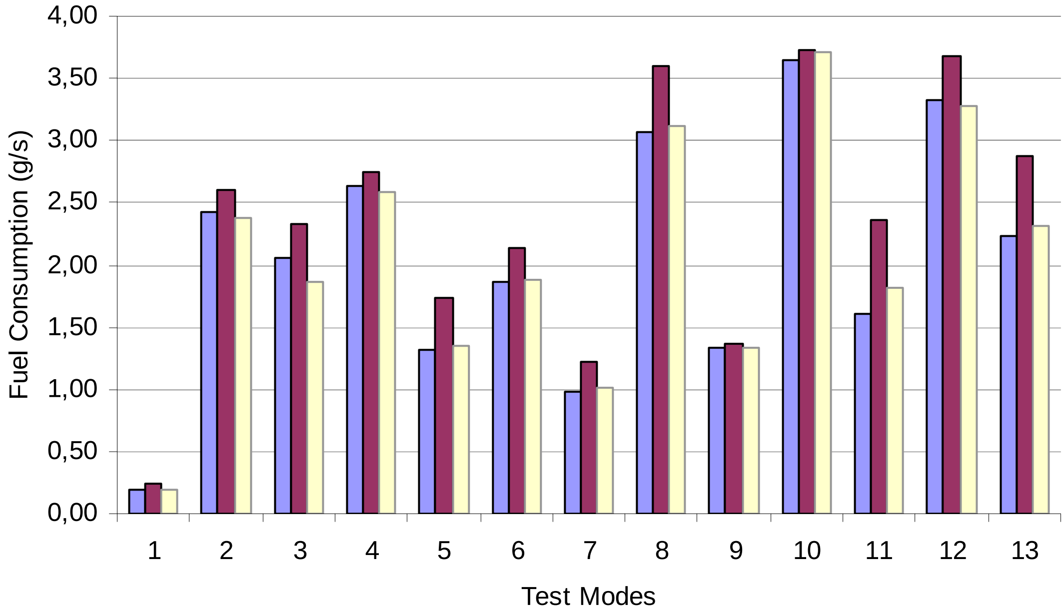

Figure 6.10: Fuel consumption rates for the empty filter, the filters with 7 kg and 2.7 kg copper metal chip at 13 modes.

Fuel consumption rates for the empty filter and the filter with 7 kg and 2.7 kg copper metal chip are plotted in Figure 6.10. Because fuel consumption rate is related with speed and engine load, as seen in the figure, the highest rates are at the modes of 10, 12 and 8 respectively. These test modes are 100 and 75 % loads at 2600 rpm, and 100 % load at 2100 rpm respectively.

6.4 Gaseous Emissions

HC emissions of filters in g/HPh and ppm at 13 test modes are plotted in following figures. As seen in Table 6.1, HC emissions decreased with increased metal chip. For the last filter with copper chip, reduction rate is 20 %. In Figure 6.11, emission rates for each filter type are plotted. As seen in the figure, HC emission rate for the last filter is approximately 9 g/h.

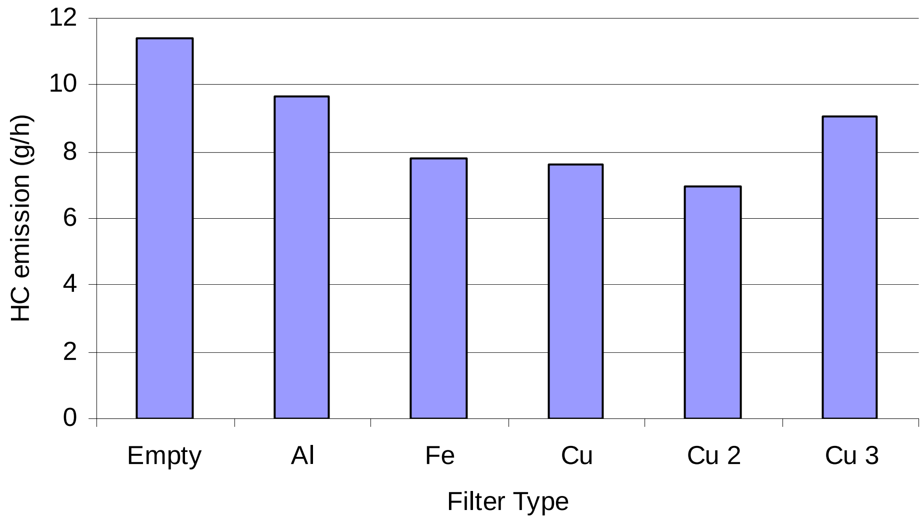

Figure 6.11: Average HC emissions for filters.

Amount of HC emissions decreases with increased engine speed and load (Karel, 1996), as seen in Figure 6.12, highest amounts occur at lowest load and speed levels, test modes of 6, 8 and 10 in graph. HC emissions for different filter types at 13 test modes are between 5-15 ppm as seen in Figure 6.13.

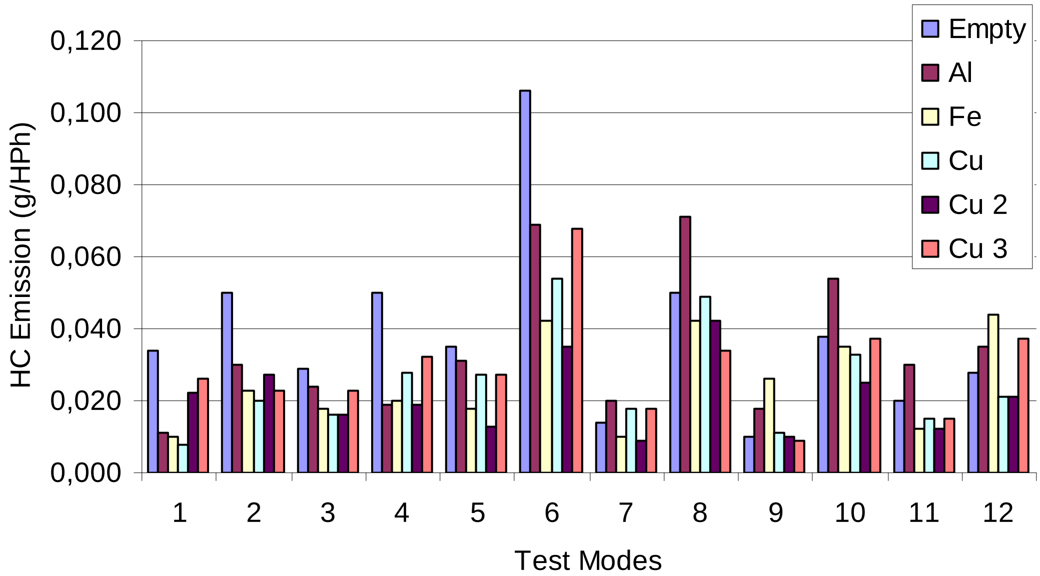

Figure 6.12: HC emissions for filters at 12 modes (g/HPh).

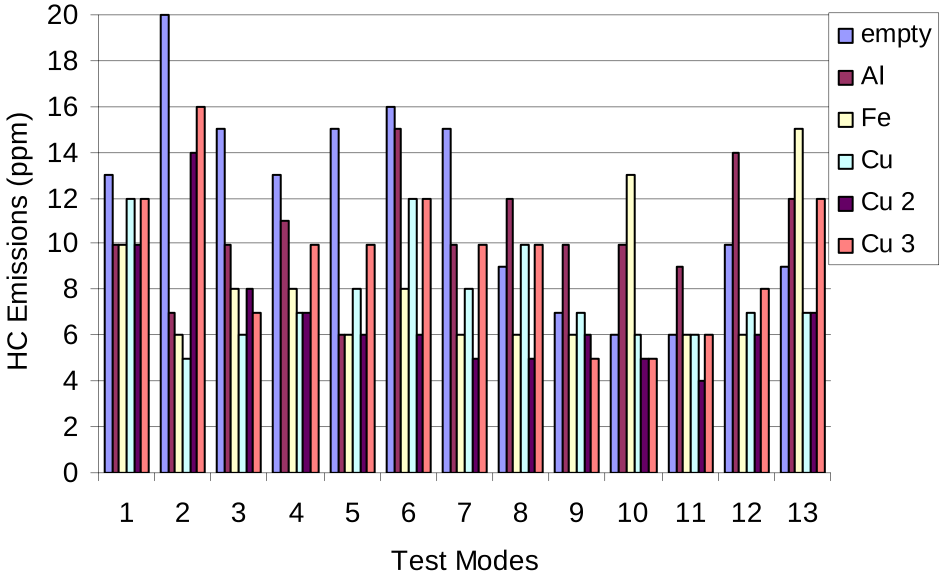

Figure 6.13: HC emissions for filters at 13 modes (ppm).

Average opacity rates for different filters are listed in Table 6.1. For the filters except the filter with aluminum chip opacity rates increased. For the filters with 3,9 kg iron, 4,5 kg copper and 7 kg copper, rates are 113, 64 and 114 %. For the last filter, opacity increase rate is 30 %. Figure 6.14 shows opacity rates per HP for each filter type.

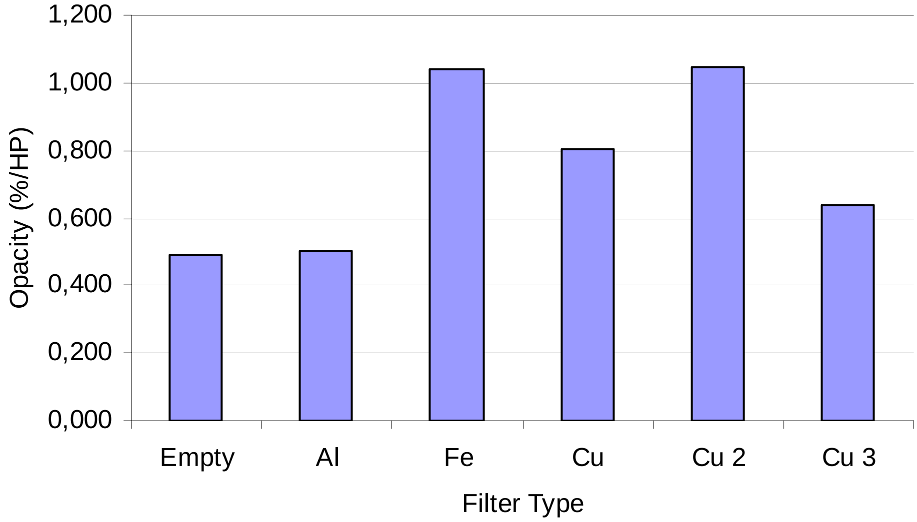

Figure 6.14: Average opacity rates for filters.

Opacity rates per test modes are plotted in the following figures. At the high engine speed and loads opacity level increased, as seen in Figure 6.16. Maximum opacity rates occur at 2. test mode, where maximum engine torques are obtained. For the high speed and load, opacity levels pass 50 %. If opacity per brake power is checked in Figure 6.17, except the modes at high load and speed, first mode amounts are high; because brake power at this mode is very low (around 0.5 HP).

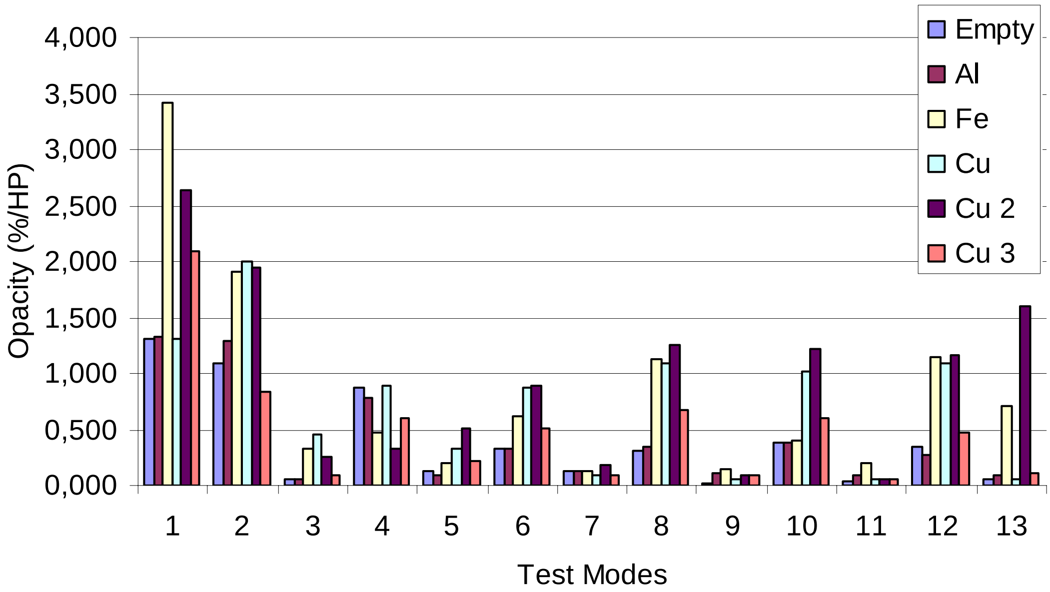

Figure 6.15: Opacity rates for filters at 13 modes.

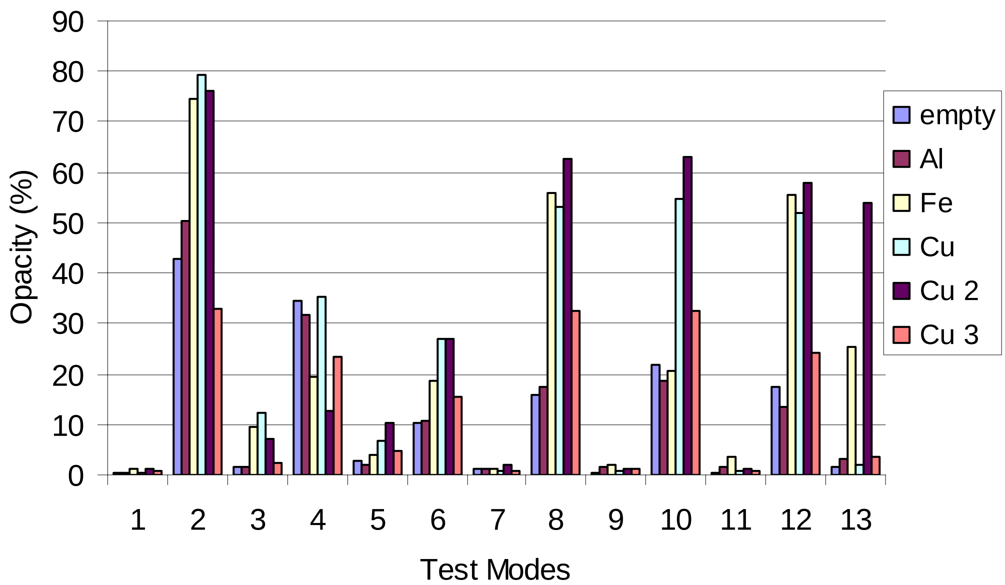

Figure 6.16: Opacity amounts for filters at 13 modes.

CO_2 emissions for each filter type are shown in Figure 6.17. This emission gas increased with metal chip addition in filters approximately 10 %. For the last filter, CO_2 emission increased 3 % (Table 6.2). Figure 6.18 shows emission rates per brake power. These rates are higher at lower loads. Maximum emission rate occurs at the 6. test mode in the figure, where engine speed is 1600 rpm, and load is 25 %. Figure 6.19 gives emission rates in percentage, as seen in the figure at the high engine speed and load rates are higher, passes 10 %. For the low engine loads emission rates are around 4 %.

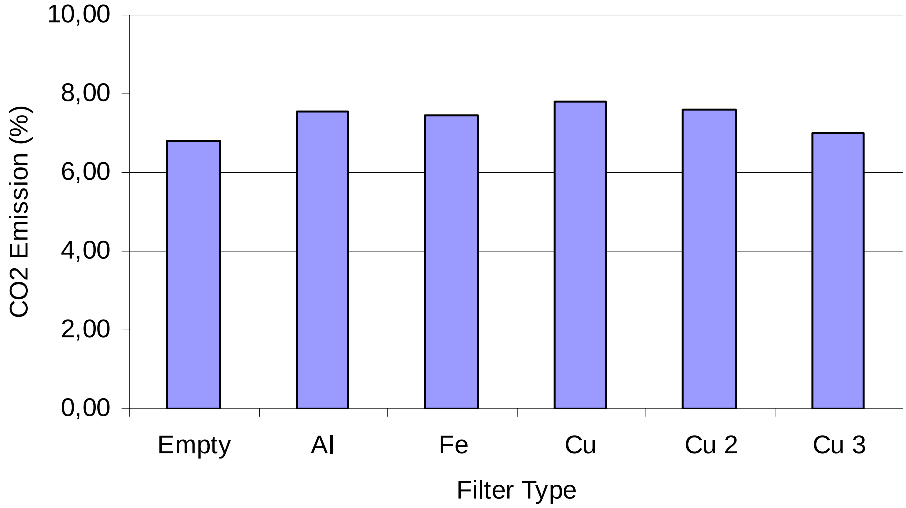

Figure 6.17: Average CO_2 emission rates for filters.

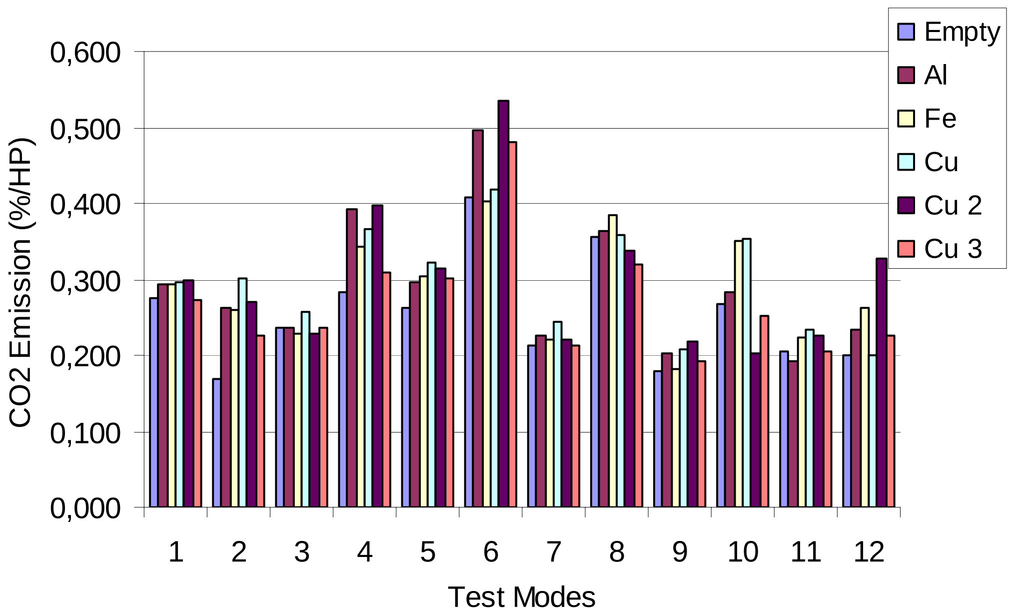

Figure 6.18: CO_2 emission rates for filters at 12 modes.

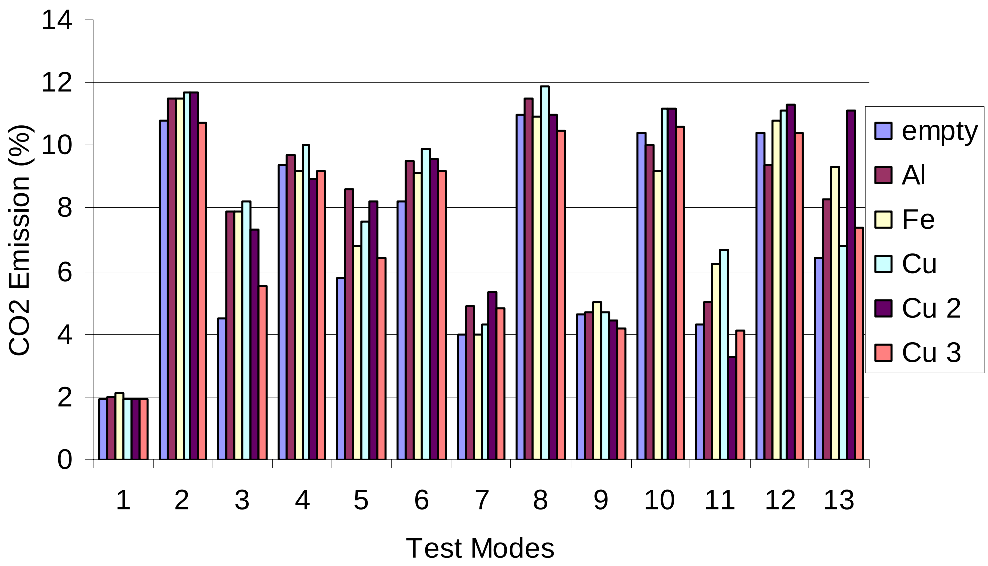

Figure 6.19: CO_2 emissions for filters at 13 modes.

CO emission rates for each filter type are plotted in Figure 6.20. As seen in the figure, emission rates increased with metal chip addition. For the third and fourth filters (Cu and Cu-2) emission rate increase more than 100%. For the last filter CO emission increased 45% (Table 6.2).

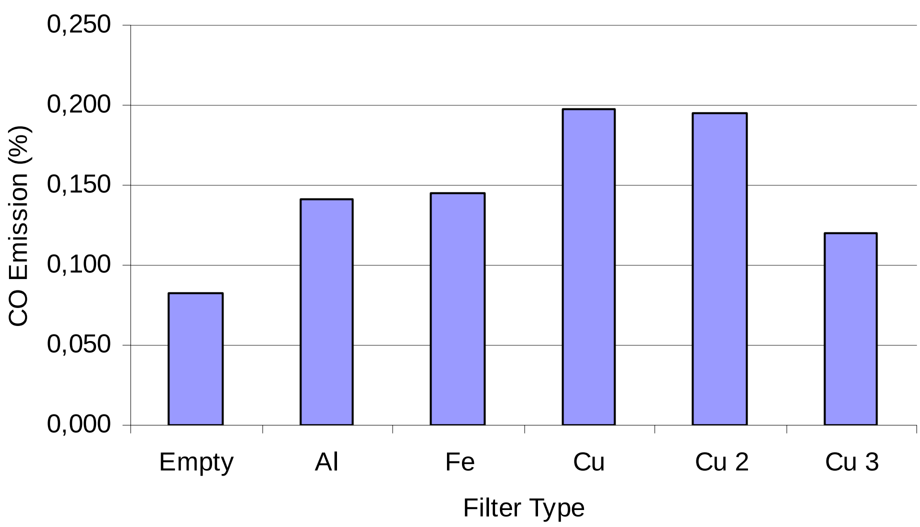

Figure 6.20: Average CO emissions for filters.

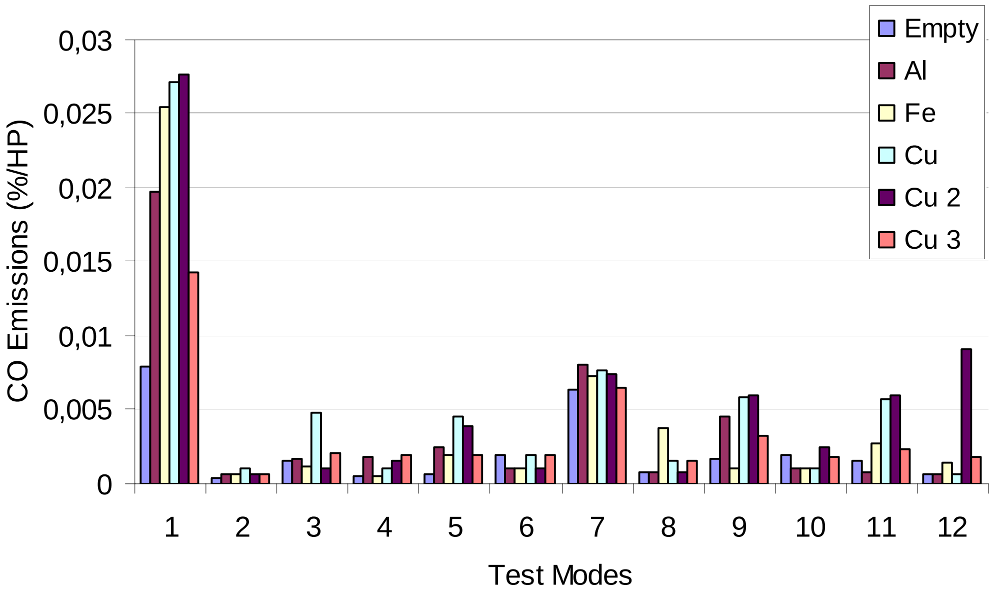

Figure 6.21: CO emission rates for filters at 13 modes.

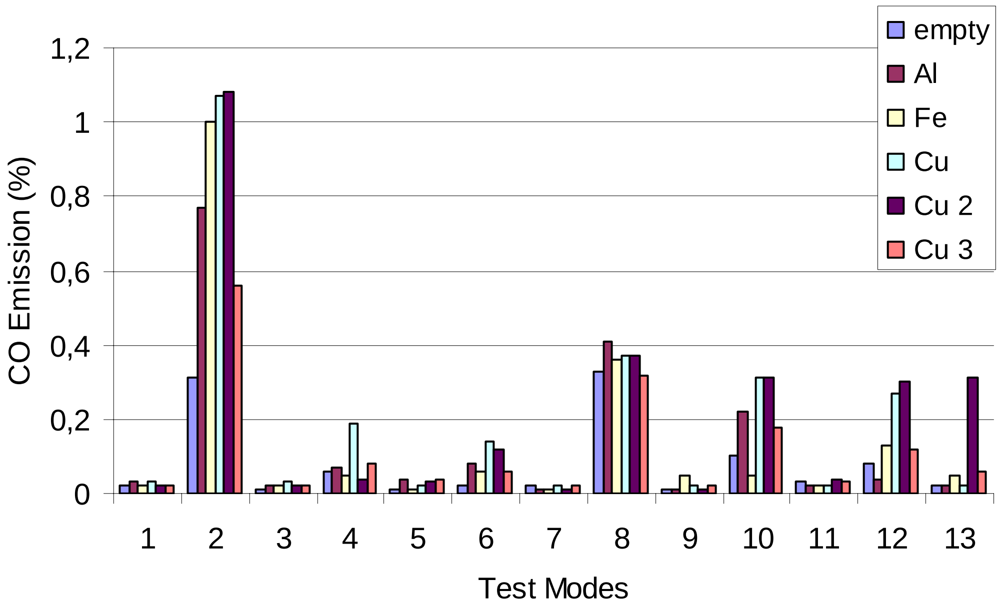

Figure 6.22: CO emissions for filters at 13 modes.

CO emission rates are higher at the test modes of high engine speed and load, and highest amounts occur at 2. mode, where speed is 1600 rpm and load is 100 %

(Figure 6.22). Figure 6.21 shows emission rates per brake power except low idle mode, where rates are high; because brake power is very low. First mode in the graph is 2. mode of experiments, 1600 rpm speed, 100 % load. Emission rates are highest at this mode for each filter type. Also CO emission rates per brake power are high at high engine speed and load.

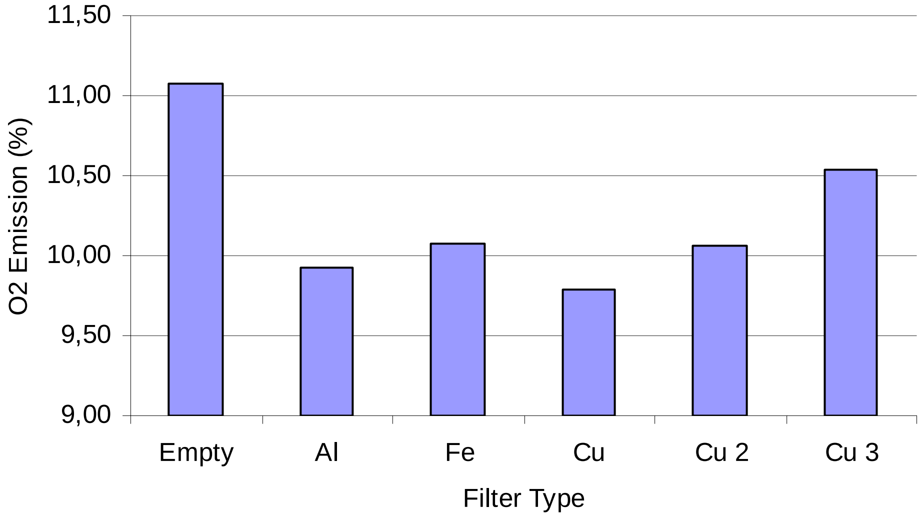

Figure 6.23: Average O_2 emission for filters.

Oxygen concentration in the exhaust gas is important about the regeneration of soot in the filter. If this concentration decreases during experiments, this means oxygen is used in the filter. O_2 emission rates are plotted in Figure 6.23. As seen in the figure, O_2 emission decreased with the metal chip addition to filters. For the last filter, and the other filters, O_2 amount decreased approximately 5 % and 10 % respectively.

Oxygen rates are high for the test modes at low engine load (Figure 6.25). For the high engine loads, oxygen rate decrease. Figure 6.24 shows the O_2 rate per brake power, as seen in the figure concentration is high at low engine loads, and it reaches to maximum at 6. mode, where engine speed is 1600 rpm and load is 25 %.

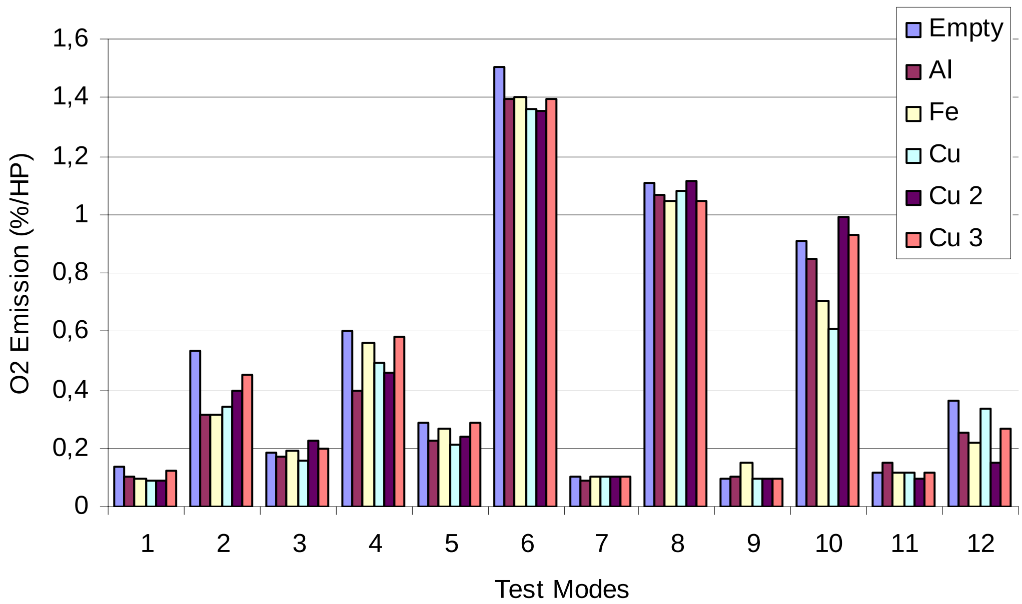

Figure 6.24: O_2 emission rates for filters at 12 modes.

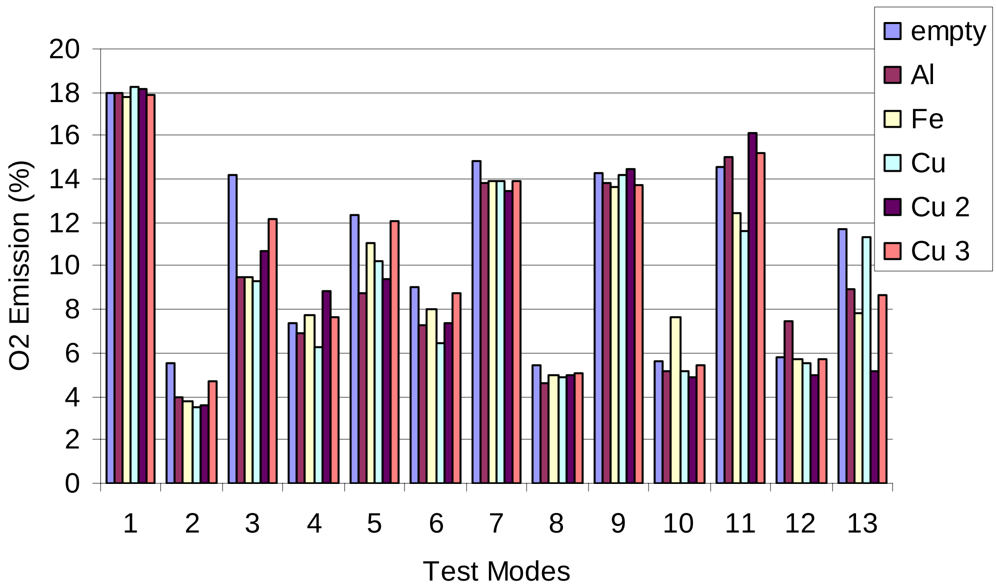

Figure 6.25: O_2 emissions for filters at 13 modes.

6.5 Volumetric and Thermal Efficiencies

Volumetric and thermal efficiencies for different filters are listed in Table 6.1. As seen in the table, volumetric efficiencies didn't changed significantly with filter type. In Figure 6.26, volumetric efficiencies for test modes are plotted, they are approximately 64 %.

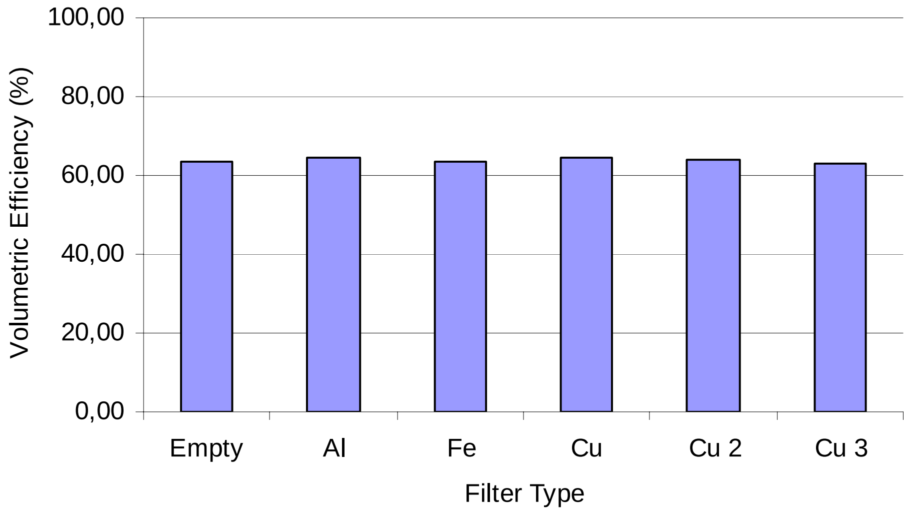

Figure 6.26: Average volumetric efficiency for filters.

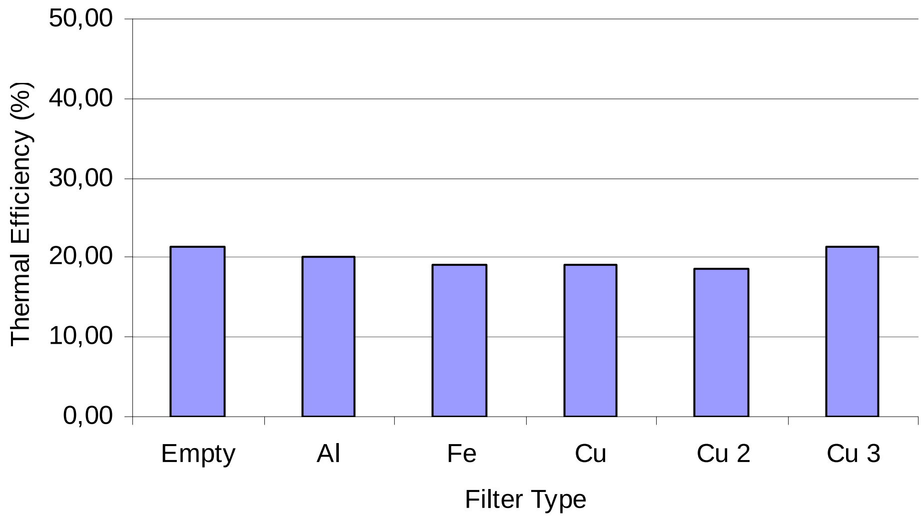

Figure 6.27: Average thermal efficiency for filters.

In the Figure 6.28, volumetric efficiencies for 13 test modes are plotted. As seen in the figure, for the test mode, where engine works at low idle, efficiencies are approximately 100 %. However for other modes, efficiencies are calculated between 55-60 %.

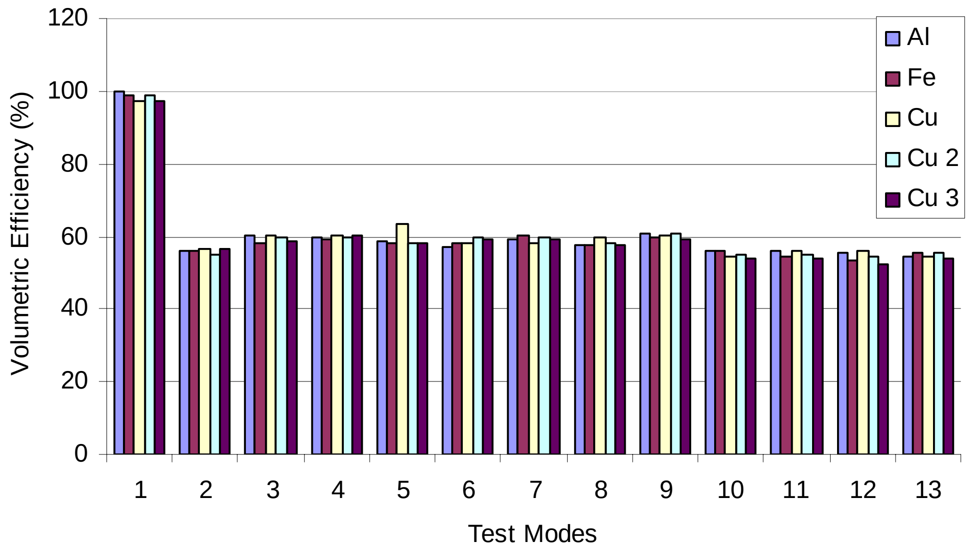

Figure 6.28: Volumetric efficiency for filters at 13 modes.

Thermal efficiency is related to fuel consumption rate. Therefore thermal efficiencies for different filters vary with the metal chip amount used in the filter. For the last filter, calculated thermal eff. is similar to empty filter's eff. as seen in Figure 6.27, because fuel consumption rates are similar for these filter types. Thermal efficiencies for 13 test modes are plotted in Figure 6.29. As seen in the figure, efficiencies for the modes of 1, 7, 9 and 11 are lower, these are low idle and

25 % load modes. Maximum eff.'s were obtained at the 2. test mode, where engine speed is1600 rpm, and load is 100 %.

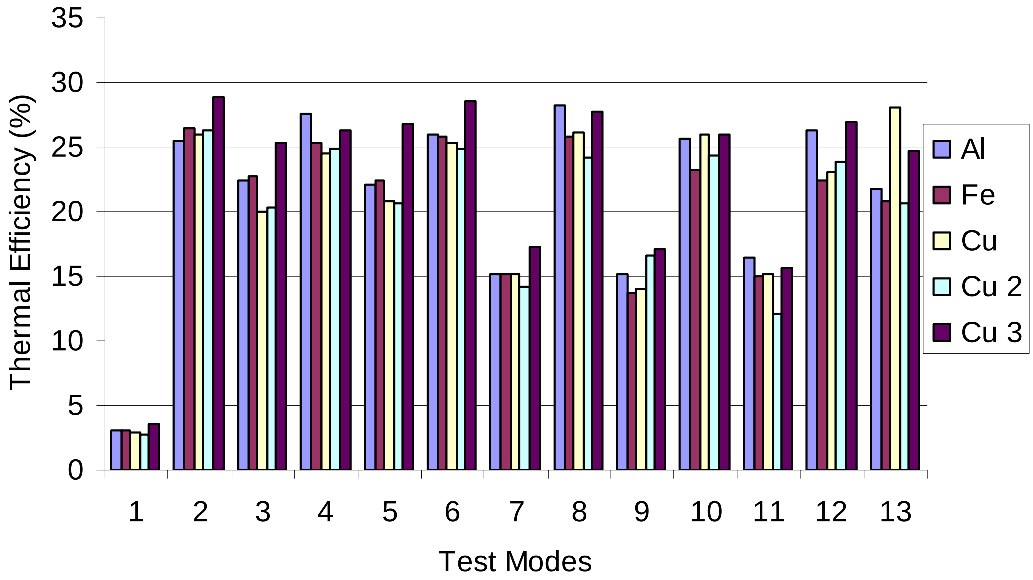

Figure 6.29: Thermal efficiency for filters at 13 modes.

6.6 Backpressure

Backpressure is most important parameter affects the fuel consumption. As seen in Figure 6.30, pressure increased related to amount of metal chip in the filters. For the filter with 7 kg copper chip it reached the highest level. With the last tested filter, pressure occurs similar to empty filter.

Backpressure increases with engine speed proportionally. Pressure levels at the speeds of 1600 (modes 2, 5, 6, 7), 2100 (modes 3, 4, 8, 9) and 2600 (modes 10, 11, 12, 13) can be seen in Figure 6.31. Pressures at an engine speed occur similar for different test modes, therefore it means; dynamometer load do not affect the pressure significantly.

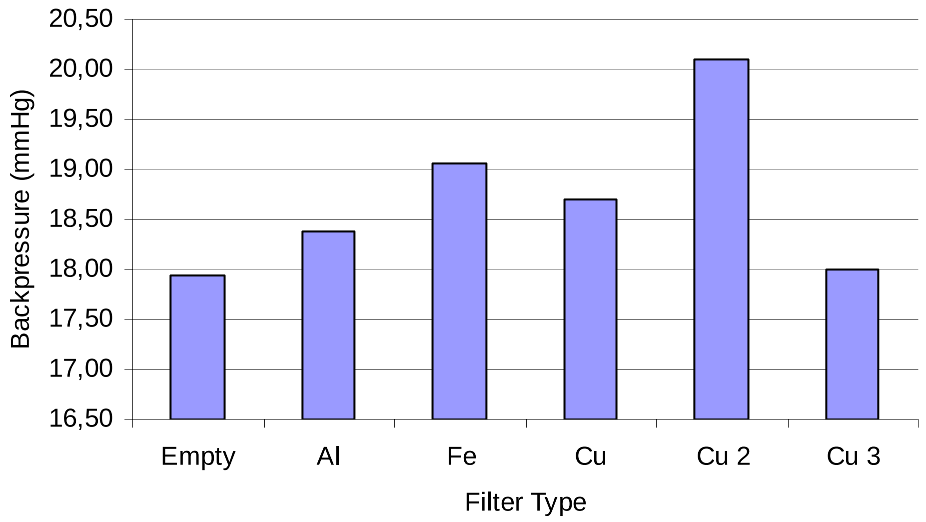

Figure 6.30: Average backpressure for filters.

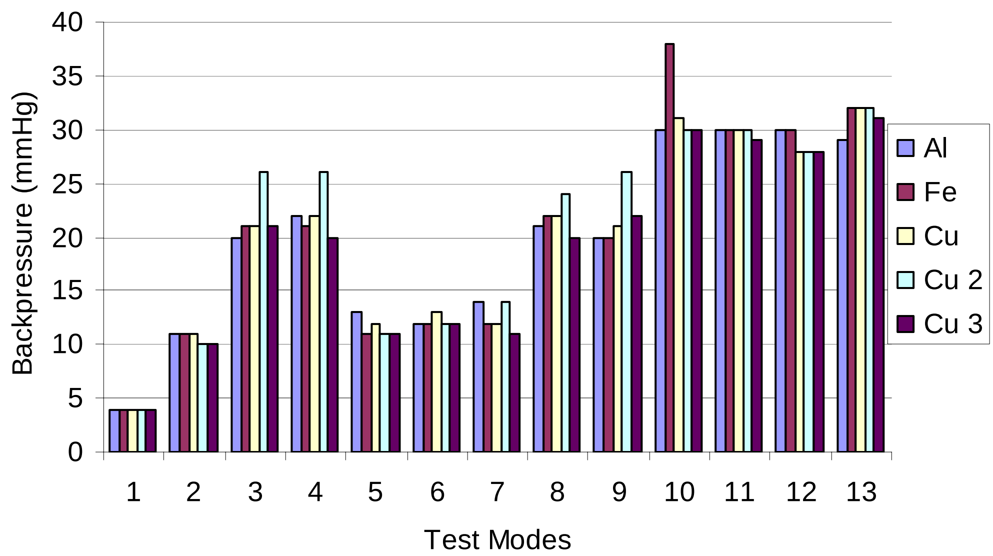

Figure 6.31: Backpressure for filters at 13 modes.

6.7 Temperature in Filters

Filter temperature is important parameter for particulate emission rate. Temperatures at different test modes are plotted in following Figure. At the modes of 8, 10 and 12 temperature increased to highest levels, 350-450 ^{o}C. These test modes are high load and speed modes for engine. Therefore, filter temperature increases with engine speed and load proportionally, as expected.

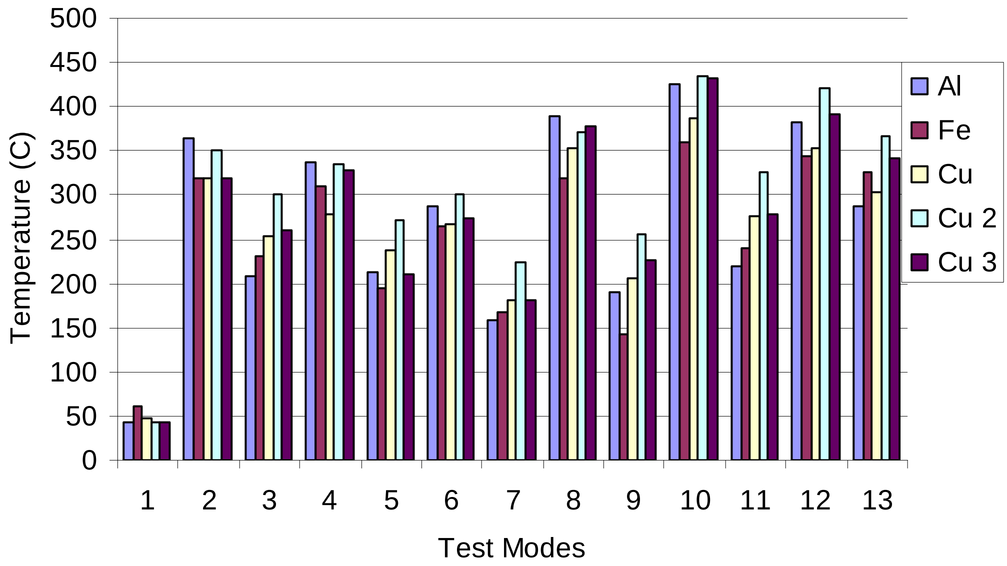

Figure 6.32: Temperature for filters at 13 modes.

CHAPTER 7

DISCUSSION and CONCLUSIONS

In this chapter, filters designed and tested, and parts of the experimental setup installed will be discussed about their problems at the usage, main advantages and disadvantages.

Particulate emission rate decreases with metal chip addition. For the last filter (Cu-3), reduction is approximately 75 % in g/HPh, and 60 % in g/h. Copper chip results are better than aluminum and iron chip. Filter performance is related with two parameters, particulate holding and burning performances. Consequently, we can say that copper chip particulate holding performance is better at least. With the simple metal chip and without using any costly system this performance can be accepted successfully.

Brake specific fuel consumption is important parameter to consider on filter design. For the last filter it is measured similar to BSFC for empty filter. Also, thermal efficiencies are similar for these two conditions; because thermal efficiency of an engine depends on fuel consumption rate. Moreover, backpressure is important factor, which effects the fuel consumption. Backpressure on the engine increases with metal chip addition in the filter. However, backpressure does not increase significantly for the last filter.

Brake power and torque are important parameters, which show engine performance. These parameters are calculated approximately same for all filter types. Also volumetric efficiency does not change for different filter types. Therefore comparison of experimental results between filters can be discussed properly.

Beside particulate emissions, gaseous emissions are important for filter design. Hydrocarbon emissions are reduced with metal chip addition. For the last filter with copper chip, reduction rate is 20 %. For the filters except the filter with aluminum chip opacity rates were increased. Cooling water, and oil used during machining operation on metal chip cause these smoke probably. Although metal chip was washed with hot water prior to experiments, some of the residue on the metal chip may still exist. For the last filter, carbon dioxide emission increased 3 %, and carbon monoxide emission increased 45 %.

Oxygen concentration decreases with the metal chip addition to filters. For the last filter, O_2 amount decrease approximately 5 %. Oxygen concentration in the exhaust gas is important about the regeneration of soot in the filter. If this concentration decreases during experiments, this means oxygen is used in the filter, for the soot regeneration probably.

Fuel measurement system; one of the most important parts of experimental setup is fuel measurement system because; filters are evaluated for their effect on fuel consumption rate of an engine generally. One problem of the system was unexpected signals comes from optic sensors. Optic sensor light passes flag on the glass buoy. Black plastic material, which can obstruct the sensor light, was used to solve this problem. Other problem related with this system is computer program input checking time. If it is adjusted to very small interval, computer can't do calculations with high speed. But if it is adjusted to high interval, optic sensor signals may missed. Therefore program timer interval is adjusted to 50 ms to solve this problem.

Amplifiers of the temperature measurement system may send high voltages when the device is warmed. Therefore amplifiers should be closed when experiments are finished. Also, cables connected to thermocouples should not be touched other cables have high voltages.

At the start of computer program, data acquisition card selection is necessary. Afterward the card is selected; voltage ranges for analog signals should be selected. These ranges selected should include negative voltages also; because amplifiers send negative signals at low temperatures (< 100 ^oC).

Fiberglass filters are changed between each experiment. During this process, position of stopple and particulate sampling probe changes. After the filter is changed, position of probe is adjusted and stopple is fixed with tape. This process takes time at the start of each experiment. If filter holder design is improved, this may reduce the experiments time.

At the iso kinetic sampling point (ISP), a pressure transducer can be used to measure pressure difference between the two pipes, exhaust and transfer tube pipes. Also a step motor can be attached on the valve at the end of dilution tunnel. If these devices connected to computer, pressure difference at the ISP can be adjusted with the help of a computer program.

To improve experimental setup, a load cell, and a step motor can be attached to dynamometer. During experiments, load indicator on dynamometer oscillates, because of the high vibration. A step motor can be attached on the load adjustment handle of dynamometer, and it can be connected to computer. Thus, dynamometer load on engine can be adjusted with computer program properly. Load cell can be connected to computer also, therefore, this device is used to measure exact load on engine.

On the experimental setup, more nylon bags can be used to increase continuity of experiments. Also, nylon bag edges can be seamed to increase their reliability. Position of fiberglass filter in the filter holder is important. If filter can not be fixed at suitable position, some of the sampled gas may pass through outside of the filter.

In addition, NO_x emissions should be measured to see effect of filters on these emissions. High temperatures may increase the NO_x emissions.

Designed filter should be tested on a bus to see real performance. Working life of the filter should be measured.

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APPENDIX A

EXPERIMENTAL DATA

Table A.1: Measured Data for Empty Silencer (Mode 1- 6).

		1	2	3	4	5	6
Filter Material	-	-	-	-	-	-	-
Room Temperature	C	24	28	30	29	30	29
Relative Humidity	%	64	58	52	52	51	52
Room Pressure	mmHg	742	744	744	743	743	743
Engine Speed	rpm	750	1600	2100	2100	1600	1650
Dynamometer Reading	-	0,1	4,8	2,5	3,7	2,5	3,7
Load	%	0	100	50	75	50	75
Go Power Reading	in	0,58	0,92	1,62	1,62	0,96	0,94
Fuel Flow Rate	g/s	0,19	2,42	2,05	2,63	1,31	1,86
Filter Temperature	C	41,9	364	208	337	212	288
ISP Temperature	C	35,4	324	186	324	179	255
Sample Temperature	C	24	41	32	42	31	35
Backpressure	mmHg	4	10	20	21	12	11
Tunnel Pressure	in	0,176	0,384	0,548	0,636	0,64	0,648
Sampling Rate	scfm	1,3	1,1	1	0,8	0,8	0,8
AVL HC	ppm	13	20	15	13	15	16
AVL Opacity	%	0,5	42,7	1,7	34,5	2,7	10,4
CO2	%	1,9	10,8	4,5	9,4	5,8	8,2
CO	%	0,02	0,31	0,01	0,06	0,01	0,02
O2	%	17,96	5,49	14,21	7,39	12,32	9,01
Filter Weight #1	mg	205,920	204,850	206,270	206,990	206,120	204,930
Filter Weight #2	mg	208,055	205,620	207,875	208,420	207,755	206,235
Soot	mg	2,135	0,770	1,605	1,430	1,635	1,305
Weight factor	%	15	8	10	10	5	5
Duration	min	4	2	2	2	2	2
Water Vapor Pressure	mmHg	22,36	28,34	31,82	30,04	31,82	30,04

Table A.2: Measured Data for Empty Silencer (Mode 7- 13).

	7	8	9	10	11	12	13
Filter Material	-	-	-	-	-	-	-
Room Temperature	31	29	30	32	32	32	33
Relative Humidity	50	60	54	54	53	52	50
Room Pressure	743	743	743	743	743	742	742
Engine Speed	1600	2100	2100	2500	2600	2600	2600
Dynamometer Reading	1,2	4,8	1,2	4,5	1,2	3,8	2,4
Load	25	100	25	100	25	75	50
Go Power Reading	0,98	1,4	1,72	1,92	2,2	2,12	2,16
Fuel Flow Rate	0,98	3,07	1,33	3,64	1,6	3,32	2,23
Filter Temperature	159	390	189	426	220	382	287
ISP Temperature	137	381	153	418	175	375	275
Sample Temperature	28	43	30	51	30	46	37
Backpressure	12	21	20	30	26	31	31
Tunnel Pressure	0,632	0,756	0,724	0,784	0,712	0,636	0,644
Sampling Rate	0,75	0,7	0,7	0,65	0,65	0,65	0,65
AVL HC	15	9	7	6	6	10	9
AVL Opacity	1,2	15,7	0,3	21,8	0,5	17,4	1,6
CO2	4	11	4,6	10,4	4,3	10,4	6,4
CO	0,02	0,33	0,01	0,1	0,03	0,08	0,02
O2	14,81	5,43	14,32	5,66	14,58	5,84	11,67
Filter Weight #1	205,670	202,565	205,520	204,550	203,395	208,990	204,560
Filter Weight #2	206,155	205,565	205,820	206,420	203,715	210,240	205,865
Soot	0,485	3,000	0,300	1,870	0,320	1,250	1,305
Weight factor	5	9	10	8	5	5	5
Duration	2	2	2	2	2	2	2
Water Vapor Pressure	33,7	30,04	31,82	35,67	35,67	35,67	37,74

Table A.3: Calculated Parameters for Empty Silencer (Mode 1- 6).

		1	2	3	4	5	6
Dry Air Pressure	mmHg	727,7	727,6	727,5	727,4	726,8	727,4
Power Correction Factor	-	1,012	1,018	1,022	1,020	1,023	1,020
Brake Power	HP	0,4	39,1	26,8	39,6	20,5	31,1
Engine Torque	Nm	3,6	171,7	89,7	132,6	89,8	132,6
Brake Sp. Fuel Cons.	kg/HPh	1,803	0,223	0,275	0,239	0,231	0,215
Air Flow Rate	kg/h	105,0	131,8	174,2	174,2	134,6	133,2
Air / Fuel Ratio	-	153,47	15,13	23,61	18,40	28,53	19,89
Excess Air Coeff.	-	10,67	1,05	1,64	1,28	1,98	1,38
Equivalence Ratio	-	0,09	0,95	0,61	0,78	0,50	0,72
Theoretical Air Cons.	kg/h	105,9	225,9	296,5	296,5	225,9	233,0
Volumetric Eff.	%	99,1	58,3	58,8	58,8	59,6	57,2
Thermal Eff.	%	3,5	28,3	22,9	26,4	27,3	29,3
Exhaust Flow Rate	m3/h	87,3	111,2	146,2	146,6	112,7	112,0
Exh. Flow R.on Dry B.	m3/h	87,0	107,5	143,1	142,6	110,7	109,1
Dilution T. Flow Rate	m3/h	39,3	40,3	41,2	41,6	41,6	41,7
Dilution Ratio	%	10,4	12,9	16,7	16,5	12,7	12,6
Particulate Emissions	g/HPh	32,0	0,3	0,9	0,7	1,6	0,8
Particulate Emissions2	g/h	12,1	10,6	24,8	28,0	32,0	25,6
HC emissions	g/HPh	1,845	0,034	0,050	0,029	0,050	0,035
Opacity	%/HP	1,318	1,092	0,063	0,870	0,132	0,334
CO2	%/HP	5,009	0,276	0,168	0,237	0,284	0,263
CO	%/HP	0,0527	0,0079	0,0004	0,0015	0,0005	0,0006
O2	%/HP	47,347	0,140	0,530	0,186	0,602	0,289
Backpressure	mmHg/HP	10,545	0,256	0,746	0,530	0,587	0,353

Table A.4: Calculated Parameters for Empty Silencer (Mode 7- 13).

		7	8	9	10	11	12	13
Dry Air Pressure	mmHg	726,2	725,0	725,8	723,7	724,1	723,5	723,1
Power Correction Factor	-	1,025	1,022	1,023	1,029	1,028	1,029	1,031
Brake Power	HP	9,8	51,5	12,9	57,9	16,0	50,8	32,2
Engine Torque	Nm	43,2	172,4	43,1	162,6	43,3	137,3	86,9
Brake Sp. Fuel Cons.	kg/HPh	0,359	0,214	0,371	0,226	0,359	0,235	0,250
Air Flow Rate	kg/h	135,9	162,4	179,2	188,3	200,7	197,1	198,9
Air / Fuel Ratio	-	38,53	14,69	37,42	14,37	34,84	16,49	24,78
Excess Air Coeff.	-	2,68	1,02	2,60	1,00	2,42	1,15	1,72
Equivalence Ratio	-	0,37	0,98	0,38	1,00	0,41	0,87	0,58
Theoretical Air Cons.	kg/h	225,9	296,5	296,5	353,0	367,1	367,1	367,1
Volumetric Eff.	%	60,2	54,8	60,4	53,4	54,7	53,7	54,2
Thermal Eff.	%	17,6	29,4	17,0	27,8	17,6	26,8	25,3
Exhaust Flow Rate	m3/h	113,6	137,1	149,7	159,1	167,8	166,1	166,8
Exh. Flow R.on Dry B.	m3/h	112,1	132,4	147,7	153,6	165,4	161,1	163,4
Dilution T. Flow Rate	m3/h	41,6	42,2	42,0	42,3	42,0	41,6	41,6
Dilution Ratio	%	12,8	15,2	16,7	17,6	18,8	18,7	18,8
Particulate Emissions	g/HPh	1,0	1,3	0,5	0,8	0,5	0,6	1,0
Particulate Emissions2	g/h	10,1	68,0	6,8	45,8	7,8	30,1	31,4
HC emissions	g/HPh	0,106	0,014	0,050	0,010	0,038	0,020	0,028
Opacity	%/HP	0,122	0,305	0,023	0,377	0,031	0,342	0,050
CO2	%/HP	0,407	0,213	0,357	0,180	0,268	0,205	0,199
CO	%/HP	0,0020	0,0064	0,0008	0,0017	0,0019	0,0016	0,0006
O2	%/HP	1,505	0,105	1,111	0,098	0,909	0,115	0,363
Backpressure	mmHg/ HP	1,220	0,408	1,551	0,518	1,621	0,610	0,964

Table A.5: Measured Data for Aluminum Chip (Mode 1- 6).

		1	2	3	4	5	6
Filter Material	-	Al	Al	Al	Al	Al	Al
Room Temperature	C	24	27	30	31	29	31
Relative Humidity	%	66	65	60	58	59	52
Room Pressure	mm-Hg	743	743	743	742	741	740
Engine Speed	rpm	750	1600	2100	2100	1650	1650
Dynamometer Reading	-	0,1	4,8	2,8	3,8	2,6	3,8
Load	%	0	100	50	75	50	75
Go Power Reading	in	0,62	0,85	1,72	1,68	1	0,94
Fuel Flow Rate	g/s	0,22	2,68	2,36	2,6	1,74	2,17
Filter Temperature	C	61	320	230	310	195	265
ISP Temperature	C	53	315	217	308	185	248
Sample Temperature	C	26	39	32	38	30	34
Backpressure	mm-Hg	4	11	20	22	13	12
Tunnel Pressure	in	0,18	0,448	0,474	0,462	0,62	0,74
Sampling Rate	scfm	0,7	0,65	0,65	0,65	0,65	0,65
AVL HC	ppm	10	7	10	11	6	15
AVL Opacity	%	0,5	50,5	1,5	31,7	1,8	10,8
CO2	%	2	11,5	7,9	9,7	8,6	9,5
CO	%	0,03	0,77	0,02	0,07	0,04	0,08
O2	%	17,96	3,94	9,51	6,94	8,78	7,31
Filter Weight #1	mg	205,775	204,030	203,890	205,330	206,510	204,060
Filter Weight #2	mg	205,935	204,610	204,320	206,985	207,555	205,155
Soot	mg	0,160	0,580	0,430	1,655	1,045	1,095
Weight factor	%	15	8	10	10	5	5
Duration	min	4	2	2	2	2	2
Water Vapor Pressure	mmHg	22,36	26,73	31,82	33,7	30,04	33,70

Table A.6: Measured Data for Aluminum Chip (Mode 7- 13).

	7	8	9	10	11	12	13
Filter Material	Al	Al	Al	Al	Al	Al	Al
Room Temperature	32	33	31	36	36	36	37
Relative Humidity	52	52	51	50	48	47	46
Room Pressure	740	740	739	739	739	738	737
Engine Speed	1600	2050	2100	2250	2600	2600	2600
Dynamometer Reading	1,2	4,8	1,2	4,2	1,3	3,6	2,6
Load	25	100	25	100	25	75	50
Go Power Reading	0,94	1,48	1,74	1,7	2,32	2,28	2,2
Fuel Flow Rate	1,14	3,16	1,49	3,37	1,87	3,25	2,85
Filter Temperature	168	320	142	360	240	345	326
ISP Temperature	162	306	139	329	231	327	320
Sample Temperature	29	38	26	46	36	44	42
Backpressure	14	21	20	30	30	30	29
Tunnel Pressure	0,68	0,8	0,72	0,648	0,728	0,544	0,648
Sampling Rate	0,65	0,65	0,65	0,65	0,65	0,65	0,65
AVL HC	10	12	10	10	9	14	12
AVL Opacity	1,2	17,3	1,5	18,6	1,6	13,6	3
CO2	4,9	11,5	4,7	10	5	9,4	8,3
CO	0,01	0,41	0,01	0,22	0,02	0,04	0,02
O2	13,8	4,63	13,82	5,17	14,98	7,45	8,97
Filter Weight #1	203,245	203,745	204,415	206,985	206,520	203,970	207,790
Filter Weight #2	203,685	206,275	204,825	208,445	206,685	205,770	209,165
Soot	0,440	2,530	0,410	1,460	0,165	1,800	1,375
Weight factor	5	9	10	8	5	5	5
Duration	2	2	2	2	2	2	2
Water Vapor Pressure	35,67	37,74	33,7	44,58	44,58	44,58	47,09

Table A.7: Calculated Parameters for Aluminum Chip (Mode 1- 6).

		1	2	3	4	5	6
Dry Air Pressure	mmHg	728,2	725,6	723,9	722,5	723,3	722,5
Power Correction Factor	-	1,011	1,019	1,025	1,028	1,024	1,028
Brake Power	HP	0,4	39,1	30,1	41,0	22,0	32,2
Engine Torque	Nm	3,6	171,7	100,8	137,2	93,5	137,2
Brake Sp. Fuel Cons.	kg/HPh	2,089	0,247	0,282	0,228	0,285	0,242
Air Flow Rate	kg/h	108,6	126,8	179,2	177,2	137,3	133,2
Air / Fuel Ratio	-	137,12	13,14	21,09	18,93	21,92	17,05
Excess Air Coeff.	-	9,53	0,91	1,47	1,32	1,52	1,18
Equivalence Ratio	-	0,10	1,09	0,68	0,76	0,66	0,84
Theoric Air Cons.	kg/h	105,9	225,9	296,5	296,5	233,0	233,0
Volumetric Eff.	%	102,6	56,1	60,4	59,8	58,9	57,2
Thermal Eff.	%	3,0	25,5	22,4	27,6	22,1	26,0
Exhaust Flow Rate	m3/h	90,3	107,3	150,5	149,1	115,3	112,2
Exh. Flow R.on Dry B.	m3/h	90,0	103,2	146,9	145,1	112,6	108,9
Dilution T. Flow Rate	m3/h	39,3	40,7	40,8	40,7	41,5	42,1
Dilution Ratio	%	10,8	12,4	17,3	17,2	13,0	12,5
Particulate Emissions	g/HPh	4,5	0,3	0,3	1,0	1,1	0,8
Particulate Emissions2	g/h	1,7	13,6	10,1	39,0	25,1	26,7
HC emissions	g/HPh	1,469	0,011	0,030	0,024	0,019	0,031
Opacity	%/HP	1,319	1,291	0,050	0,773	0,082	0,335
CO2	%/HP	5,275	0,294	0,262	0,236	0,392	0,295
CO	%/HP	0,0791	0,0197	0,0007	0,0017	0,0018	0,0025
O2	%/HP	47,371	0,101	0,316	0,169	0,400	0,227
Backpressure	mmHg/ HP	10,550	0,281	0,664	0,536	0,592	0,372

Table A.8: Calculated Parameters for Aluminum Chip (Mode 7- 13).

		7	8	9	10	11	12	13
Dry Air Pressure	mmHg	721,5	720,4	721,8	716,7	717,6	717,0	715,3
Power Correction Factor	-	1,031	1,034	1,029	1,042	1,041	1,042	1,045
Brake Power	HP	9,9	50,8	13,0	49,2	17,6	48,8	35,3
Engine Torque	Nm	43,4	174,3	43,4	153,7	47,5	131,7	95,4
Brake Sp. Fuel Cons.	kg/HPh	0,415	0,224	0,414	0,246	0,383	0,240	0,290
Air Flow Rate	kg/h	133,2	166,8	180,1	178,2	206,3	204,4	200,7
Air / Fuel Ratio	-	32,45	14,67	33,58	14,69	30,64	17,47	19,56
Excess Air Coeff.	-	2,26	1,02	2,33	1,02	2,13	1,21	1,36
Equivalence Ratio	-	0,44	0,98	0,43	0,98	0,47	0,82	0,74
Theoric Air Cons.	kg/h	225,9	289,4	296,5	317,7	367,1	367,1	367,1
Volumetric Eff.	%	59,0	57,6	60,7	56,1	56,2	55,7	54,7
Thermal Eff.	%	15,2	28,2	15,2	25,6	16,5	26,3	21,7
Exhaust Flow Rate	m3/h	111,4	140,9	150,6	150,5	172,6	172,1	168,8
Exh. Flow R.on Dry B.	m3/h	109,7	136,1	148,4	145,4	169,8	167,2	164,4
Dilution T. Flow Rate	m3/h	41,8	42,4	42,0	41,7	42,1	41,1	41,7
Dilution Ratio	%	12,5	15,6	16,8	17,0	19,3	19,6	19,0
Particulate Emissions	g/HPh	1,1	1,2	0,8	0,7	0,2	0,9	0,9
Particulate Emissions2	g/h	10,6	62,1	10,0	35,2	4,0	42,9	33,2
HC emissions	g/HPh	0,069	0,020	0,071	0,018	0,054	0,030	0,035
Opacity	%/HP	0,121	0,340	0,116	0,378	0,091	0,279	0,085
CO2	%/HP	0,495	0,226	0,363	0,203	0,284	0,193	0,235
CO	%/HP	0,0010	0,0081	0,0008	0,0045	0,0011	0,0008	0,0006
O2	%/HP	1,395	0,091	1,066	0,105	0,851	0,153	0,254
Backpressure	mmHg/ HP	1,415	0,413	1,543	0,609	1,705	0,615	0,821

Table A.9: Measured Data for Iron Chip (Mode 1- 6).

		1	2	3	4	5	6
Filter Material	-	Fe	Fe	Fe	Fe	Fe	Fe
Room Temperature	C	25	27	31	32	33	33
Relative Humidity	%	62	63	59	57	55	55
Room Pressure	mm-Hg	739	739	739	739	739	739
Engine Speed	rpm	750	1600	2100	2100	1600	1600
Dynamometer Reading	-	0,1	4,8	2,8	3,7	2,4	3,6
Load	%	0	100	50	75	50	75
Go Power Reading	in	0,58	0,84	1,58	1,64	0,92	0,92
Fuel Flow Rate	g/s	0,22	2,60	2,34	2,78	1,55	2,02
Filter Temperature	C	44	312	259	311	220	260
ISP Temperature	C	43	308	243	303	209	245
Sample Temperature	C	25	36	30	35	28	31
Backpressure	mm-Hg	4	11	21	21	11	12
Tunnel Pressure	in	0,38	0,204	0,74	0,652	0,632	0,624
Sampling Rate	scfm	0,625	0,675	0,75	0,7	0,7	0,75
AVL HC	ppm	10	6	8	8	6	8
AVL Opacity	%	1,3	74,6	9,7	19,3	3,9	18,5
CO2	%	2,1	11,5	7,9	9,2	6,8	9,1
CO	%	0,02	1	0,02	0,05	0,01	0,06
O2	%	17,79	3,77	9,53	7,75	11,1	8,02
Filter Weight #1	mg	206,875	205,340	207,445	206,680	205,015	203,175
Filter Weight #2	mg	206,990	205,475	208,305	207,805	205,655	203,685
Soot	mg	0,115	0,135	0,860	1,125	0,640	0,510
Weight factor	%	15	8	10	10	5	5
Duration	min	4	2	2	2	2	2
Water Vapor Pressure	mmHg	22,36	26,73	33,7	35,67	37,74	37,74

Table A.10: Measured Data for Iron Chip (Mode 7- 13).

	7	8	9	10	11	12	13
Filter Material	Fe	Fe	Fe	Fe	Fe	Fe	Fe
Room Temperature	34	37	32	35	36	37	36
Relative Humidity	53	52	55	52	50	49	47
Room Pressure	739	738	738	738	736	735	735
Engine Speed	1600	2100	2100	2500	2600	2500	2600
Dynamometer Reading	1,2	4,5	1,2	3,9	1,3	3,7	2,6
Load	25	100	25	100	25	75	50
Go Power Reading	0,98	1,56	1,68	2,14	2,2	1,94	2,28
Fuel Flow Rate	1,16	3,35	1,66	3,82	2,07	3,80	2,98
Filter Temperature	181	339	223	338	221	347	272
ISP Temperature	172	320	211	326	226	322	268
Sample Temperature	26	40	30	41	31	42	34
Backpressure	12	22	20	38	30	30	32
Tunnel Pressure	0,604	0,656	0,656	0,544	0,408	0,312	0,396
Sampling Rate	0,75	0,75	0,7	0,85	0,75	0,8	0,8
AVL HC	6	6	6	13	6	6	15
AVL Opacity	1,2	56,1	1,9	20,5	3,4	55,7	25,2
CO2	4	10,9	5	9,2	6,2	10,8	9,3
CO	0,01	0,36	0,05	0,05	0,02	0,13	0,05
O2	13,96	5	13,63	7,62	12,48	5,73	7,83
Filter Weight #1	205,935	204,750	206,510	208,010	205,175	205,625	201,025
Filter Weight #2	206,090	205,420	206,990	211,155	205,745	207,935	202,910
Soot	0,155	0,670	0,480	3,145	0,570	2,310	1,885
Weight factor	5	9	10	8	5	5	5
Duration	2	2	2	2	2	2	2
Water Vapor Pressure	39,91	47,09	35,67	42,19	44,58	47,09	44,58

Table A.11: Calculated Parameters for Iron Chip (Mode 1- 6).

		1	2	3	4	5	6
Dry Air Pressure	mmHg	725,1	722,2	719,1	718,7	718,2	718,2
Power Correction Factor	-	1,016	1,022	1,031	1,033	1,036	1,036
Brake Power	HP	0,4	39,2	30,3	40,1	19,9	29,8
Engine Torque	Nm	3,6	172,3	101,4	134,3	87,3	130,9
Brake Sp. Fuel Cons.	kg/HPh	2,080	0,239	0,278	0,249	0,281	0,244
Air Flow Rate	kg/h	105,0	126,1	172,2	175,2	131,8	131,8
Air / Fuel Ratio	-	132,54	13,47	20,44	17,51	23,62	18,12
Excess Air Coeff.	-	9,21	0,94	1,42	1,22	1,64	1,26
Equivalence Ratio	-	0,11	1,07	0,70	0,82	0,61	0,79
Theoric Air Cons.	kg/h	105,9	225,9	296,5	296,5	225,9	225,9
Volumetric Eff.	%	99,1	55,8	58,1	59,1	58,3	58,3
Thermal Eff.	%	3,0	26,4	22,7	25,3	22,5	25,8
Exhaust Flow Rate	m3/h	87,3	106,6	144,7	147,6	110,6	110,9
Exh. Flow R.on Dry B.	m3/h	87,0	102,7	141,1	143,3	108,2	107,8
Dilution T. Flow Rate	m3/h	40,3	39,4	42,1	41,7	41,6	41,5
Dilution Ratio	%	10,2	12,7	16,1	16,6	12,5	12,5
Particulate Emissions	g/HPh	3,7	0,1	0,6	0,6	0,7	0,4
Particulate Emissions2	g/h	1,4	3,0	18,2	25,2	14,3	10,6
HC emissions	g/HPh	1,413	0,010	0,023	0,018	0,020	0,018
Opacity	%/HP	3,414	1,901	0,320	0,481	0,196	0,620
CO2	%/HP	5,514	0,293	0,261	0,229	0,342	0,305
CO	%/HP	0,0525	0,0255	0,0007	0,0012	0,0005	0,0020
O2	%/HP	46,713	0,096	0,314	0,193	0,558	0,269
Backpressure	mmHg/HP	10,503	0,280	0,693	0,523	0,553	0,402

Table A.12: Calculated Parameters for Iron Chip (Mode 7- 13).

		7	8	9	10	11	12	13
Dry Air Pressure	mmHg	717,8	713,5	718,4	716,1	713,7	711,9	714,0
Power Correction Factor	-	1,038	1,047	1,034	1,041	1,045	1,048	1,045
Brake Power	HP	10,0	49,5	13,0	50,7	17,7	48,5	35,3
Engine Torque	Nm	43,7	165,5	43,6	142,6	47,7	136,2	95,4
Brake Sp. Fuel Cons.	kg/HP h	0,417	0,244	0,459	0,271	0,421	0,282	0,303
Air Flow Rate	kg/h	135,9	171,1	177,2	198,0	200,7	189,2	204,4
Air / Fuel Ratio	-	32,69	14,19	29,65	14,40	26,98	13,84	19,08
Excess Air Coeff.	-	2,27	0,99	2,06	1,00	1,87	0,96	1,33
Equivalence Ratio	-	0,44	1,01	0,49	1,00	0,53	1,04	0,75
Theoric Air Cons.	kg/h	225,9	296,5	296,5	353,0	367,1	353,0	367,1
Volumetric Eff.	%	60,2	57,7	59,8	56,1	54,7	53,6	55,7
Thermal Eff.	%	15,1	25,8	13,7	23,3	15,0	22,4	20,8
Exhaust Flow Rate	m3/h	113,7	144,6	148,3	167,3	168,2	160,0	171,9
Exh. Flow R.on Dry B.	m3/h	111,9	139,5	145,8	161,5	165,0	154,2	167,4
Dilution T. Flow Rate	m3/h	41,4	41,7	41,7	41,1	40,5	40,0	40,4
Dilution Ratio	%	12,9	16,3	16,7	19,1	19,5	18,8	20,0
Particulate Emissions	g/HPh	0,3	0,3	0,8	1,1	0,7	0,9	1,0
Particulate Emissions2	g/h	3,2	14,0	10,8	57,3	11,6	43,4	35,8
HC emissions	g/HPh	0,042	0,010	0,042	0,026	0,035	0,012	0,044
Opacity	%/HP	0,120	1,134	0,146	0,404	0,193	1,149	0,714
CO2	%/HP	0,402	0,220	0,384	0,181	0,351	0,223	0,263
CO	%/HP	0,0010	0,0073	0,0038	0,0010	0,0011	0,0027	0,0014
O2	%/HP	1,402	0,101	1,046	0,150	0,707	0,118	0,222
Backpressure	mmHg /HP	1,205	0,445	1,536	0,749	1,699	0,619	0,906

Table A.13: Measured Data for Cupper Chip-1 (Mode 1- 6).

		1	2	3	4	5	6
Filter Material	-	Cu	Cu	Cu	Cu	Cu	Cu
Room Temperature	C	27	30	32	35	35	34
Relative Humidity	%	60	56	53	48	46	47
Room Pressure	mm-Hg	737	738	738	738	738	738
Engine Speed	rpm	750	1600	2100	2100	1600	1650
Dynamometer Reading	-	0,1	4,8	2,5	3,6	2,5	3,6
Load	%	0	100	50	75	50	75
Go Power Reading	in	0,56	0,86	1,7	1,7	1,1	0,98
Fuel Flow Rate	g/s	0,23	2,66	2,37	2,81	1,75	2,12
Filter Temperature	C	48	320	254	278	238	268
ISP Temperature	C	46	303	241	284	232	252
Sample Temperature	C	26	40	33	35	34	36
Backpressure	mm-Hg	4	11	21	22	12	13
Tunnel Pressure	in	0,2	0,62	0,672	0,684	0,644	0,628
Sampling Rate	scfm	0,7	0,7	0,7	0,7	0,7	0,825
AVL HC	ppm	12	5	6	7	8	12
AVL Opacity	%	0,5	79,3	12,3	35,3	6,8	27
CO2	%	1,9	11,7	8,2	10,05	7,6	9,9
CO	%	0,03	1,07	0,03	0,19	0,02	0,14
O2	%	18,25	3,49	9,28	6,26	10,19	6,43
Filter Weight #1	mg	203,175	201,920	202,155	210,540	209,475	210,975
Filter Weight #2	mg	203,355	202,195	203,045	210,945	209,670	211,415
Soot	mg	0,180	0,275	0,890	0,405	0,195	0,440
Weight factor	%	15	8	10	10	5	5
Duration	min	4	2	2	2	2	2
Water Vapor Pressure	mmHg	22,36	31,82	35,67	42,19	42,19	39,91

Table A.14: Measured Data for Cupper Chip-1 (Mode 7- 13).

	7	8	9	10	11	12	13
Filter Material	Cu	Cu	Cu	Cu	Cu	Cu	Cu
Room Temperature	34	34	36	37	37	36	37
Relative Humidity	45	46	44	44	43	42	42
Room Pressure	737	737	737	736	736	735	735
Engine Speed	1650	2050	2100	2500	2600	2450	2600
Dynamometer Reading	1,2	4,6	1,2	4,1	1,4	3,7	2,5
Load	25	100	25	100	25	75	50
Go Power Reading	0,98	1,6	1,72	2	2,3	2,06	2,2
Fuel Flow Rate	1,18	3,27	1,63	3,62	2,19	3,58	2,12
Filter Temperature	182	354	206	386	275	352	304
ISP Temperature	168	341	198	362	263	242	287
Sample Temperature	27	41	32	46	38	43	41
Backpressure	12	22	21	31	30	28	32
Tunnel Pressure	0,624	0,68	0,63	0,652	0,708	0,62	0,608
Sampling Rate	0,825	0,8	0,8	0,9	0,9	0,95	0,85
AVL HC	8	10	7	6	6	7	7
AVL Opacity	0,9	53	0,8	54,8	0,9	51,9	2,1
CO2	4,3	11,9	4,7	11,2	6,7	11,1	6,8
CO	0,02	0,37	0,02	0,31	0,02	0,27	0,02
O2	13,96	4,87	14,18	5,17	11,59	5,52	11,35
Filter Weight #1	211,315	210,425	210,255	212,055	211,095	206,970	207,595
Filter Weight #2	211,420	210,490	210,355	212,925	211,535	207,285	208,545
Soot	0,105	0,065	0,100	0,870	0,440	0,315	0,950
Weight factor	5	9	10	8	5	5	5
Duration	2	2	2	2	2	2	2
Water Vapor Pressure	39,91	39,91	44,58	47,09	47,09	44,58	47,09

Table A.15: Calculated Parameters for Cupper Chip-1 (Mode 1- 6).

		1	2	3	4	5	6
Dry Air Pressure	mmHg	723,6	720,2	719,1	717,7	718,6	719,2
Power Correction Factor	-	1,020	1,029	1,033	1,039	1,039	1,036
Brake Power	HP	0,4	39,5	27,1	39,3	20,8	30,8
Engine Torque	Nm	3,6	173,4	90,7	131,4	91,2	131,0
Brake Sp. Fuel Cons.	kg/HPh	2,164	0,242	0,315	0,257	0,303	0,248
Air Flow Rate	kg/h	103,1	127,5	178,2	178,2	143,9	135,9
Air / Fuel Ratio	-	124,50	13,32	20,88	17,61	22,84	17,81
Excess Air Coeff.	-	8,65	0,93	1,45	1,22	1,59	1,24
Equivalence Ratio	-	0,12	1,08	0,69	0,82	0,63	0,81
Theoric Air Cons.	kg/h	105,9	225,9	296,5	296,5	225,9	233,0
Volumetric Eff.	%	97,4	56,5	60,1	60,1	63,7	58,3
Thermal Eff.	%	2,9	26,0	20,0	24,5	20,8	25,4
Exhaust Flow Rate	m3/h	85,7	107,9	149,7	150,0	120,8	114,4
Exh. Flow R.on Dry B.	m3/h	85,4	103,8	146,1	145,8	118,1	111,2
Dilution T. Flow Rate	m3/h	39,4	41,5	41,8	41,8	41,6	41,6
Dilution Ratio	%	10,2	12,2	16,8	16,8	13,6	12,9
Particulate Emissions	g/HPh	5,0	0,2	0,7	0,2	0,2	0,3
Particulate Emissions2	g/h	1,9	6,1	20,0	9,1	4,4	8,3
HC emissions	g/HPh	1,657	0,008	0,020	0,016	0,028	0,027
Opacity	%/HP	1,307	2,008	0,454	0,899	0,327	0,877
CO2	%/HP	4,965	0,296	0,302	0,256	0,366	0,322
CO	%/HP	0,0784	0,0271	0,0011	0,0048	0,0010	0,0045
O2	%/HP	47,695	0,088	0,342	0,159	0,491	0,209
Backpressure	mmHg/HP	10,454	0,278	0,774	0,560	0,578	0,422

Table A.16: Calculated Parameters for Cupper Chip-1 (Mode 7- 13).

		7	8	9	10	11	12	13
Dry Air Pressure	mmHg	719,0	718,6	717,4	715,3	715,8	716,3	715,2
Power Correction Factor	-	1,036	1,037	1,041	1,045	1,045	1,042	1,045
Brake Power	HP	10,3	48,9	13,1	53,6	19,0	47,2	34,0
Engine Torque	Nm	43,7	167,5	43,9	150,5	51,4	135,5	91,8
Brake Sp. Fuel Cons.	kg/HPh	0,414	0,241	0,447	0,243	0,415	0,273	0,225
Air Flow Rate	kg/h	135,9	173,2	179,2	191,8	205,3	194,5	200,7
Air / Fuel Ratio	-	32,00	14,71	30,53	14,72	26,04	15,09	26,30
Excess Air Coeff.	-	2,22	1,02	2,12	1,02	1,81	1,05	1,83
Equivalence Ratio	-	0,45	0,98	0,47	0,98	0,55	0,95	0,55
Theoric Air Cons.	kg/h	233,0	289,4	296,5	353,0	367,1	345,9	367,1
Volumetric Eff.	%	58,3	59,8	60,4	54,4	55,9	56,2	54,7
Thermal Eff.	%	15,2	26,2	14,1	25,9	15,2	23,1	28,0
Exhaust Flow Rate	m3/h	113,7	146,3	149,9	162,0	172,1	164,2	168,2
Exh. Flow R.on Dry B.	m3/h	111,9	141,3	147,5	156,5	168,8	158,7	165,0
Dilution T. Flow Rate	m3/h	41,5	41,8	41,6	41,7	42,0	41,5	41,5
Dilution Ratio	%	12,8	16,4	16,9	18,2	19,2	18,6	19,0
Particulate Emissions	g/HPh	0,2	0,03	0,1	0,3	0,4	0,1	0,5
Particulate Emissions2	g/h	2,0	1,3	2,0	15,2	7,7	5,2	17,4
HC emissions	g/HPh	0,054	0,018	0,049	0,011	0,033	0,015	0,021
Opacity	%/HP	0,088	1,084	0,061	1,023	0,047	1,098	0,062
CO2	%/HP	0,419	0,243	0,358	0,209	0,352	0,235	0,200
CO	%/HP	0,0019	0,0076	0,0015	0,0058	0,0011	0,0057	0,0006
O2	%/HP	1,361	0,100	1,081	0,097	0,610	0,117	0,334
Backpressure	mmHg/ HP	1,169	0,450	1,600	0,579	1,578	0,593	0,942

Table A.17: Measured Data for Cupper Chip-2 (Mode 1- 6).

		1	2	3	4	5	6
Filter Material	-	Cu 2	Cu 2	Cu 2	Cu 2	Cu 2	Cu 2
Room Temperature	C	26	28	32	32	32	31
Relative Humidity	%	61	60	55	54	53	53
Room Pressure	mm-Hg	742	742	742	741	741	740
Engine Speed	rpm	750	1600	2100	2100	1600	1600
Dynamometer Reading	-	0,1	4,8	2,5	3,6	2,5	3,7
Load	%	0	100	50	75	50	75
Go Power Reading	in	0,58	0,82	1,68	1,68	0,92	0,96
Fuel Flow Rate	g/s	0,24	2,61	2,33	2,75	1,74	2,14
Filter Temperature	C	44	351	300	334	272	301
ISP Temperature	C	40	342	285	316	249	278
Sample Temperature	C	25	42	38	44	41	43
Backpressure	mm-Hg	4	10	26	26	11	12
Tunnel Pressure	in	0,26	0,656	0,836	0,812	0,692	0,7
Sampling Rate	scfm	0,7	0,7	0,675	0,7	0,7	0,7
AVL HC	ppm	10	14	8	7	6	6
AVL Opacity	%	1,0	76,0	7,0	12,7	10,4	26,9
CO2	%	1,9	11,7	7,3	8,9	8,2	9,6
CO	%	0,02	1,08	0,02	0,04	0,03	0,12
O2	%	18,14	3,57	10,66	8,83	9,38	7,33
Filter Weight #1	mg	211,345	213,075	213,610	212,340	208,840	206,395
Filter Weight #2	mg	211,415	213,215	213,730	212,645	209,035	206,845
Soot	mg	0,070	0,140	0,120	0,305	0,195	0,450
Weight factor	%	15	8	10	10	5	5
Duration	min	4	2	2	2	2	2
Water Vapor Pressure	mmHg	22,36	28,34	35,67	35,67	35,67	33,7

Table A.18: Measured Data for Cupper Chip-2 (Mode 7- 13).

	7	8	9	10	11	12	13
Filter Material	Cu 2	Cu 2	Cu 2	Cu 2	Cu 2	Cu 2	Cu 2
Room Temperature	32	32	33	32	36	35	36
Relative Humidity	53	53	53	52	51	50	50
Room Pressure	740	740	740	739	739	738	738
Engine Speed	1600	2100	2100	2500	2600	2600	2600
Dynamometer Reading	1,2	4,6	1,2	4	1,2	3,7	2,5
Load	25	100	25	100	25	75	50
Go Power Reading	0,96	1,6	1,74	2,06	2,24	2,18	2,26
Fuel Flow Rate	1,22	3,6	1,37	3,72	2,36	3,68	2,87
Filter Temperature	223	370	256	435	325	420	367
ISP Temperature	202	346	220	410	291	410	359
Sample Temperature	31	49	35	56	45	51	47
Backpressure	14	24	26	30	30	28	32
Tunnel Pressure	0,672	0,86	0,876	0,9	0,9	0,88	0,91
Sampling Rate	0,7	0,7	0,7	0,7	0,65	0,65	0,65
AVL HC	5	5	6	5	4	6	7
AVL Opacity	1,8	62,8	1,2	62,9	1	57,9	54
CO2	5,3	11	4,4	11,2	3,3	11,3	11,1
CO	0,01	0,37	0,01	0,31	0,04	0,3	0,31
O2	13,43	4,98	14,48	4,84	16,14	4,96	5,13
Filter Weight #1	208,365	211,315	210,915	209,735	210,435	212,365	212,145
Filter Weight #2	208,710	211,535	210,980	210,495	210,585	212,445	212,175
Soot	0,345	0,220	0,065	0,760	0,150	0,080	0,030
Weight factor	5	9	10	8	5	5	5
Duration	2	2	2	2	2	2	2
Water Vapor Pressure	35,67	35,67	37,74	35,67	44,58	42,19	44,58

Table A.19: Calculated Parameters for Cupper Chip-2 (Mode 1- 6).

		1	2	3	4	5	6
Dry Air Pressure	mmHg	728,4	725,0	722,4	721,7	722,1	722,1
Power Correction Factor	-	1,014	1,021	1,030	1,031	1,030	1,028
Brake Power	HP	0,4	39,2	27,0	39,0	20,6	30,4
Engine Torque	Nm	3,6	172,1	90,4	130,3	90,5	133,7
Brake Sp. Fuel Cons.	kg/HPh	2,271	0,240	0,310	0,254	0,304	0,253
Air Flow Rate	kg/h	105,0	124,6	177,2	177,2	131,8	134,6
Air / Fuel Ratio	-	121,50	13,26	21,13	17,90	21,04	17,47
Excess Air Coeff.	-	8,44	0,92	1,47	1,24	1,46	1,21
Equivalence Ratio	-	0,12	1,09	0,68	0,80	0,68	0,82
Theoric Air Cons.	kg/h	105,9	225,9	296,5	296,5	225,9	225,9
Volumetric Eff.	%	99,1	55,2	59,8	59,8	58,3	59,6
Thermal Eff.	%	2,8	26,3	20,3	24,8	20,7	24,9
Exhaust Flow Rate	m3/h	87,3	105,4	148,9	149,2	110,7	113,3
Exh. Flow R.on Dry B.	m3/h	86,9	101,5	145,3	145,0	108,1	110,1
Dilution T. Flow Rate	m3/h	39,7	41,7	42,6	42,5	41,9	41,9
Dilution Ratio	%	10,3	11,9	16,4	16,5	12,4	12,7
Particulate Emissions	g/HPh	2,0	0,1	0,1	0,2	0,2	0,3
Particulate Emissions2	g/h	0,7	3,1	2,8	7,0	4,4	10,1
HC emissions	g/HPh	1,415	0,022	0,027	0,016	0,019	0,013
Opacity	%/HP	2,629	1,939	0,259	0,326	0,505	0,884
CO2	%/HP	4,995	0,298	0,270	0,228	0,398	0,315
CO	%/HP	0,0526	0,0276	0,0007	0,0010	0,0015	0,0039
O2	%/HP	47,690	0,091	0,394	0,227	0,455	0,241
Backpressure	mmHg/HP	10,516	0,255	0,962	0,667	0,534	0,394

Table A.20: Calculated Parameters for Cupper Chip-2 (Mode 7- 13).

		7	8	9	10	11	12	13
Dry Air Pressure	mmHg	721,1	721,1	720,0	720,5	716,3	716,9	715,7
Power Correction Factor	-	1,031	1,031	1,034	1,032	1,042	1,040	1,043
Brake Power	HP	9,9	49,8	13,0	51,6	16,3	50,0	33,9
Engine Torque	Nm	43,5	166,6	43,6	145,0	43,9	135,2	91,6
Brake Sp. Fuel Cons.	kg/HPh	0,444	0,260	0,379	0,260	0,522	0,265	0,305
Air Flow Rate	kg/h	134,6	173,2	180,1	194,5	202,5	199,8	203,4
Air / Fuel Ratio	-	30,64	13,36	36,52	14,52	23,84	15,08	19,69
Excess Air Coeff.	-	2,13	0,93	2,54	1,01	1,66	1,05	1,37
Equivalence Ratio	-	0,47	1,08	0,39	0,99	0,60	0,95	0,73
Theoric Air Cons.	kg/h	225,9	296,5	296,5	353,0	367,1	367,1	367,1
Volumetric Eff.	%	59,6	58,4	60,7	55,1	55,2	54,4	55,4
Thermal Eff.	%	14,2	24,2	16,6	24,3	12,1	23,8	20,7
Exhaust Flow Rate	m3/h	112,6	146,5	150,5	164,3	169,9	168,6	171,1
Exh. Flow R.on Dry B.	m3/h	110,8	141,0	148,4	158,6	166,3	163,1	166,7
Dilution T. Flow Rate	m3/h	41,8	42,7	42,8	42,9	42,9	42,8	43,0
Dilution Ratio	%	12,7	16,1	16,5	18,0	18,6	18,5	18,7
Particulate Emissions	g/HPh	0,8	0,1	0,1	0,3	0,2	0,04	0,02
Particulate Emissions2	g/h	7,7	5,1	1,5	17,5	3,7	2,0	0,7
HC emissions	g/HPh	0,035	0,009	0,042	0,010	0,025	0,012	0,021
Opacity	%/HP	0,182	1,261	0,092	1,219	0,061	1,157	1,593
CO2	%/HP	0,535	0,221	0,338	0,217	0,203	0,226	0,327
CO	%/HP	0,0010	0,0074	0,0008	0,0060	0,0025	0,0060	0,0091
O2	%/HP	1,357	0,100	1,112	0,094	0,992	0,099	0,151
Backpressure	mmHg/ HP	1,414	0,482	1,996	0,582	1,845	0,560	0,944

Table A.21: Measured Data for Cupper Chip-3 (Mode 1- 6).

		1	2	3	4	5	6
Filter Material	-	Cu 3	Cu 3	Cu 3	Cu 3	Cu 3	Cu 3
Room Temperature	C	27	29	31	32	33	33
Relative Humidity	%	60	60	55	54	54	54
Room Pressure	mm-Hg	743	743	742	742	742	742
Engine Speed	rpm	750	1600	2100	2100	1600	1600
Dynamometer Reading	-	0,1	4,8	2,5	3,6	2,5	3,7
Load	%	0	100	50	75	50	75
Go Power Reading	in	0,56	0,86	1,62	1,72	0,92	0,94
Fuel Flow Rate	g/s	0,19	2,38	1,86	2,59	1,35	1,88
Filter Temperature	C	42	320	260	327	210	274
ISP Temperature	C	38	305	243	312	196	258
Sample Temperature	C	26	37	32	38	31	33
Backpressure	mm-Hg	4	10	21	20	11	12
Tunnel Pressure	in	0,22	0,532	0,772	0,784	0,684	0,648
Sampling Rate	scfm	0,625	0,65	0,65	0,7	0,7	0,7
AVL HC	ppm	12	16	7	10	10	12
AVL Opacity	%	0,8	32,9	2,2	23,4	4,6	15,3
CO2	%	1,9	10,7	6,1	9,2	6,4	9,2
CO	%	0,02	0,56	0,02	0,08	0,04	0,06
O2	%	17,92	4,74	12,2	7,69	12,04	8,72
Filter Weight #1	mg	210,015	211,105	212,325	210,515	210,885	211,365
Filter Weight #2	mg	210,235	211,645	212,745	211,265	211,215	211,845
Soot	mg	0,220	0,540	0,420	0,750	0,330	0,480
Weight factor	%	15	8	10	10	5	5
Duration	min	4	2	2	2	2	2
Water Vapor Pressure	mmHg	26,73	30,04	33,7	35,67	37,74	37,74

Table A.22: Measured Data for Cupper Chip-3 (Mode 7- 13).

		7	8	9	10	11	12	13
Filter Material	-	Cu 3	Cu 3	Cu 3	Cu 3	Cu 3	Cu 3	Cu 3
Room Temperature	C	35	35	35	36	36	37	36
Relative Humidity	%	53	53	52	52	51	51	51
Room Pressure	mm-Hg	738	738	738	736	736	736	736
Engine Speed	rpm	1600	2150	2100	2500	2600	2600	2600
Dynamometer Reading	-	1,2	4,4	1,2	4,2	1,2	3,7	2,4
Load	%	25	100	25	100	25	75	50
Go Power Reading	in	0,94	1,62	1,64	1,96	2,14	2,02	2,12
Fuel Flow Rate	g/s	1,01	3,11	1,34	3,71	1,82	3,28	2,32
Filter Temperature	C	180	378	227	432	278	392	342
ISP Temperature	C	169	354	201	410	252	366	336
Sample Temperature	C	29	45	31	49	35	46	42
Backpressure	mm-Hg	11	20	22	30	29	28	31
Tunnel Pressure	in	0,636	0,82	0,844	0,84	0,868	0,852	0,876
Sampling Rate	scfm	0,7	0,65	0,7	0,7	0,65	0,7	0,7
AVL HC	ppm	10	10	5	5	6	8	12
AVL Opacity	%	0,9	32,7	1,3	32,5	0,8	24,2	3,5
CO2	%	4,8	10,5	4,2	10,6	4,1	10,4	7,4
CO	%	0,02	0,32	0,02	0,18	0,03	0,12	0,06
O2	%	13,92	5,11	13,76	5,41	15,21	5,74	8,66
Filter Weight #1	mg	210,435	209,895	211,385	210,125	209,015	210,280	209,230
Filter Weight #2	mg	210,710	210,435	211,705	210,755	209,325	211,365	209,445
Soot	mg	0,275	0,540	0,320	0,630	0,310	1,085	0,215
Weight factor	%	5	9	10	8	5	5	5
Duration	min	2	2	2	2	2	2	2
Water Vapor Pressure	mmHg	42,19	42,19	42,19	44,58	44,58	47,09	44,58

Table A.23: Calculated Parameters for Cupper Chip-3 (Mode 1- 6).

		1	2	3	4	5	6
Dry Air Pressure	mmHg	727,0	725,0	723,5	722,7	721,6	721,6
Power Correction Factor	-	1,017	1,022	1,027	1,030	1,032	1,032
Brake Power	HP	0,4	39,3	27,0	38,9	20,6	30,6
Engine Torque	Nm	3,6	172,4	90,2	130,2	90,7	134,2
Brake Sp. Fuel Cons.	kg/HPh	1,793	0,218	0,248	0,240	0,235	0,221
Air Flow Rate	kg/h	103,1	127,5	174,2	179,2	131,8	133,2
Air / Fuel Ratio	-	150,71	14,88	26,02	19,21	27,11	19,68
Excess Air Coeff.	-	10,47	1,03	1,81	1,34	1,88	1,37
Equivalence Ratio	-	0,10	0,97	0,55	0,75	0,53	0,73
Theoric Air Cons.	kg/h	105,9	225,9	296,5	296,5	225,9	225,9
Volumetric Eff.	%	97,4	56,5	58,8	60,4	58,3	59,0
Thermal Eff.	%	3,5	28,9	25,4	26,3	26,8	28,5
Exhaust Flow Rate	m3/h	85,7	107,7	146,0	150,7	110,4	112,0
Exh. Flow R.on Dry B.	m3/h	85,4	104,0	143,2	146,7	108,4	109,1
Dilution T. Flow Rate	m3/h	39,5	41,1	42,3	42,3	41,8	41,7
Dilution Ratio	%	10,2	12,3	16,2	16,7	12,4	12,6
Particulate Emissions	g/HPh	6,9	0,3	0,38	0,44	0,36	0,35
Particulate Emissions2	g/h	2,6	12,8	10,3	17,1	7,4	10,7
HC emissions	g/HPh	1,663	0,026	0,023	0,023	0,032	0,027
Opacity	%/HP	2,097	0,838	0,082	0,601	0,223	0,501
CO2	%/HP	4,981	0,273	0,226	0,236	0,310	0,301
CO	%/HP	0,0524	0,0143	0,0007	0,0021	0,0019	0,0020
O2	%/HP	46,974	0,121	0,452	0,198	0,583	0,285
Backpressure	mmHg/HP	10,485	0,255	0,779	0,514	0,533	0,393

Table A.24: Calculated Parameters for Cupper Chip-3 (Mode 7- 13).

		7	8	9	10	11	12	13
Dry Air Pressure	mmHg	715,6	715,6	716,1	712,8	713,3	712,0	713,3
Power Correction Factor	-	1,041	1,041	1,041	1,046	1,045	1,048	1,045
Brake Power	HP	10,0	49,3	13,1	54,9	16,3	50,4	32,6
Engine Torque	Nm	43,9	160,9	43,9	154,3	44,1	136,2	88,1
Brake Sp. Fuel Cons.	kg/HPh	0,364	0,227	0,368	0,243	0,402	0,234	0,256
Air Flow Rate	kg/h	133,2	174,2	175,2	190,1	198,0	192,7	197,1
Air / Fuel Ratio	-	36,63	15,56	36,33	14,23	30,22	16,32	23,60
Excess Air Coeff.	-	2,55	1,08	2,52	0,99	2,10	1,13	1,64
Equivalence Ratio	-	0,39	0,92	0,40	1,01	0,48	0,88	0,61
Theoric Air Cons.	kg/h	225,9	303,5	296,5	353,0	367,1	367,1	367,1
Volumetric Eff.	%	59,0	57,4	59,1	53,9	53,9	52,5	53,7
Thermal Eff.	%	17,3	27,7	17,1	25,9	15,7	26,9	24,6
Exhaust Flow Rate	m3/h	111,3	147,0	146,5	160,6	165,7	162,5	165,4
Exh. Flow R.on Dry B.	m3/h	109,8	142,3	144,4	155,0	163,0	157,5	161,9
Dilution T. Flow Rate	m3/h	41,6	42,5	42,6	42,6	42,8	42,7	42,8
Dilution Ratio	%	12,6	16,2	16,1	17,7	18,2	17,9	18,1
Particulate Emissions	g/HPh	0,6	0,3	0,6	0,3	0,5	0,5	0,2
Particulate Emissions2	g/h	6,1	13,3	7,3	14,4	7,7	24,9	4,9
HC emissions	g/HPh	0,068	0,018	0,034	0,009	0,037	0,015	0,037
Opacity	%/HP	0,090	0,664	0,099	0,592	0,049	0,480	0,107
CO2	%/HP	0,480	0,213	0,320	0,193	0,251	0,206	0,227
CO	%/HP	0,0020	0,0065	0,0015	0,0033	0,0018	0,0024	0,0018
O2	%/HP	1,392	0,104	1,049	0,099	0,933	0,114	0,266
Backpressure	mmHg/ HP	1,100	0,406	1,677	0,546	1,778	0,555	0,951

APPENDIX B

FIBERGLASS FILTER PHOTOS

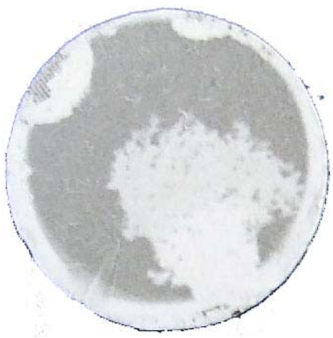
750 rpm-0%

1600 rpm-100%

2100 rpm-50%

2100 rpm-75%

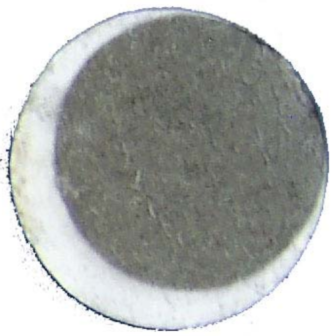
1600 rpm-50%



1600 rpm-75%

Figure B.1: Fiberglass filters for empty filter (Mode 1-6).

1600 rpm-25%



2100 rpm-100%

2100 rpm-25%

2600 rpm-100%

2600 rpm-25%

2600 rpm-75%

2600 rpm-50%

Figure B.2: Fiberglass filters for empty filter (Mode 7-13).

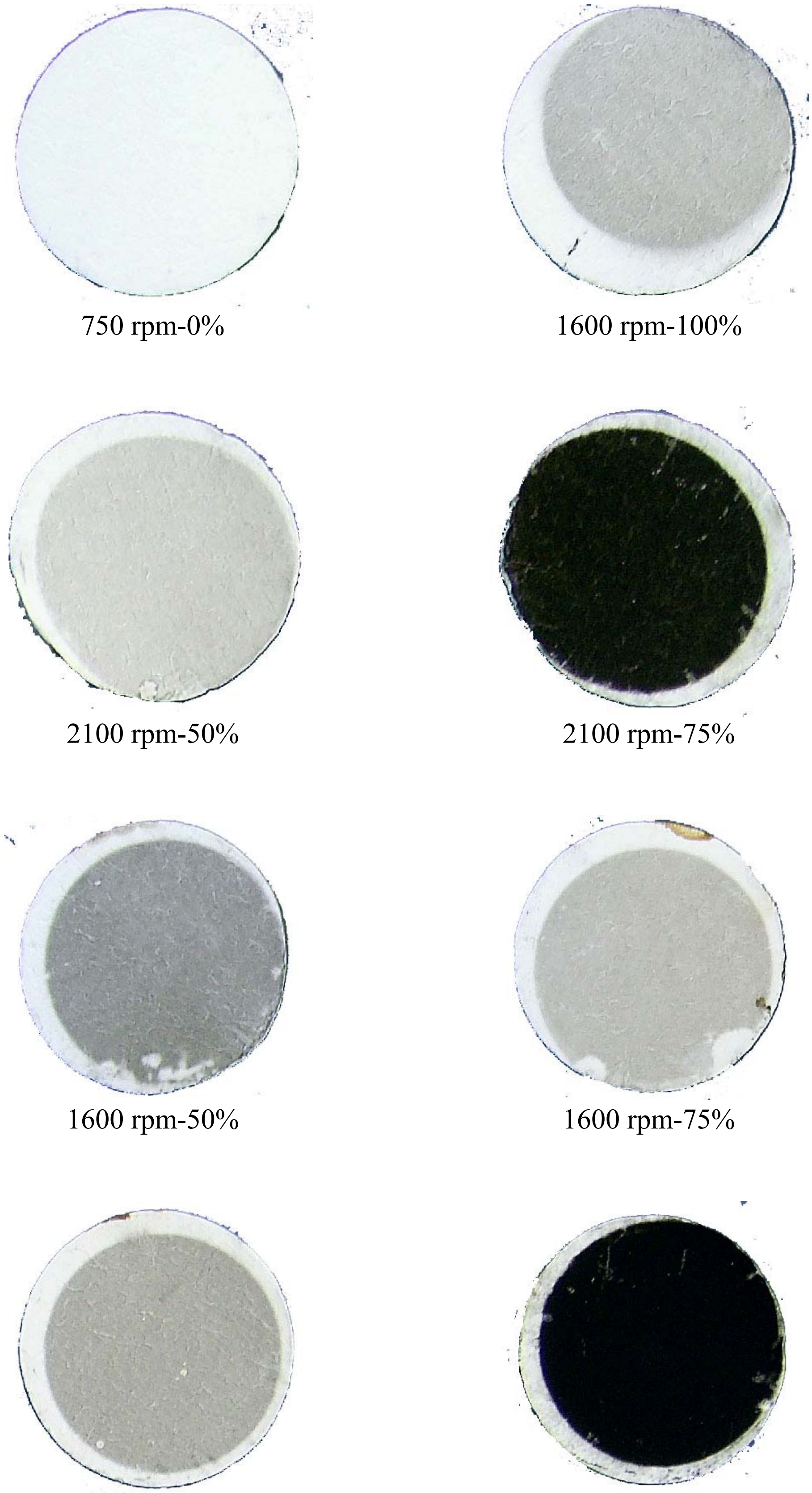


Figure B.3: Fiberglass filters for aluminum filter (Mode 1-8).

2100 rpm-25%

2600 rpm-100%

2600 rpm-25%

2600 rpm-75%

2600 rpm-50%

Figure B.4: Fiberglass filters for aluminum filter (Mode 9-13).

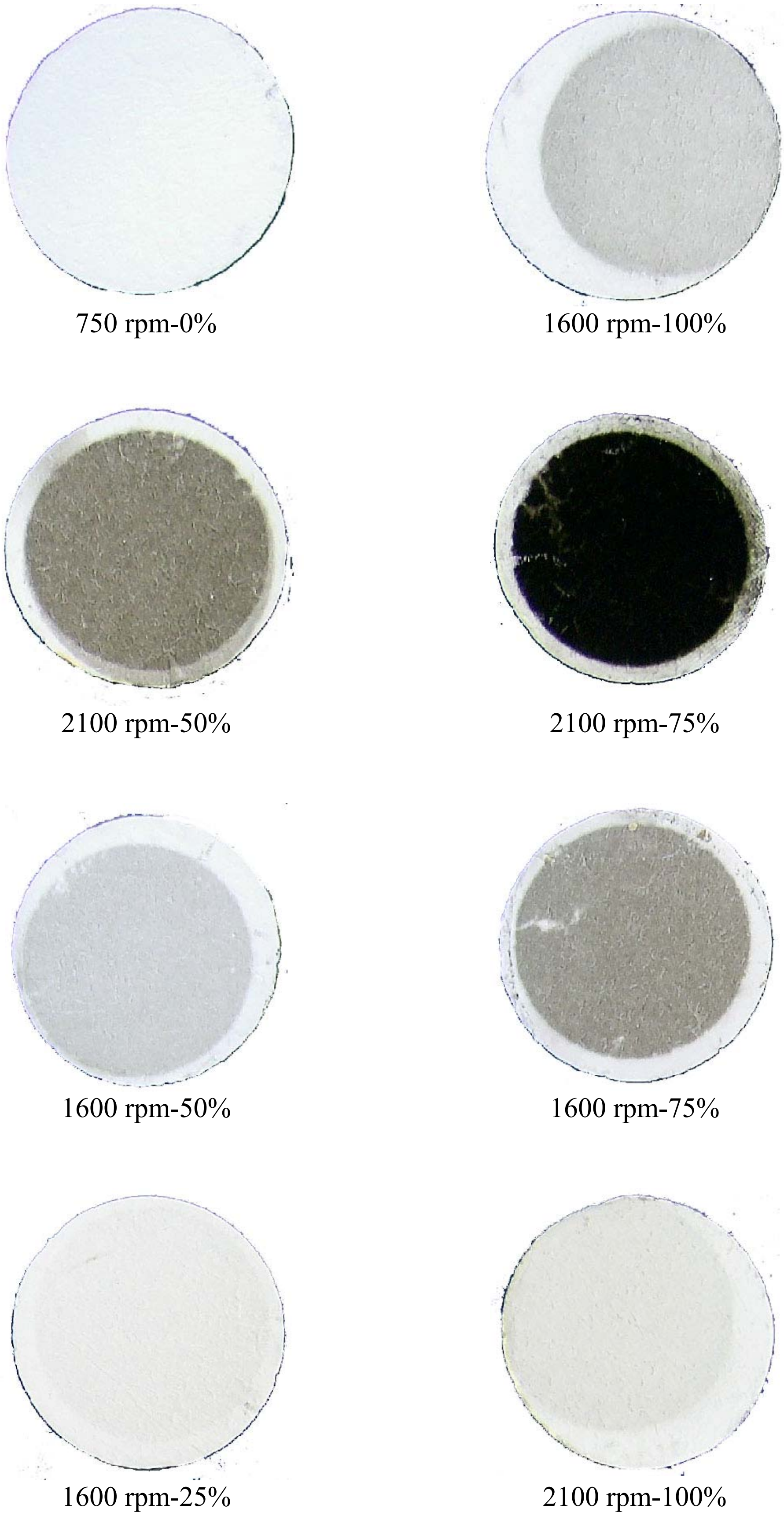
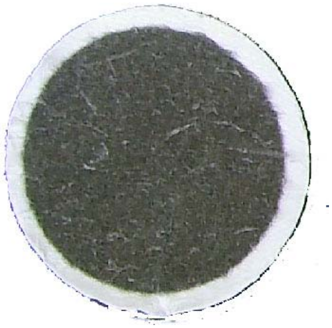
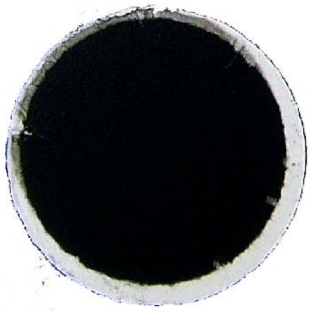


Figure B.5: Fiberglass filters for iron filter (Mode 1-8).

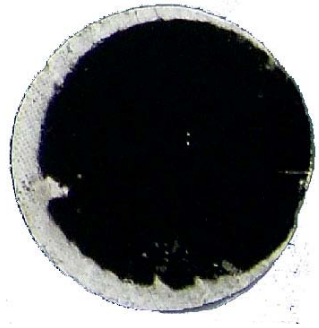


2100 rpm-25%



2600 rpm-100%

2600 rpm-25%

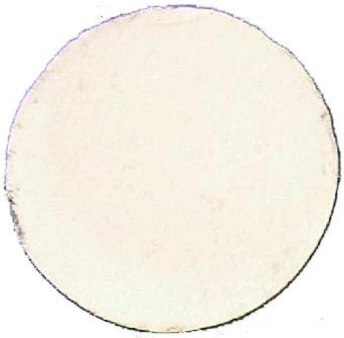


2600 rpm-75%

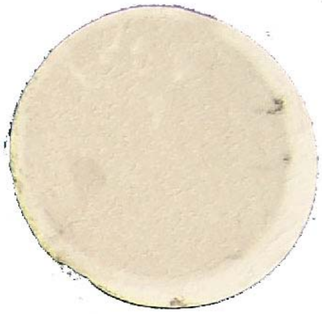
2600 rpm-50%

Figure B.6: Fiberglass filters for iron filter (Mode 9-13).


750 rpm-0%


1600 rpm-100%


2100 rpm-50%


2100 rpm-75%


1600 rpm-50%


1600 rpm-75%


1600 rpm-25%


2100 rpm-100%

Figure B.7: Fiberglass filters for copper-1 filter (Mode 1-8).

2100 rpm-25%

2600 rpm-100%

2600 rpm-25%

2600 rpm-75%

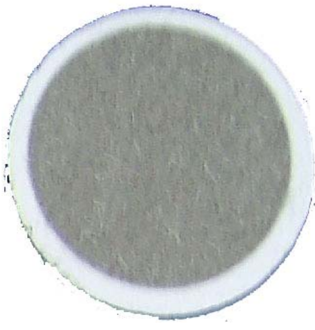
2600 rpm-50%

Figure B.8: Fiberglass filters for copper-1 filter (Mode 9-13).

750 rpm-0%

1600 rpm-100%

2100 rpm-50%



2100 rpm-75%

1600 rpm-50%

1600 rpm-75%

1600 rpm-25%

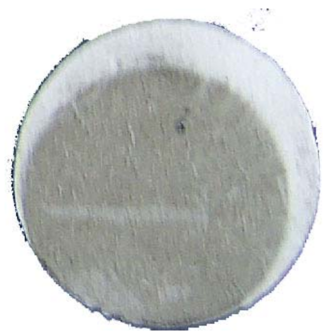
2100 rpm-100%

Figure B.9: Fiberglass filters for copper-2 filter (Mode 1-8).

2100 rpm-25%

2600 rpm-100%

2600 rpm-25%



2600 rpm-75%

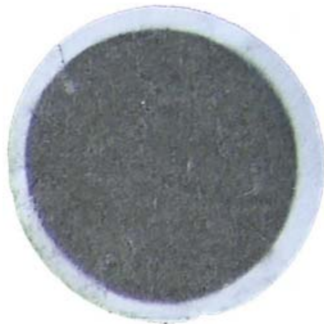
2600 rpm-50%

Figure B.10: Fiberglass filters for copper-2 filter (Mode 9-13).

750 rpm-0%

1600 rpm-100%

2100 rpm-50%



2100 rpm-75%

1600 rpm-50%

1600 rpm-75%

1600 rpm-25%

2100 rpm-100%

Figure B.11: Fiberglass filters for copper-3 filter (Mode 1-8).

2100 rpm-25%

2600 rpm-100%

2600 rpm-25%

2600 rpm-75%

2600 rpm-50%

Figure B.12: Fiberglass filters for copper-3 filter (Mode 9-13).

APPENDIX C

CALIBRATION CURVES

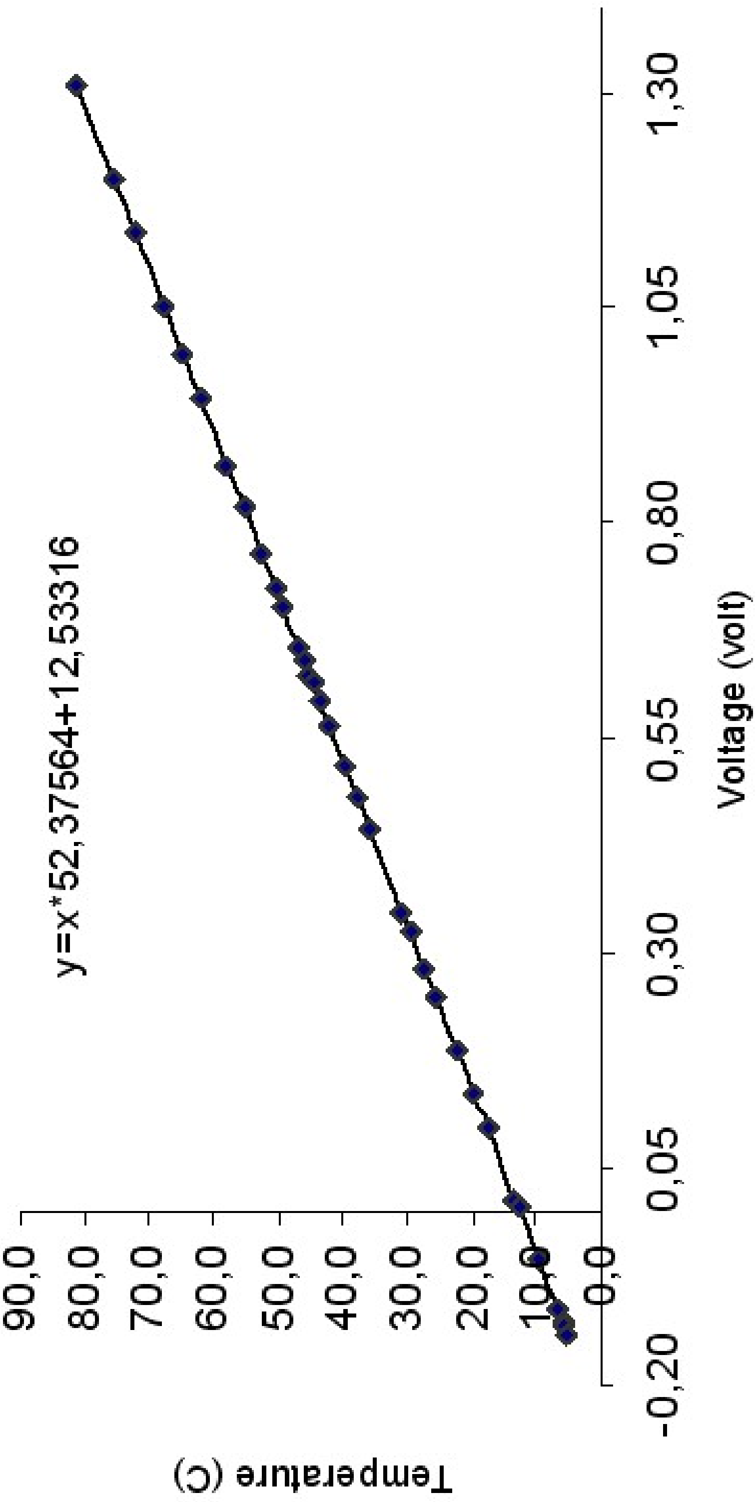


Figure C.1: Calibration curve of the amplifier-1.

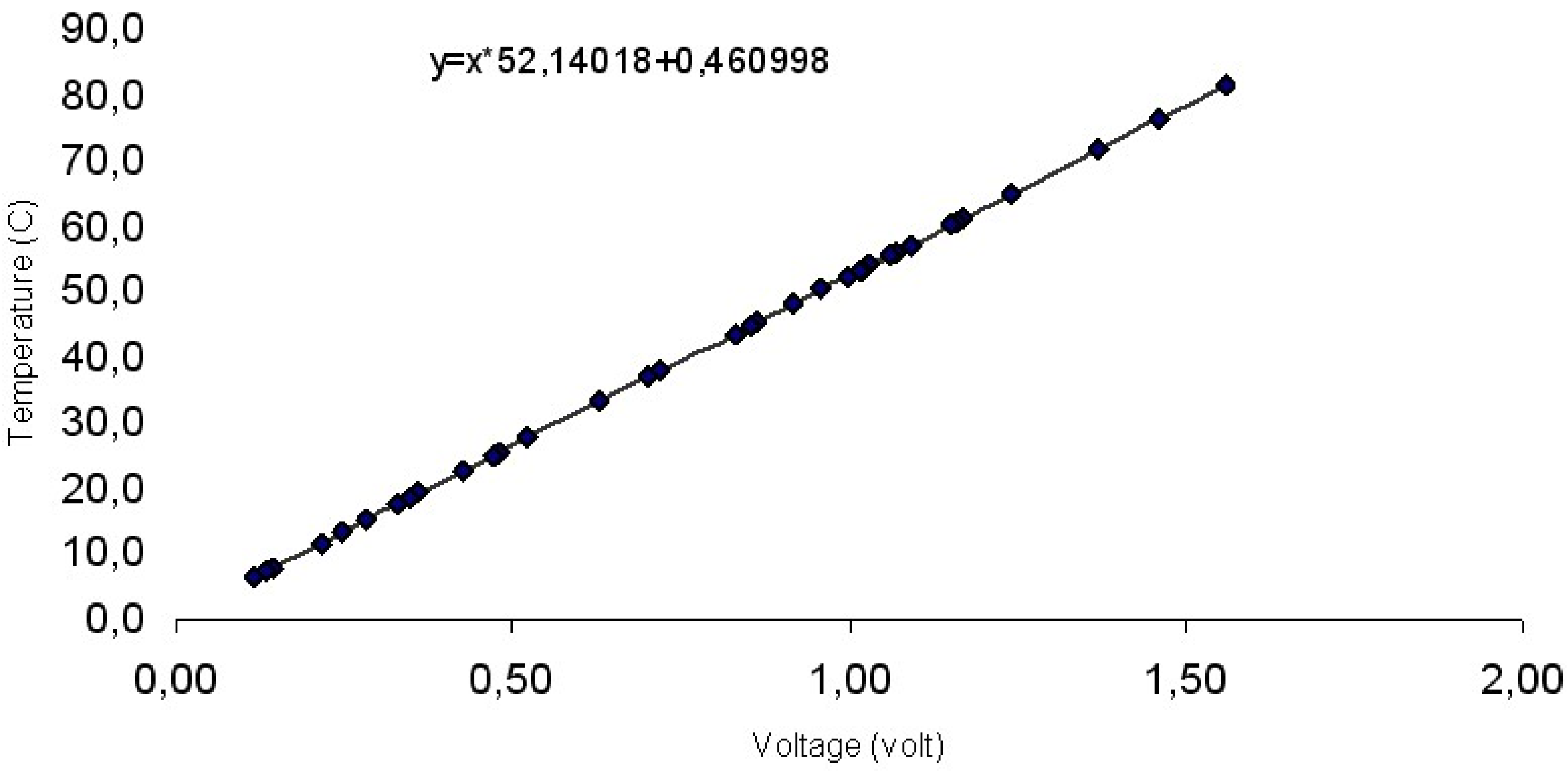


Figure C.2: Calibration curve of the amplifier-2.

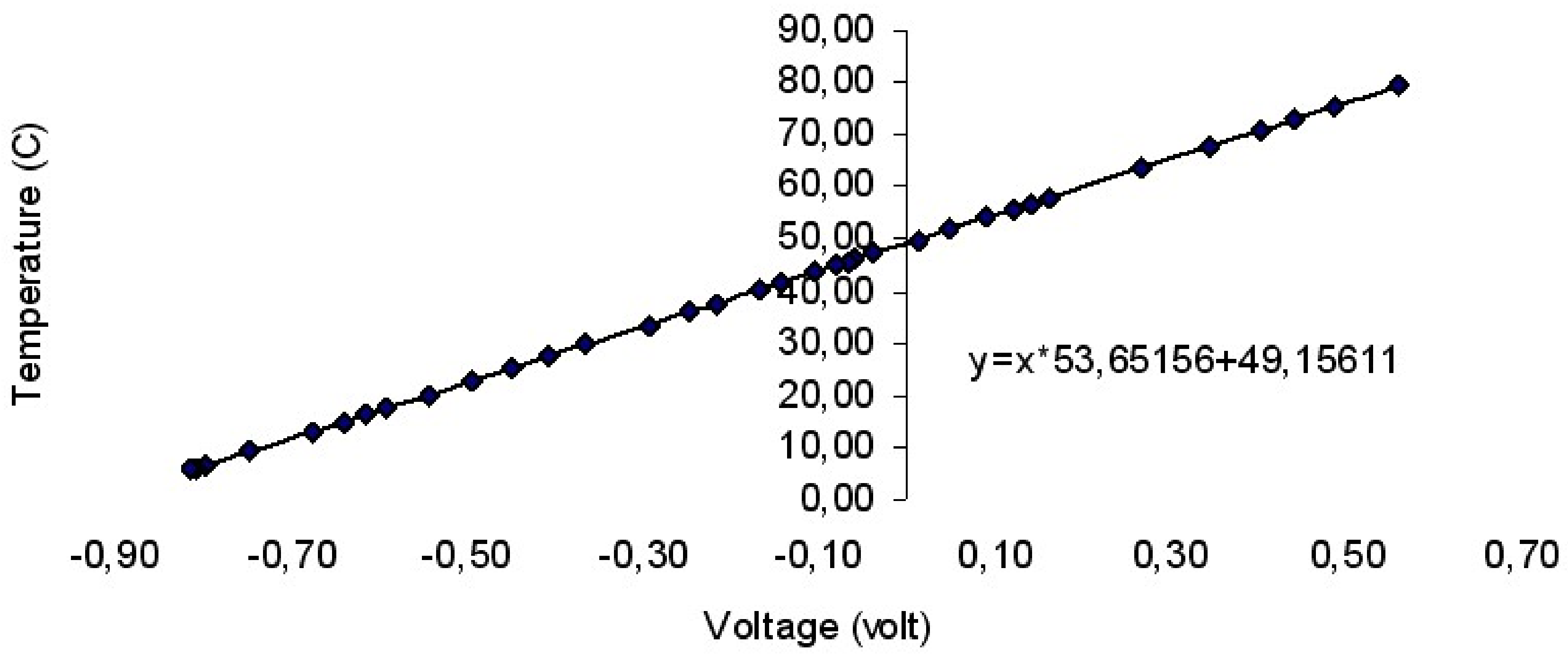


Figure C.3: Calibration curve of the amplifier-3.

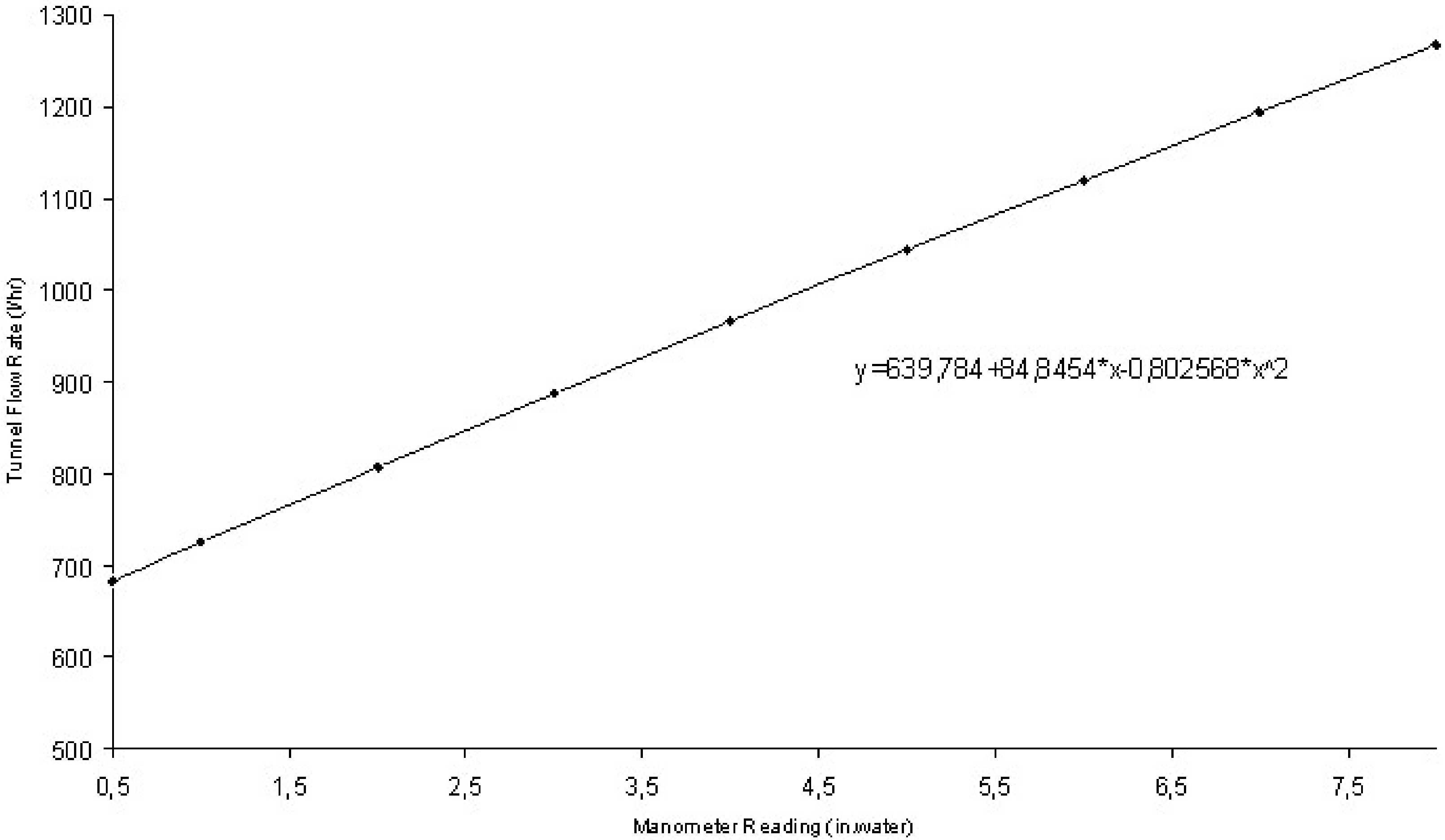


Figure C.4: Calibration Curve of Dilution Tunnel Flow Rate.

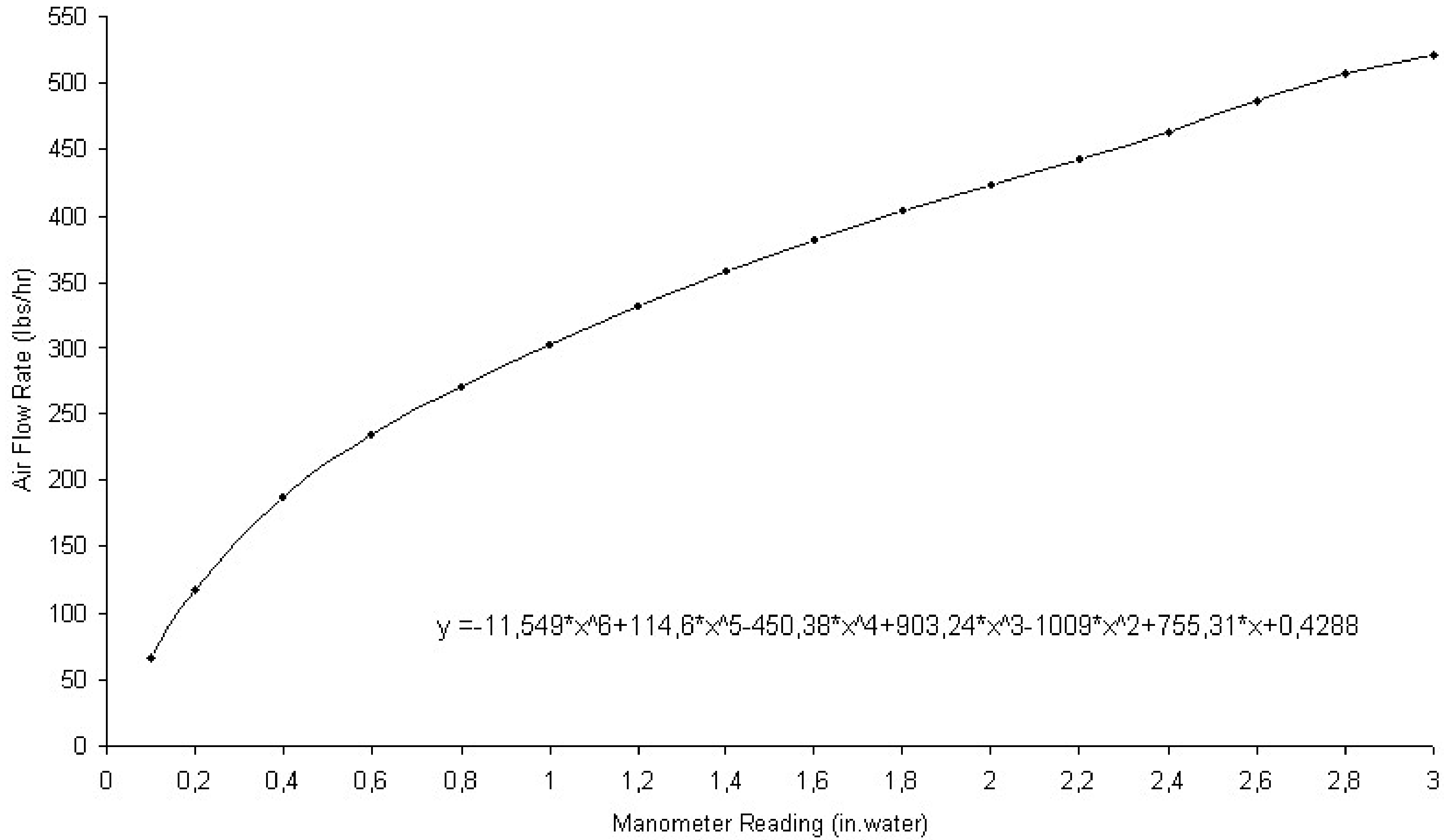


Figure C.5: Calibration Curve of Go Power Air Flow Rate.

APPENDIX D

SAMPLE CALCULATION

Sample calculation is being performed for following data.

Filter Material	: Cu
Ambient Temperature	: 30 ^{0}C
Ambient Relative Humidity	: 56 %
Ambient Pressure	: 738 mmHg
Engine Speed	: 1600 rpm
Dynamometer Reading	: 4.8
Load	: 100 %
Go Power Reading	: 0.86 inWater
Fuel Flow rate	: 2.66 g/s
Backpressure	: 11 mmHg
Tunnel Pressure	: 0.62 inWater
Sampling Rate	: 0.7 scfm
AVL HC	: 5 ppm
AVL Opacity	: 79.3 %
Filter Weight #1	: 201.920 mg
Filter Weight #2	: 202.195 mg
Weight factor	: 8 %
Duration	: 2 minute
Water Vapor Pressure	: 31,82 mmHg (at 30 ^{0}C)

D.1 Brake Power (HP)

$$P_d = P_{atm} - RH \ x \ P_v$$

$$P_d = 738 - 0,56 \ x \ 31,82 \ = 720.2 \text{ mmHg}$$

$$\text{K}_\text{d} = \left(\frac{742.56}{P_d} \right)^{0.65} x \left(\frac{T_{atmK}}{298} \right)^{0.5}$$

$$\text{K}_\text{d} = \left(\frac{742.56}{720.2} \right)^{0.65} x \left(\frac{303}{298} \right)^{0.5} = 1.029$$

$$BP = \frac{Torque \ \text{Re}ading \ x \ N_{speed}}{200} xK_d$$

$$BP = \frac{4.8 \ x \ 1600}{200} x1.029 \ = 39.5 \text{ HP}$$

D.2 Engine Torque (Nm)

$$T = \frac{BP \ x \ 60000}{2 \ x \ \pi \ x \ N_{speed} \ x \ 1.36}$$

$$T = \frac{39.5 \ x \ 60000}{2 \ x \ \pi \ x \ 1600 \ x \ 1.36} = 173.4 \text{ Nm}$$

D.3 Fuel Consumption (kg / h)

Fuel consumption of the engine at measured speed is calculated automatically by the computer program by using the following equation.

$$\dot{m}_{fuel} = \frac{86\ x\ \rho_f\ \ x\ 3.6}{t_f} = 2.66 \text{ g/s} = 9.576 \text{ kg/h}$$

D.4 Brake Specific Fuel Consumption (kg / HP h)

$$BSFC = \frac{\dot{m}_{fuel}\ x\ 3.6}{BP}$$

$$BSFC = \frac{2.66 \times 3.6}{39.5} = 0.242 \text{ kg/HPh}$$

D.5 Air Flow Rate (kg / h)

Air flow rate of the engine is measured by using Go-Power air flow meter device. The manometer readings indicate the pressure difference through the nozzle. These manometer readings are converted into volume floe rate by using the calibration curve.

$$\dot{m}_{air} = -11.549G^6 + 114.6G^5 - 450.38G^4 + 903.24G^3 - 1009G^2 + 755.31G + 0.4288$$

$$\dot{m}_{air} = 127.5 \text{ kg/h}$$

Where G (in-Water) is Go Power reading and $\dot{m}_{air}$ is calculated in Ibs/hr.

D.6 Air / Fuel Ratio

$$A/F = \frac{\dot{m}_{air}}{\dot{m}_{fuel}}$$

$$A/F = \frac{127.5}{9.576} = 13.32$$

D.7 Excess Air Coefficient

$$\lambda = \frac{(A/F)}{(A/F)_{stc}}$$

$$\lambda = \frac{13.32}{14.389} = 0.93$$

$$\Phi = 1/\lambda$$

$$\Phi = 1/0.93 = 1.08$$

D.8. Volumetric Efficiency (%)

$$\rho_{std} = \frac{P_{std}}{R_{std}\ x\ T_{std}}$$

$$\rho_{std} = \frac{101.325}{0.287\ x\ 293} = 1.205$$

$$V_s = \frac{\pi\ x\ D^2\ x\ S}{4}$$

$$\mathrm{V_s} = \frac{\pi \ x \ 0.104^2 \ x \ 0.115}{4} = 9.76 \text{ x } 10^{-4} \text{ m}^3$$

$$\dot{m}_{ath} = \frac{\rho_{std} \ x \ V_s \ x \ N_{speed} \ x \ i \ x \ 2}{j x 60}$$

$$\dot{m}_{ath} = \frac{1.205 \ x \ (9.76 \text{ x } 10^{-4}) \ x \ 1600 \ x \ 4 \ x \ 2}{4 x 60} = 225.9 \text{ kg/h}$$

$$\eta_v = \frac{\dot{m}_{air}}{\dot{m}_{ath}}$$

$$\eta_v = \frac{127.5}{225.9} = 0.5645 = 56.5 \ \%$$

D.9. Thermal Efficiency (%)

$$\eta_{th} = \frac{BP x 1000}{Q_c \ x \ \dot{m}_{fuel} \ x \ 1.36}$$

$$\eta_{th} = \frac{39.5 x 1000}{42000 \ x \ 9.576 \ x \ 1.36} = 0.26 = 26 \ \%$$

D.10. Dilution Ratio (%)

$$Q_{exh} = Q_{air} + 770 Q_{fuel}$$

$$Q_{exh} = 127.5 + 770 x 9.576 / 1000 = 107.9 \text{ m}^3\text{/h}$$

$$Q_{exd} = Q_{air} - 750Q_{fuel}$$

$$Q_{exd} = 127.5 - 750x9.576/1000 = 103.8 \text{ m}^3\text{/h}$$

$$Q_{se} = Q_{exh}\left(\frac{D_{se}}{D_{exh}}\right)^2$$

$$Q_{se} = 107.9x\left(\frac{13}{60}\right)^2 = 5.1 \text{ m}^3\text{/h}$$

$$Q_{dt} = 639,784 + 84,8454P_{dt} - 0,802568P_{dt}{}^2$$

$$Q_{dt} = (639,784 + 84,8454x0.62 - 0,802568x0.62\,\hat{}\,2)x60/1000$$

$$Q_{dt} = 41.5 \text{ m}^3\text{/h}$$

$$DR = (Q_{se}/Q_{dt})x100$$

$$DR = (5.1/41.5)x100 = 12.2\ \%$$

D.11 Particulate Emissions (g/HPh)

$$M_p = \frac{m_p \text{ x } Q_{\text{exh}} \text{ x } 100 / \text{DR}}{Q_{vp} \text{ x } t_s \text{ x BP}}$$

$$M_p = \frac{(0.275/1000) \text{ x } 107.9 \text{ x } 100/12.2}{(0.7 \text{ x } 28.317 \text{ x } 60/1000) \text{ x } (2/60) \text{ x } 39.5} = 0.2 \text{ g/HPh}$$

D.12 Gas Emissions (g/HPh)

$$M_{THC} = \frac{Q_{exd} \text{ x } \rho_{\mathrm{HC}} \text{ x } \mathrm{C}_{\mathrm{HC}} \text{ x } 10^{-3}}{BP}$$

$$M_{THC} = \frac{103.8 \text{ x } 0.619 \text{ x } 5 \text{ x } 10^{-3}}{39.5}$$

M_{THC} = 0.008 g/HPh

Weight factor defined in the ESC test procedure for this mode (2. test mode) is 8 %.

Therefore particulate emissions, fuel consumption and HC emissions are:

$M_{p\text{-}av}$ = 0.08 x 0.2 = 0.016 g/HPh

$M_{fuel\text{-}av}$ = 0.08 x 0.242 = 0.0194 kg/HPh

$M_{HC\text{-}av}$ = 0.08 x 0.008 = 0.00064 g/HPh

APPENDIX E

TECHNICAL DRAWINGS

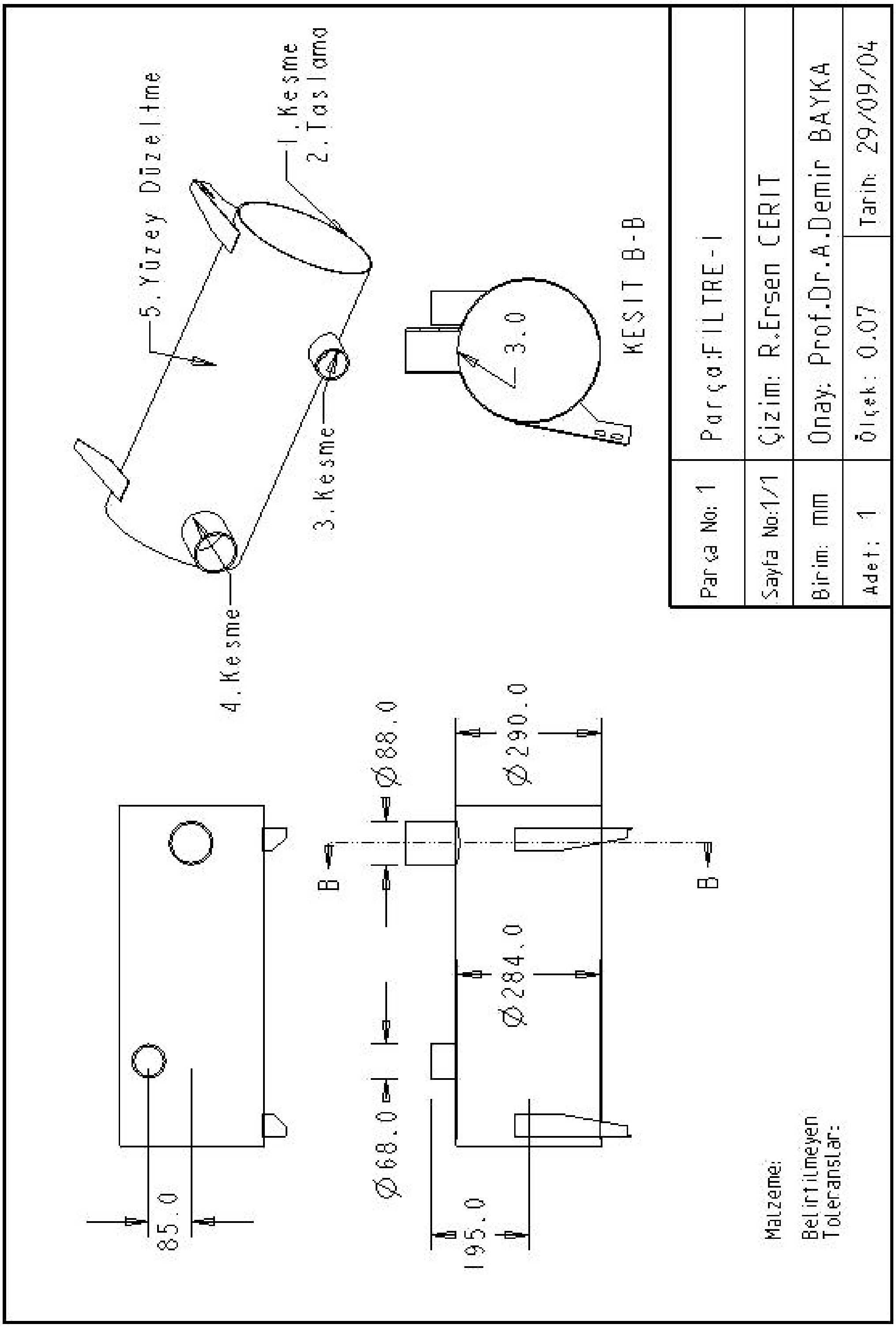


Figure E.1: Technical Drawing of Silencer Structure.

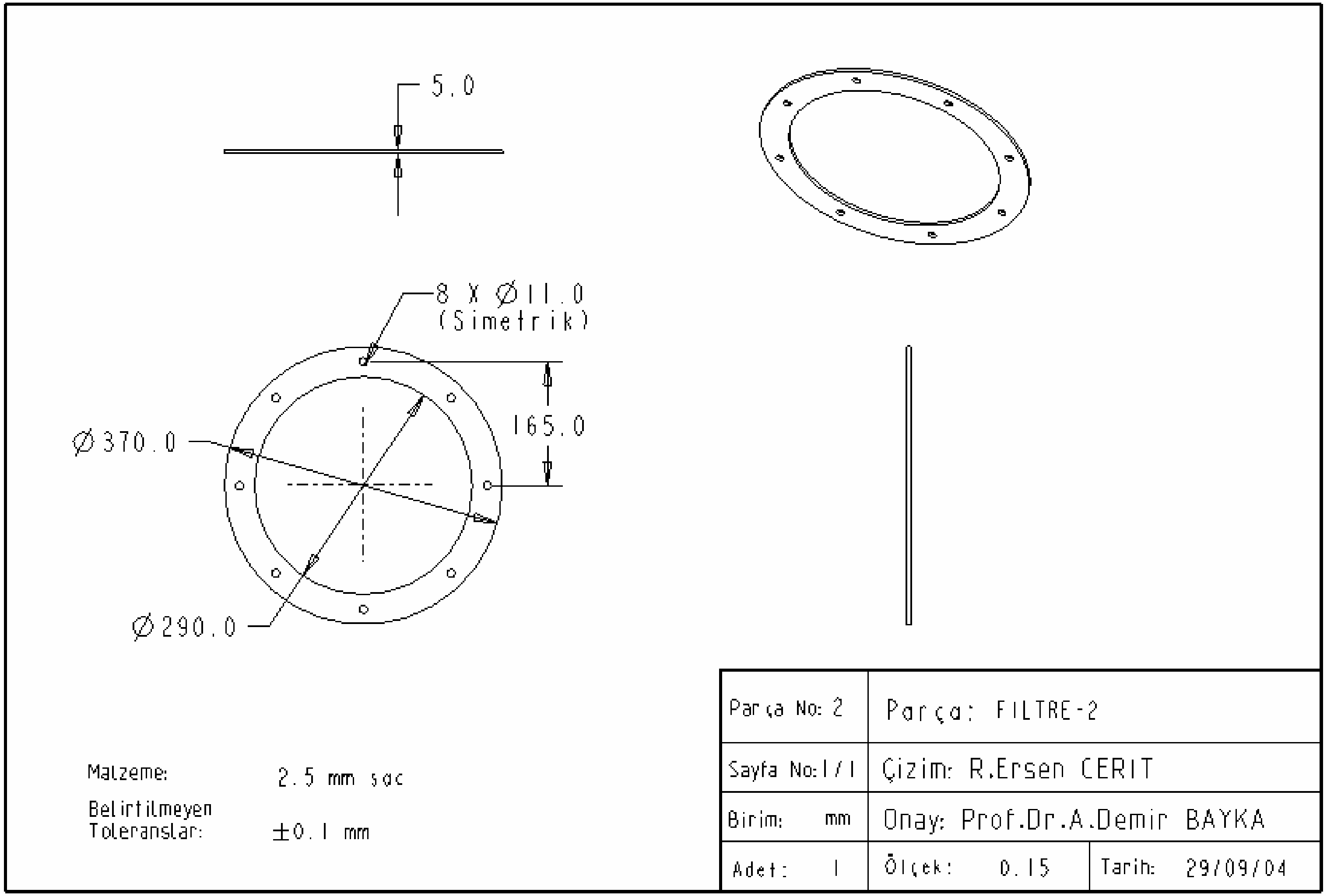


Figure E.2: Technical Drawing of Silencer Flange.

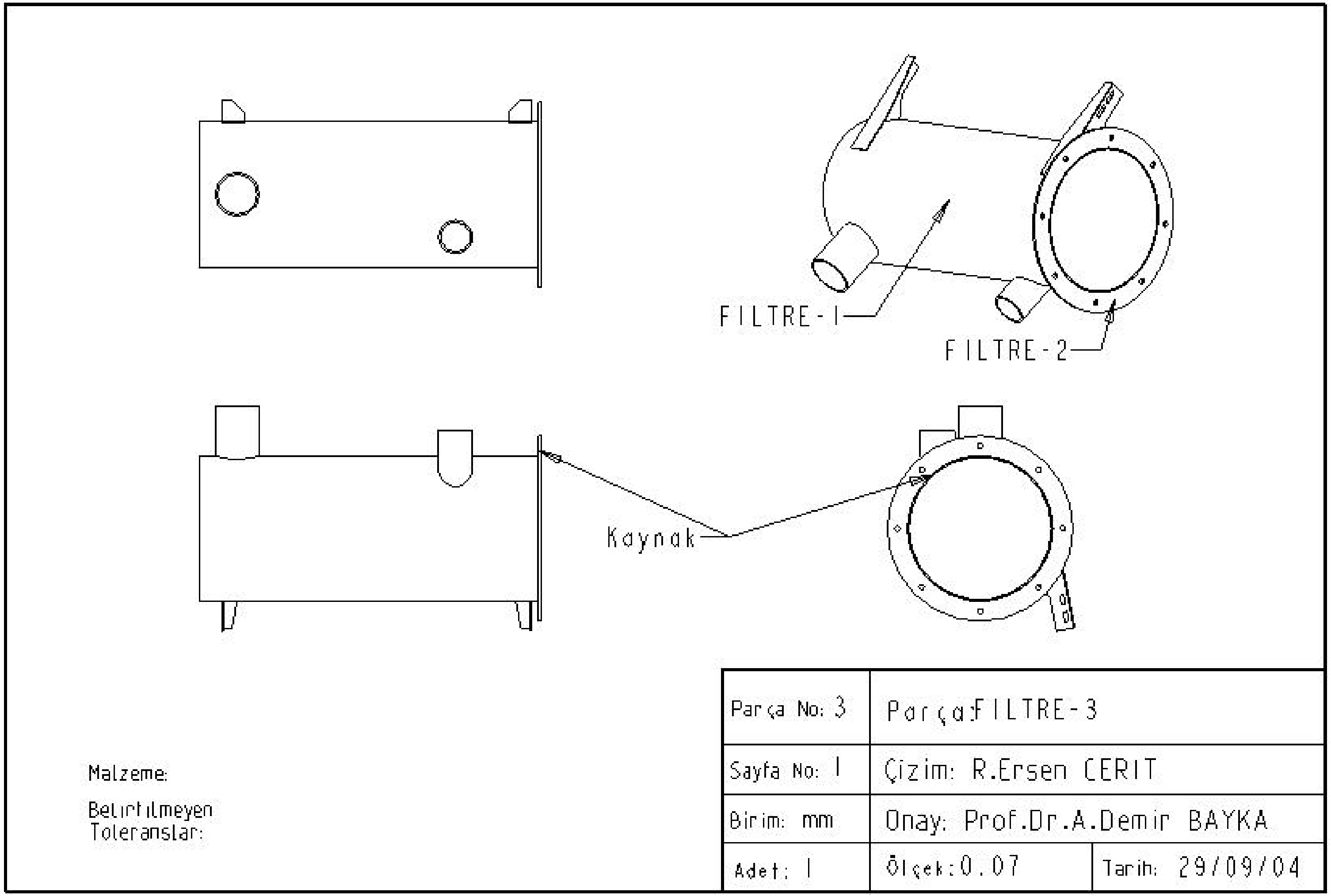


Figure E.3: Technical Drawing of Welded Silencer.

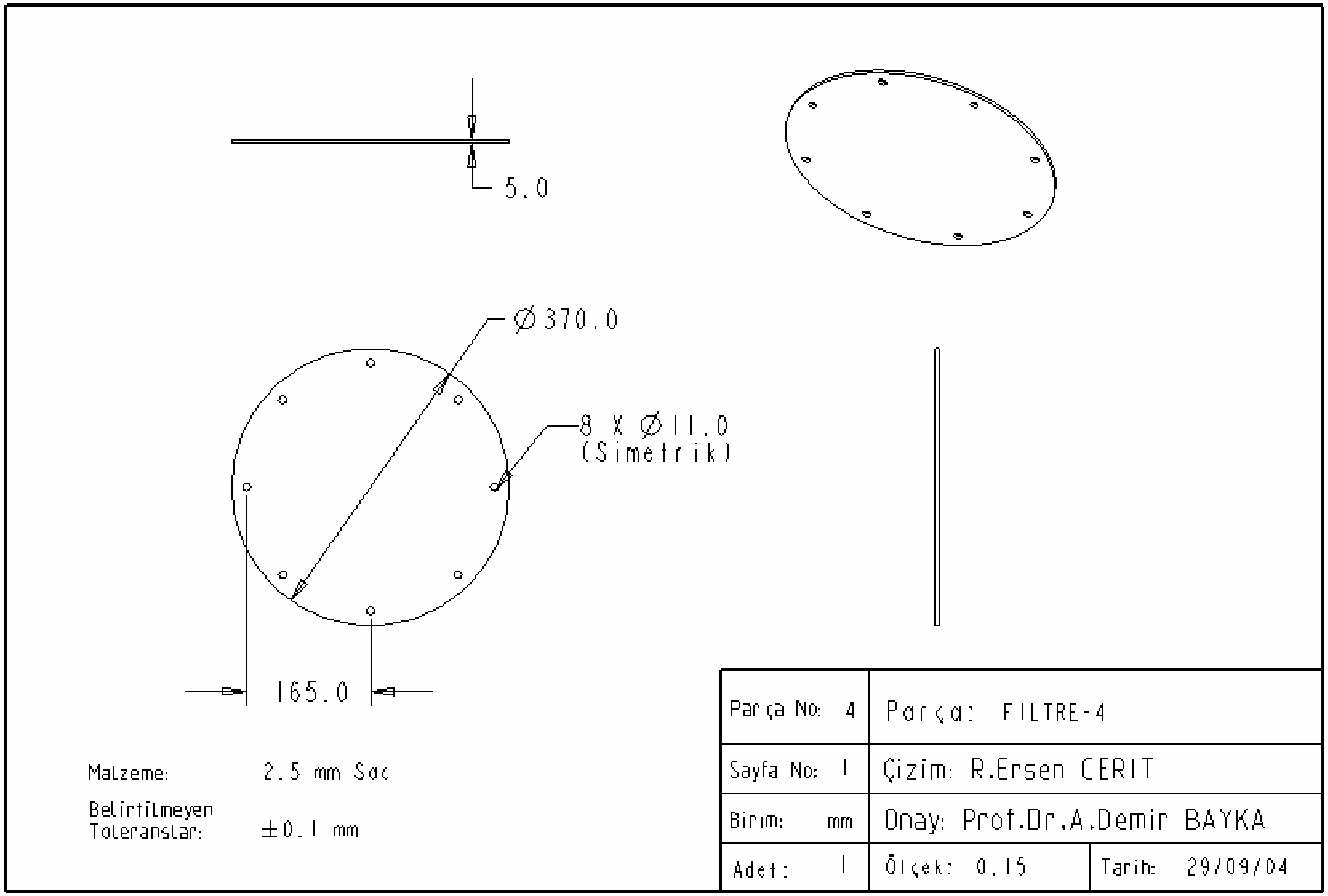


Figure E.4: Technical Drawing of Silencer Cover.

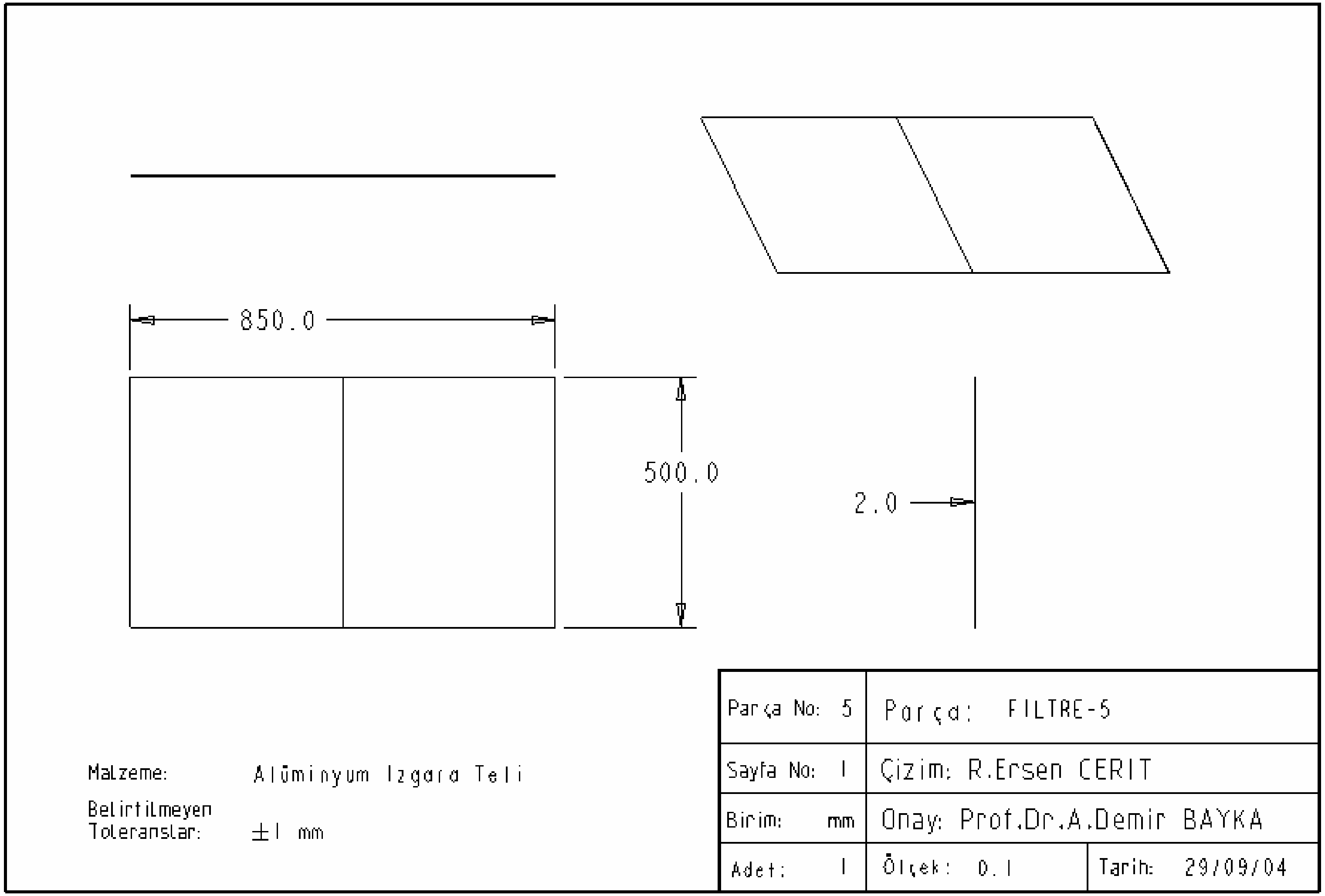


Figure E.5: Technical Drawing of Aluminum Wire Sheet

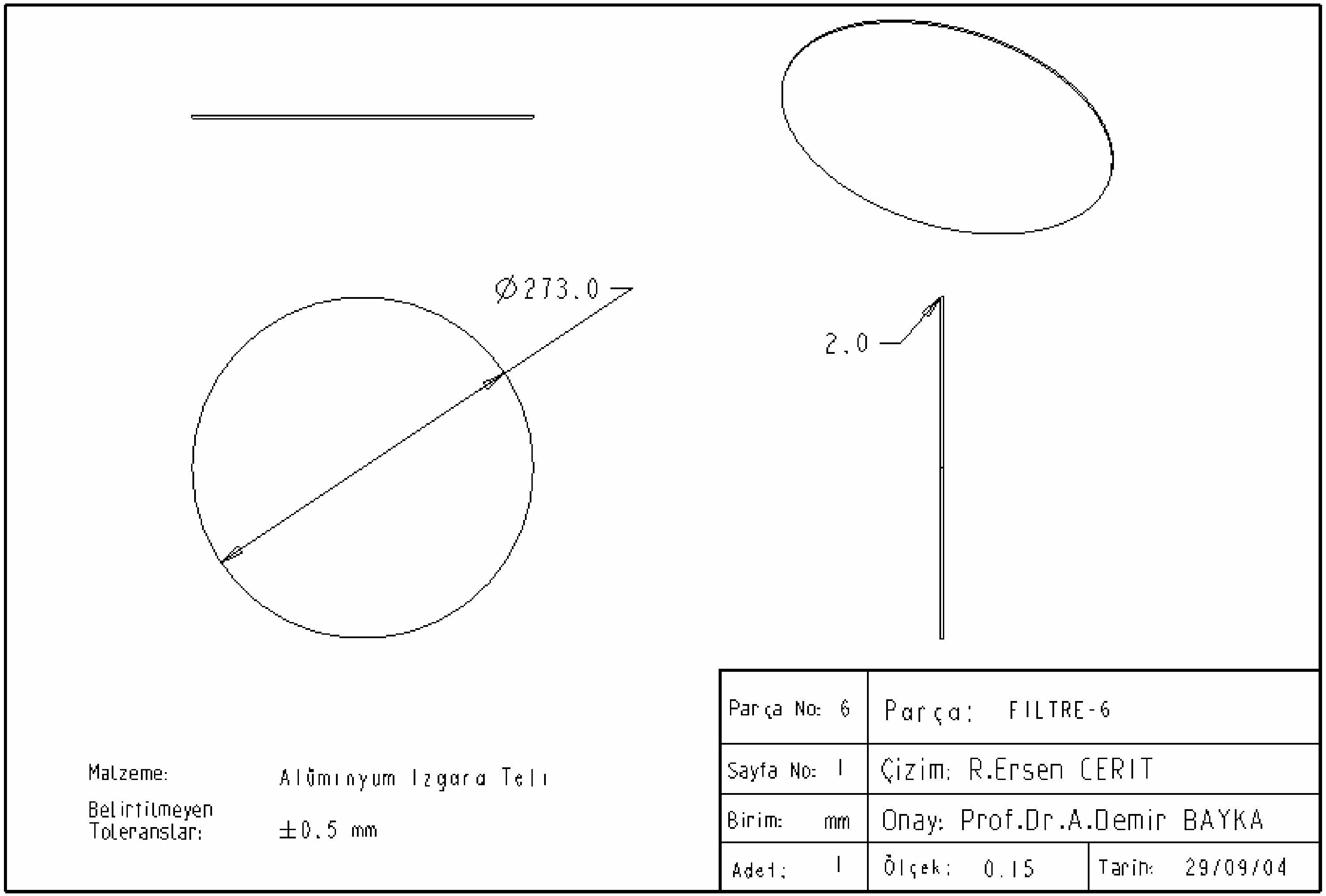


Figure E.6: Technical Drawing of Aluminum Wire Cover.

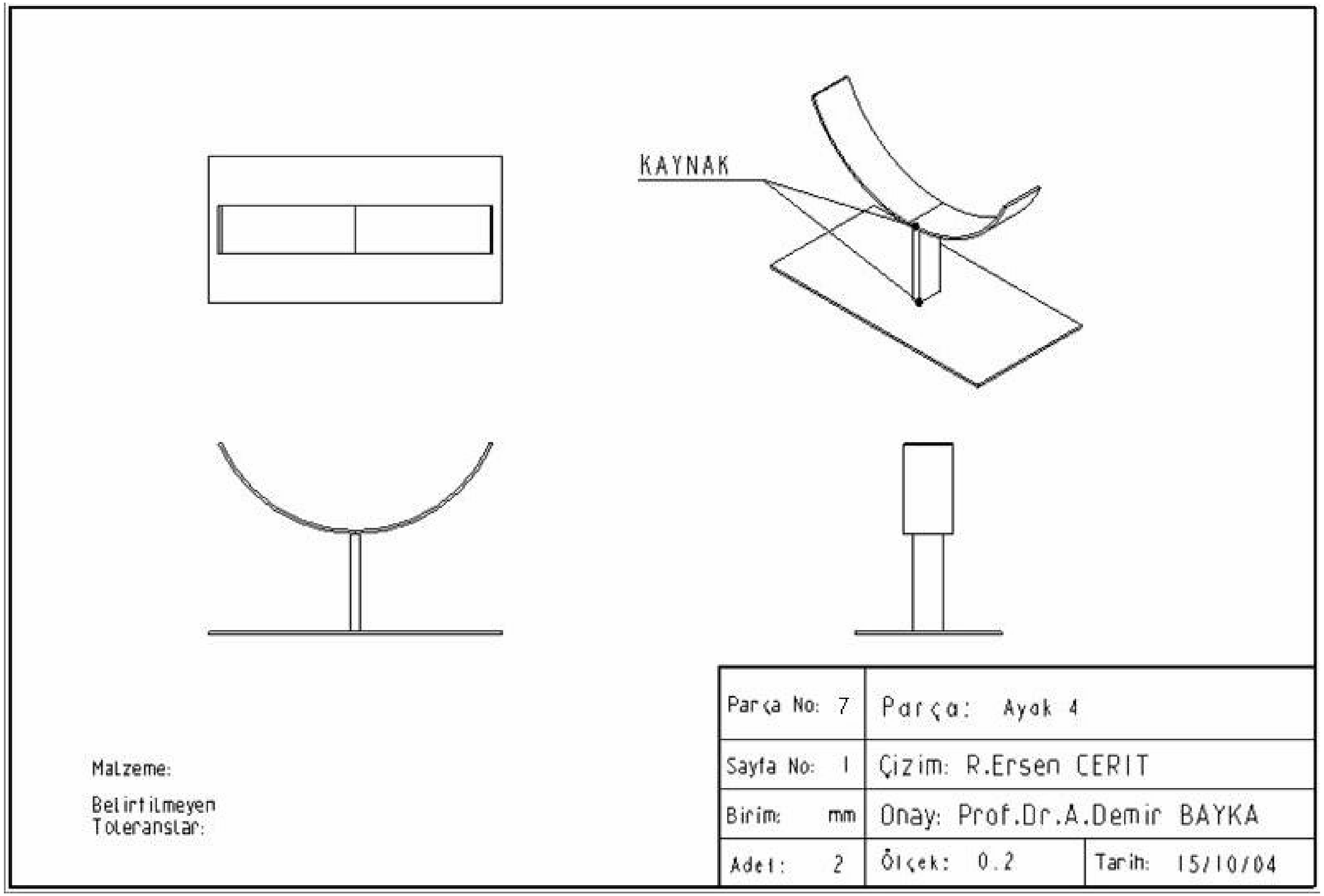


Figure E.7: Technical Drawing of Silencer Support.

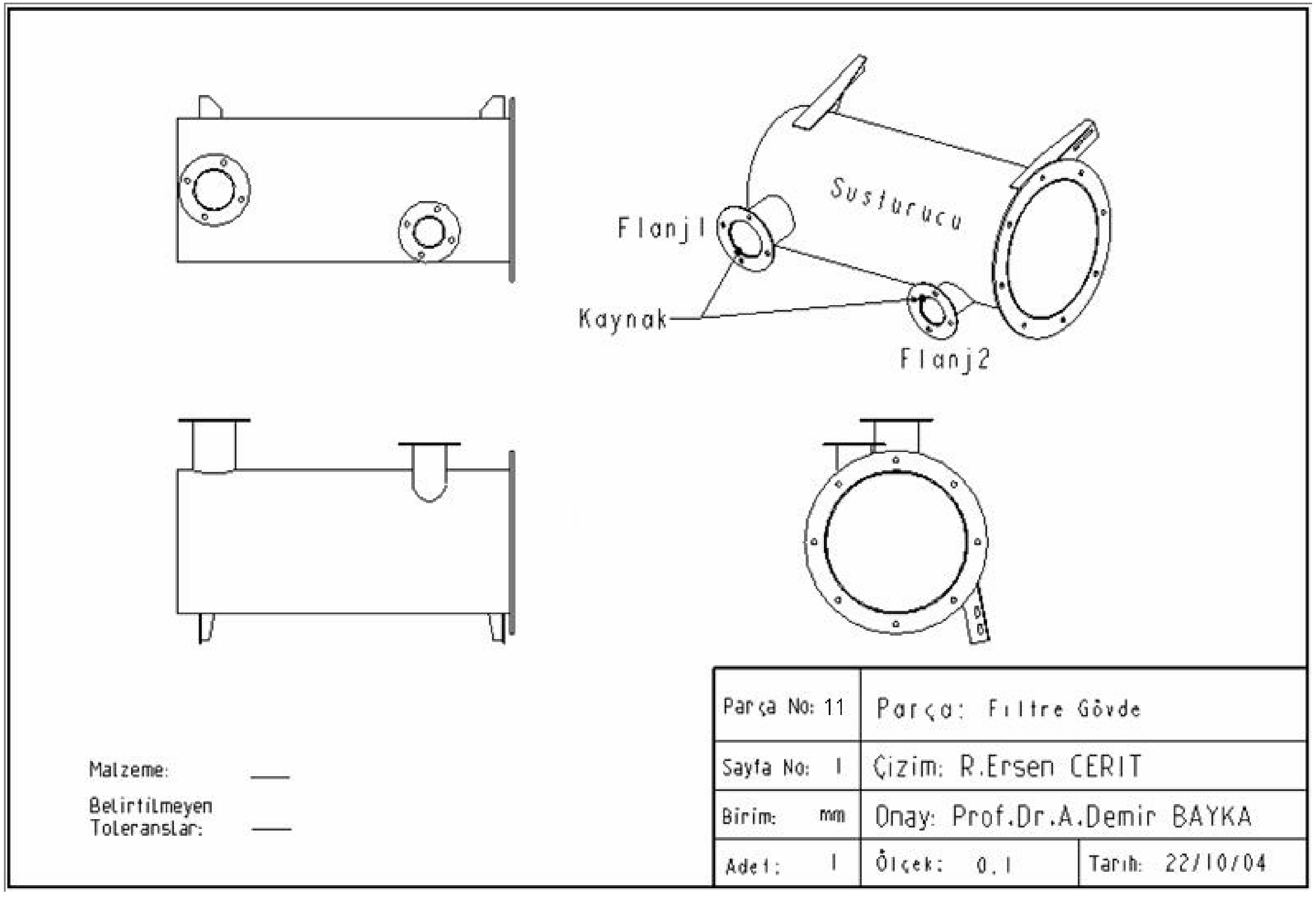


Figure E.8: Technical Drawing of Welded Silencer with Flanges.

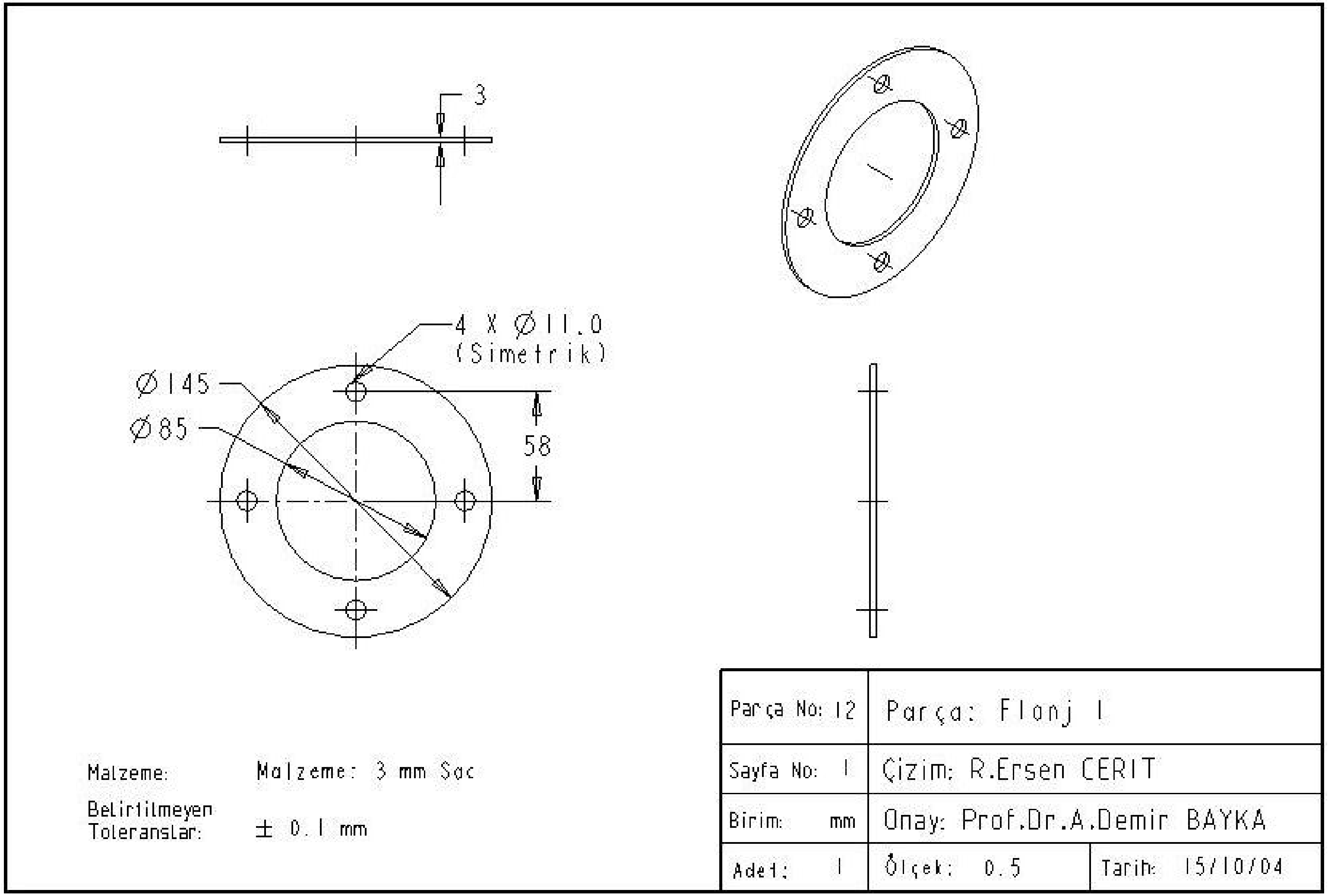


Figure E.9: Technical Drawing of Silencer Flange-1.

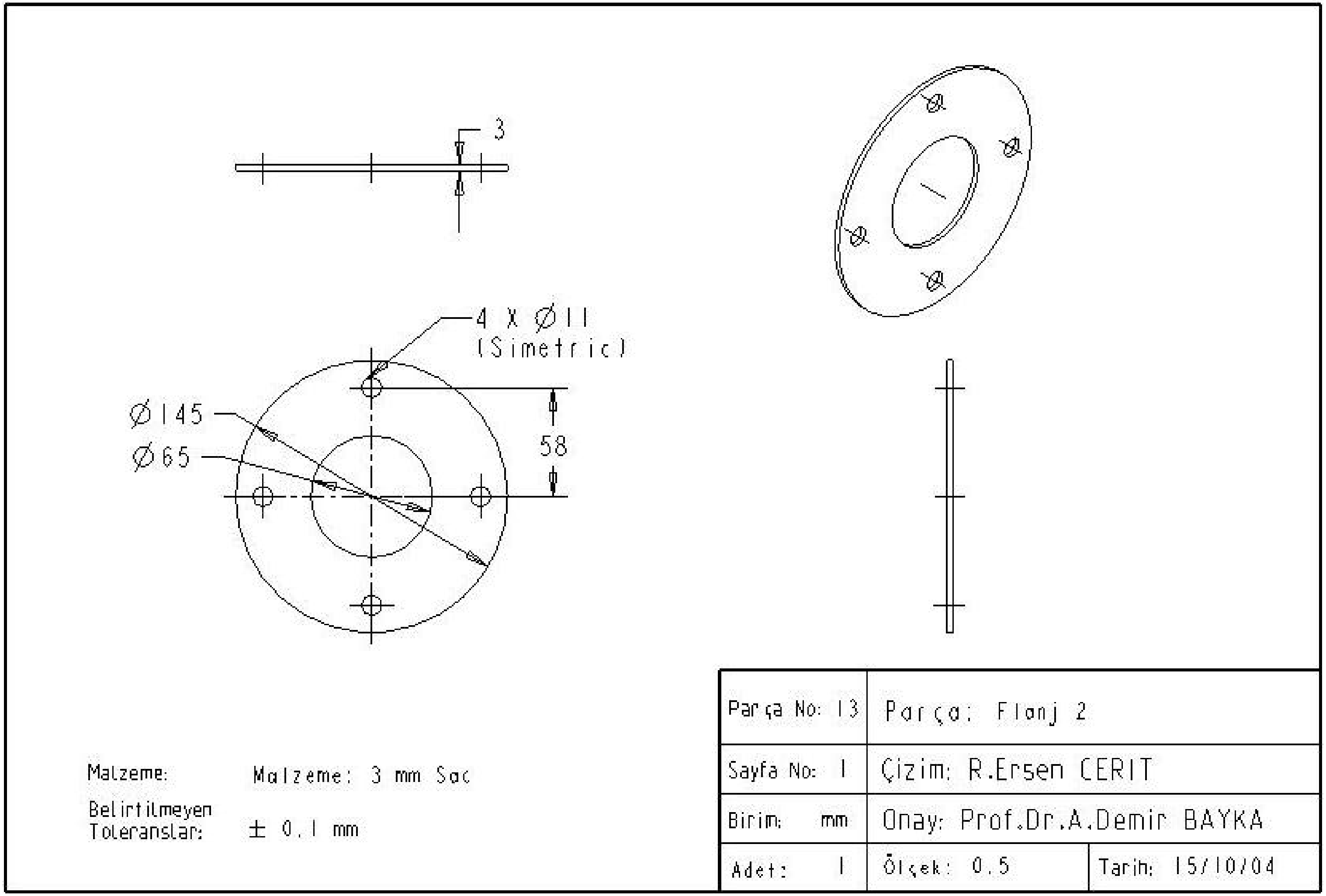


Figure E.10: Technical Drawing of Silencer Flange-2.

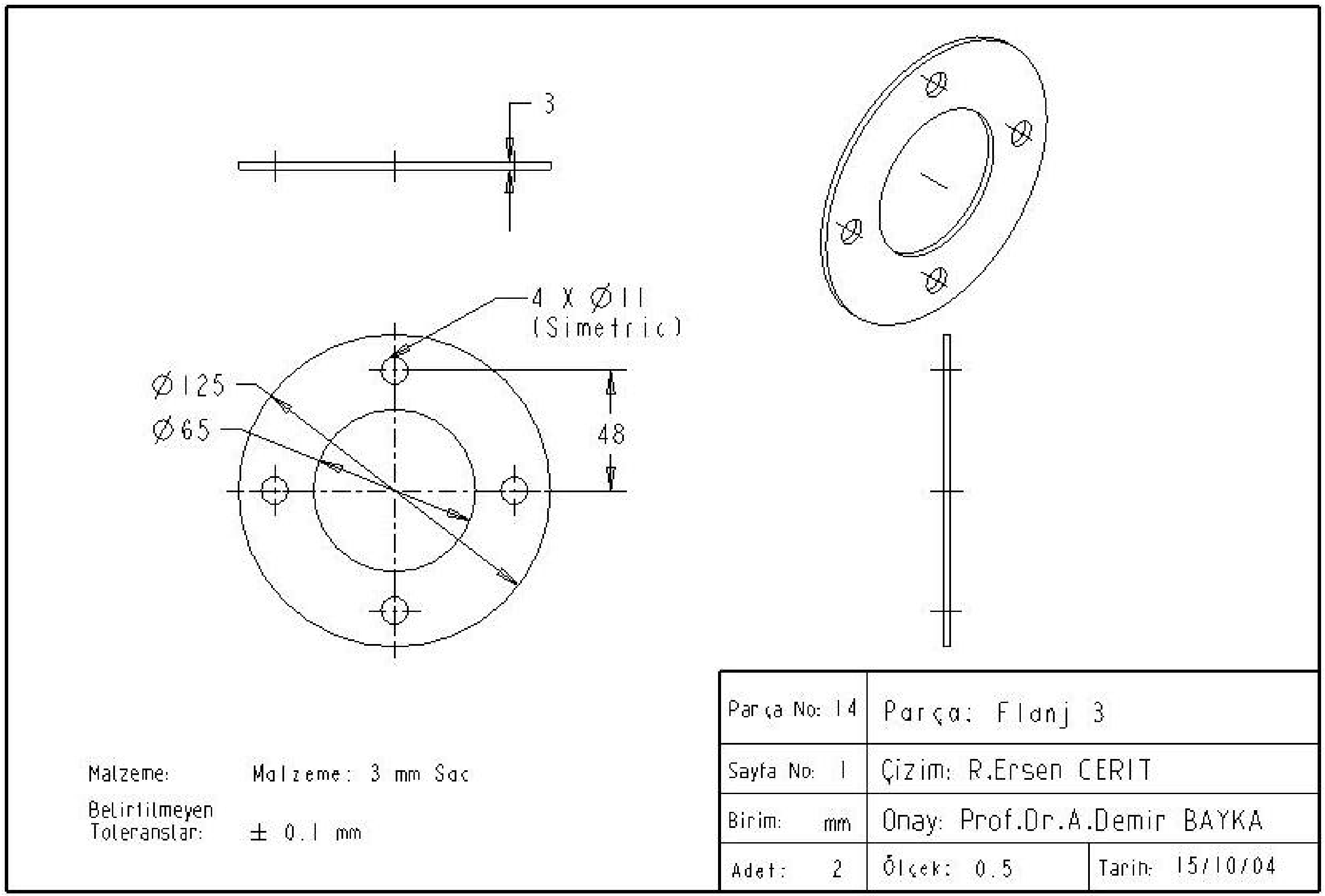


Figure E.11: Technical Drawing of Silencer Flange-3.

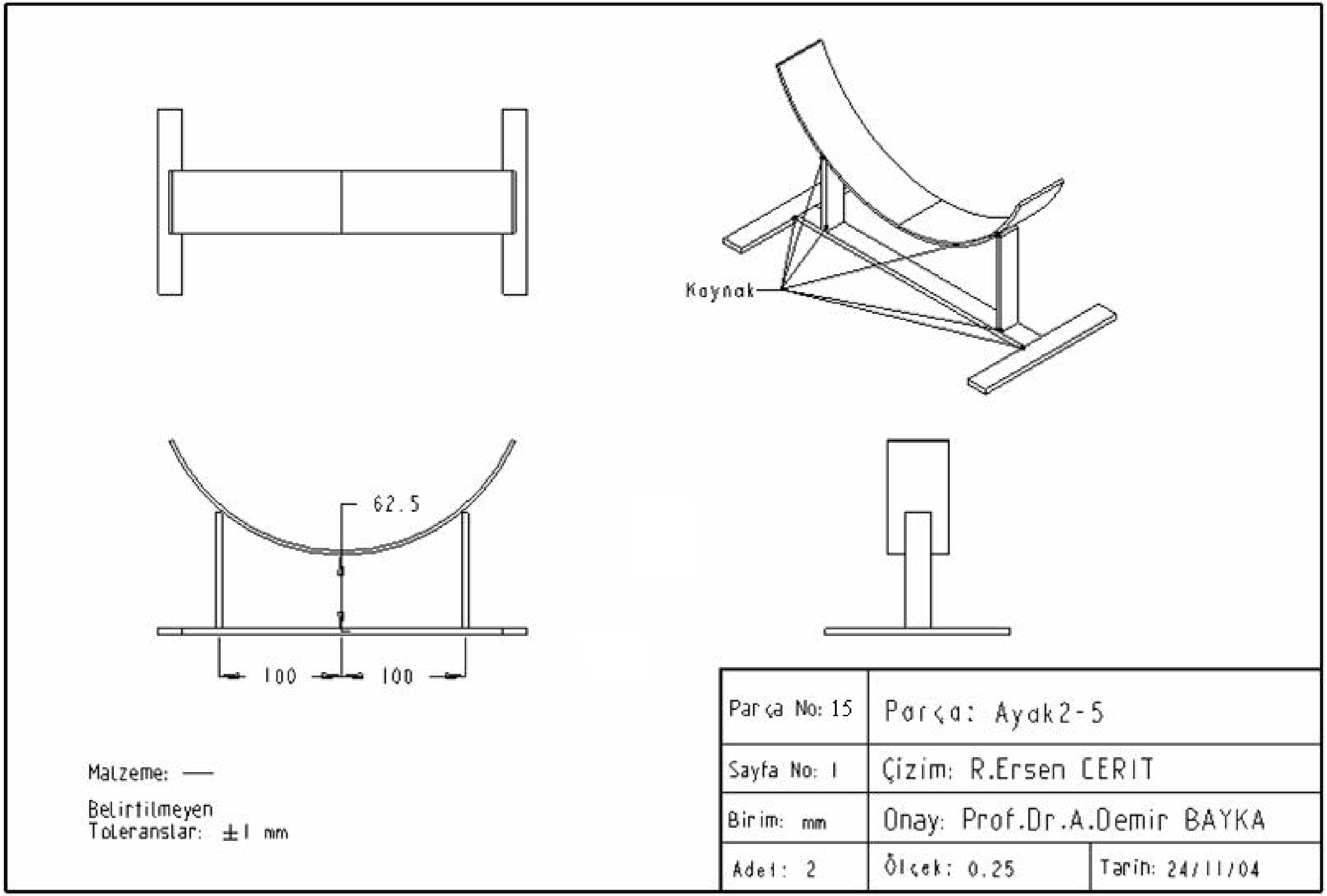


Figure E.12: Technical Drawing of Silencer Support-2

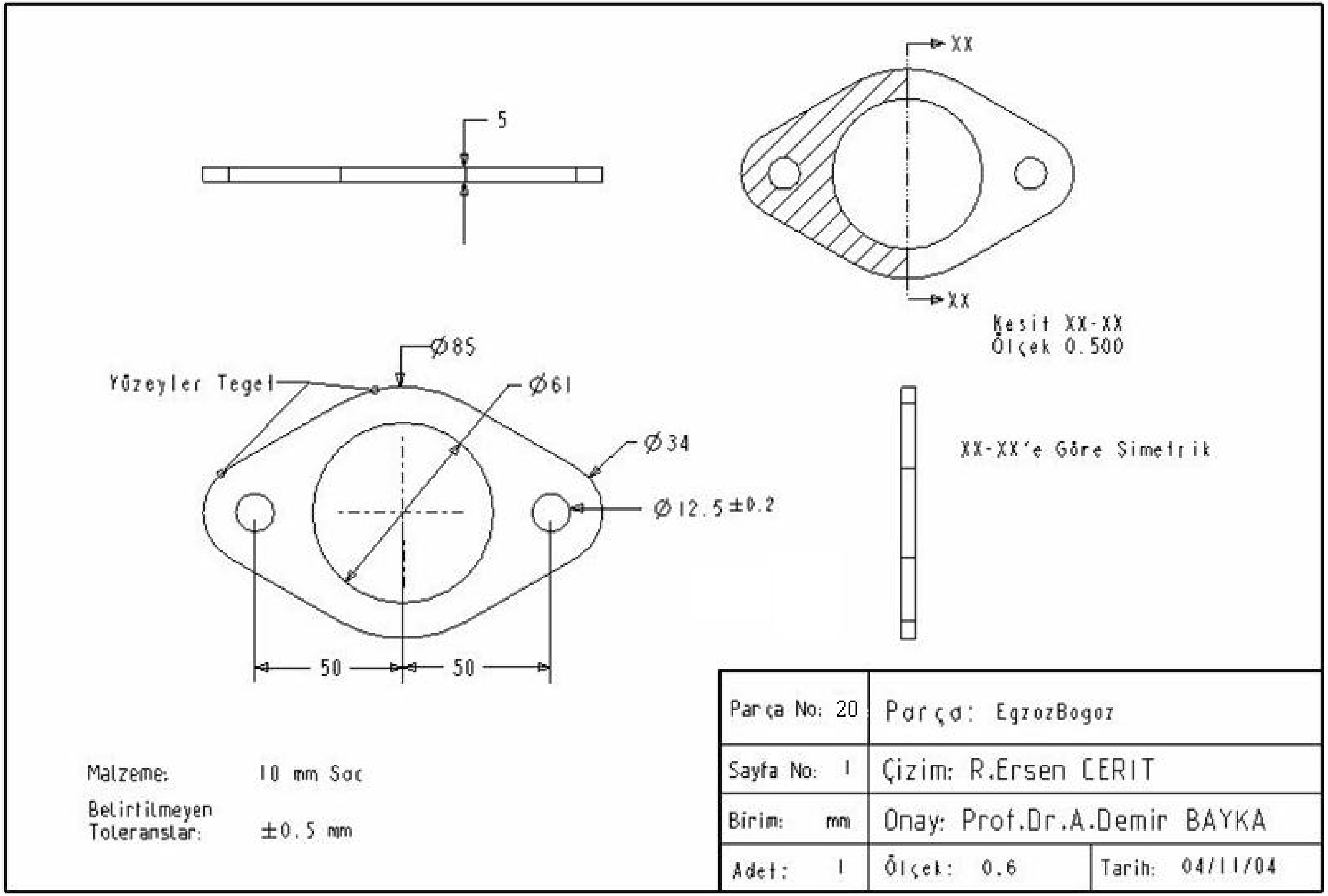


Figure E.13: Technical Drawing of Exhaust Pipe Flange.

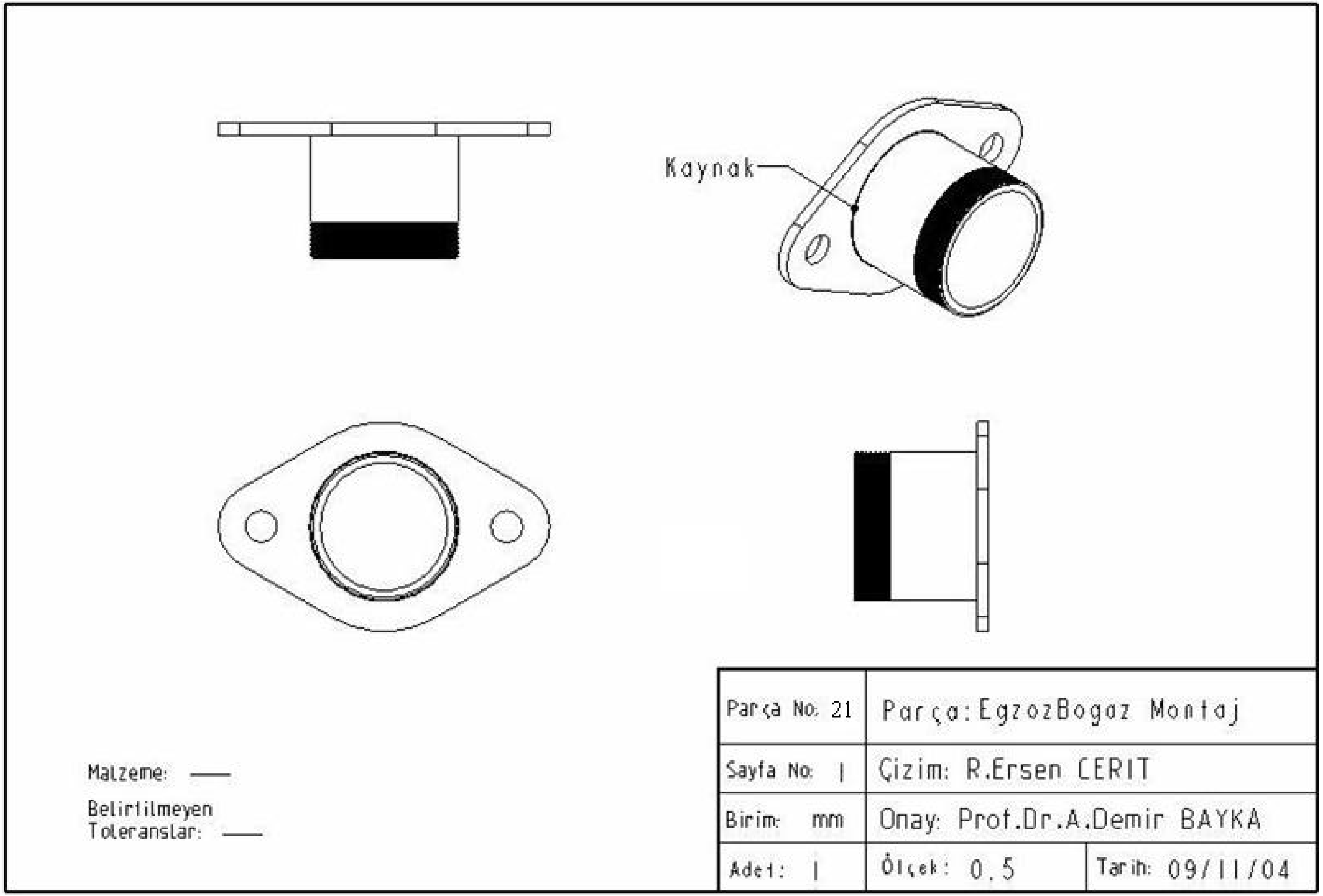


Figure E.14: Technical Drawing of Exhaust Pipe Connection.

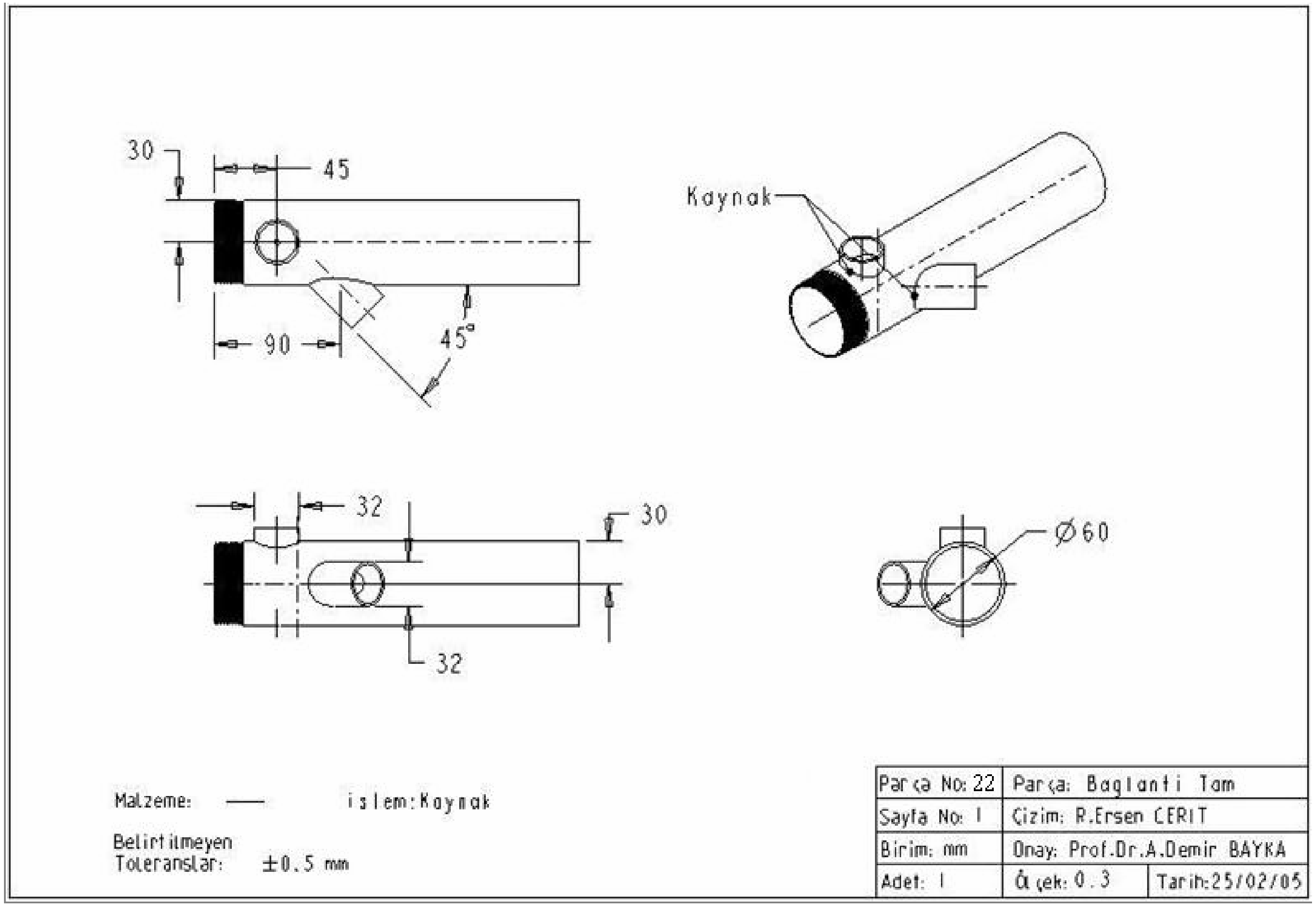


Figure E.15: Technical Drawing of ISP Connection.

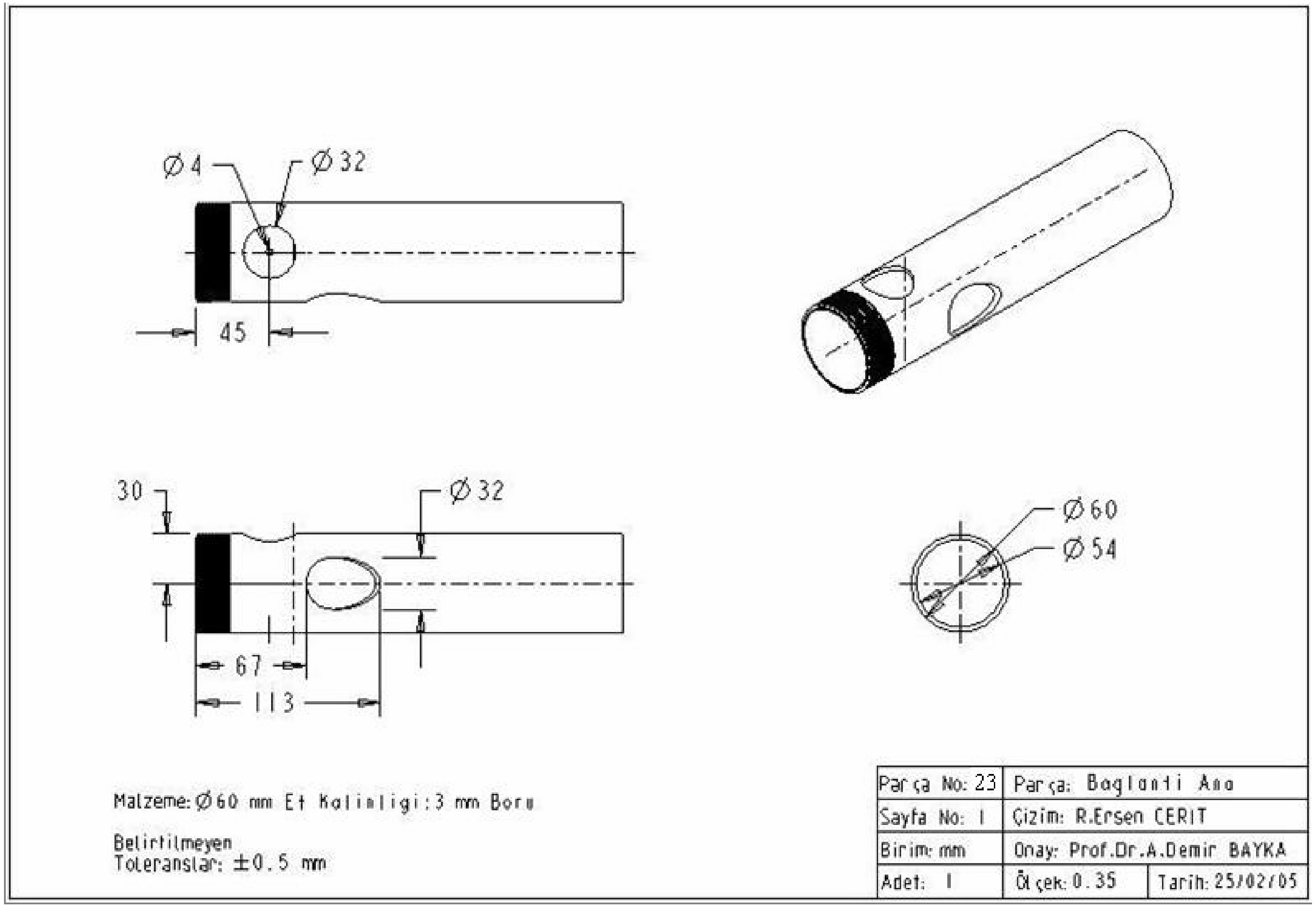


Figure E.16: Technical Drawing of ISP Pipe-1.

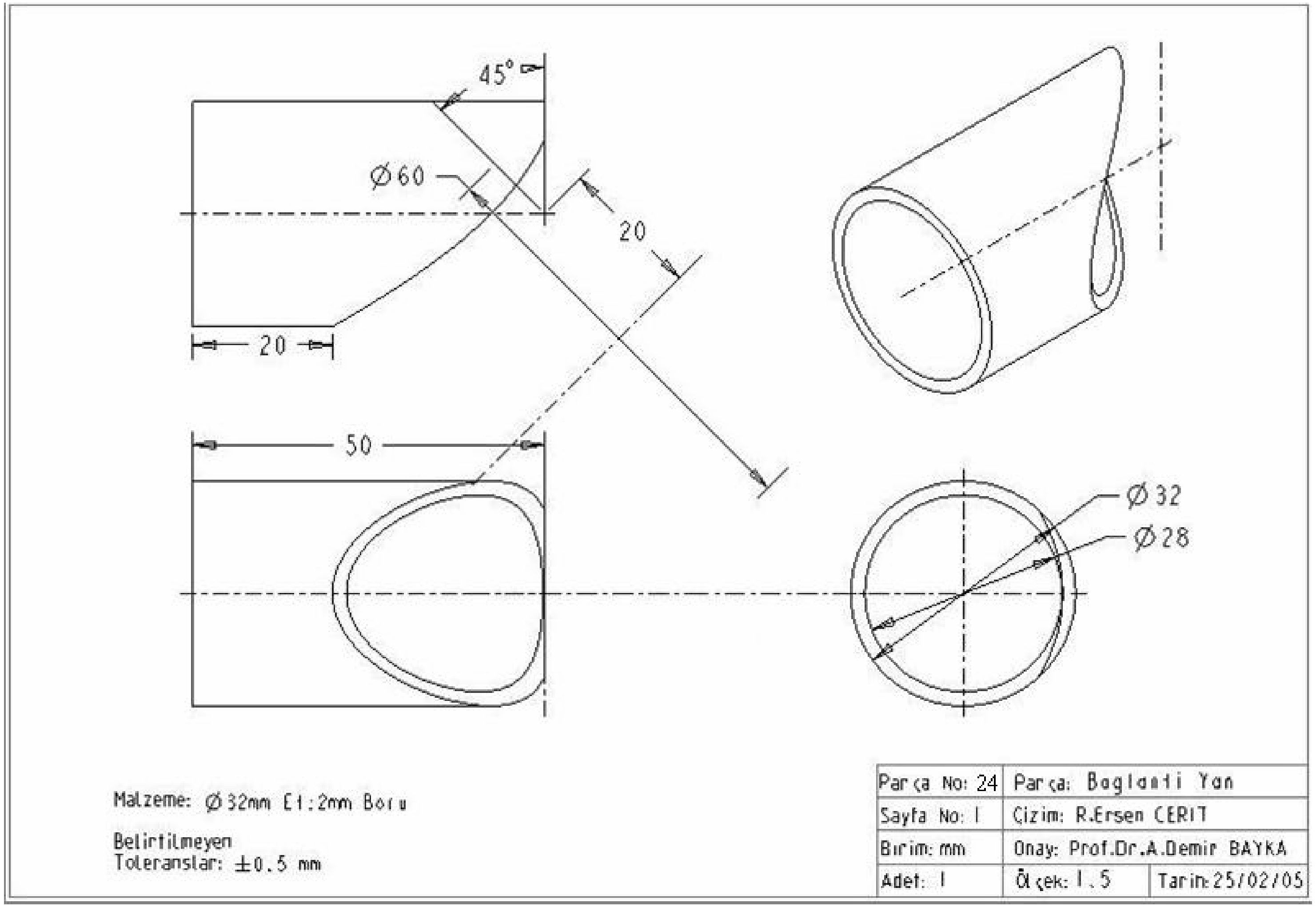


Figure E.17: Technical Drawing of ISP Pipe-2.

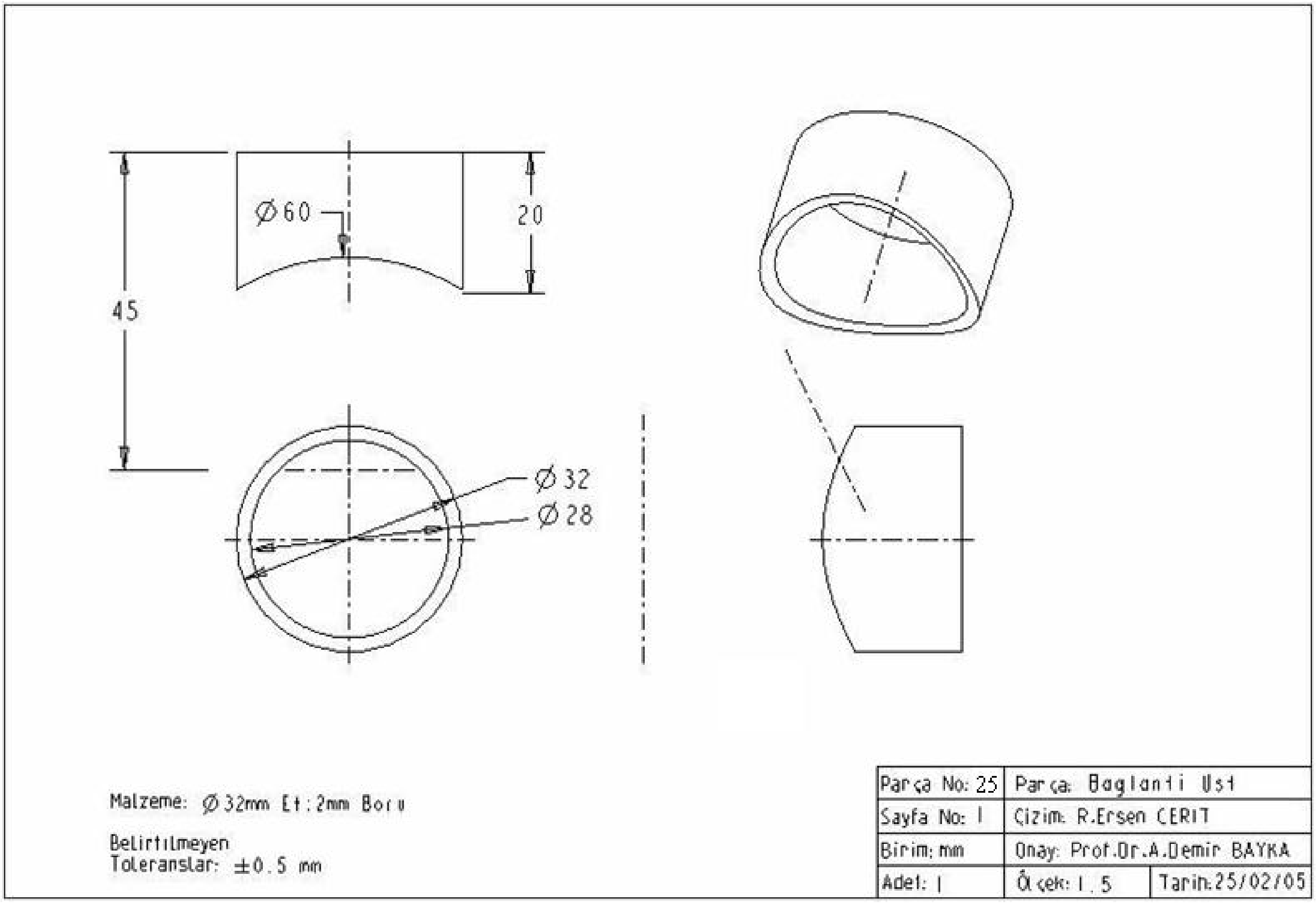


Figure E.18: Technical Drawing of ISP Pipe-3.

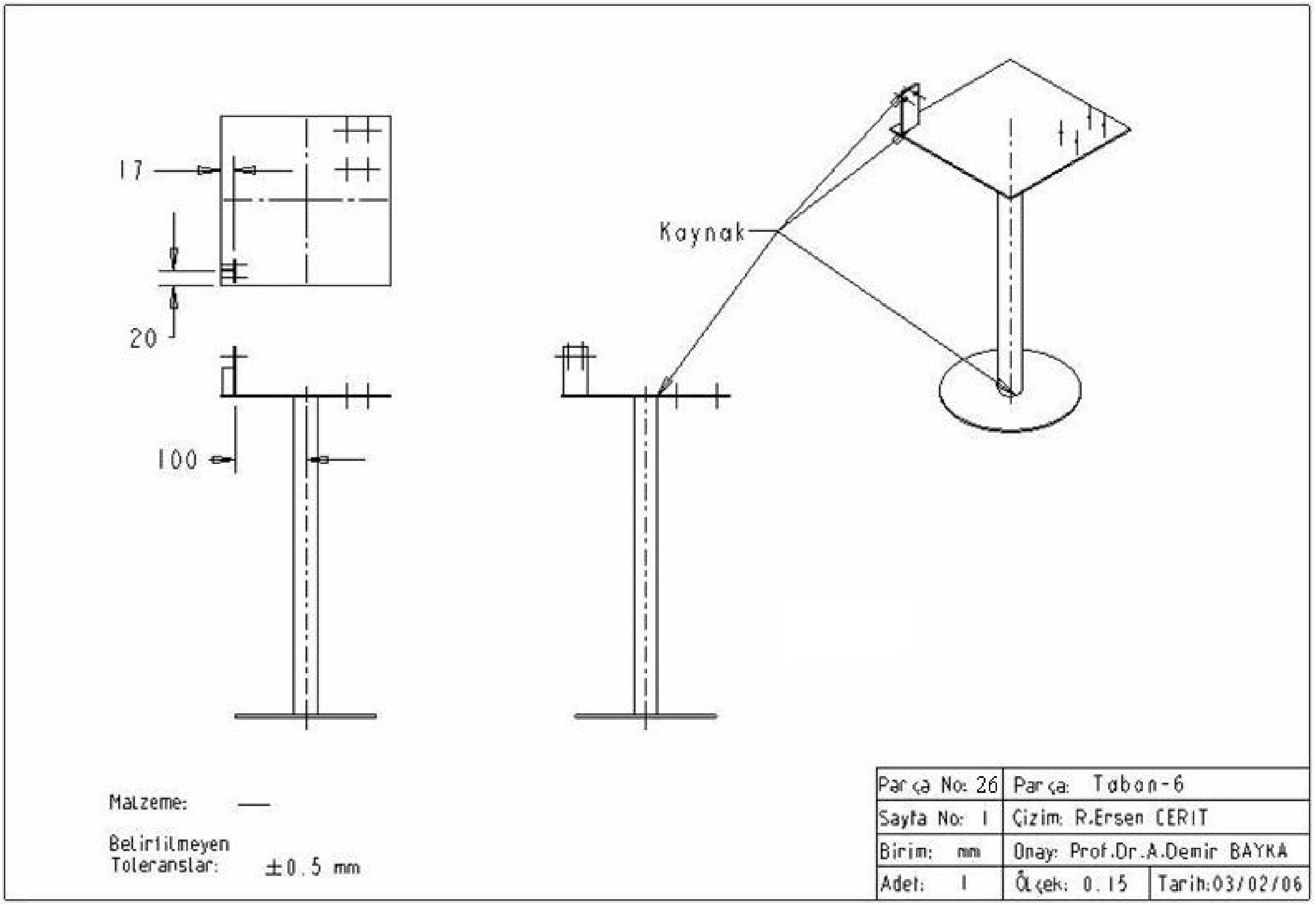


Figure E.19: Technical Drawing of Filter Holder Support.

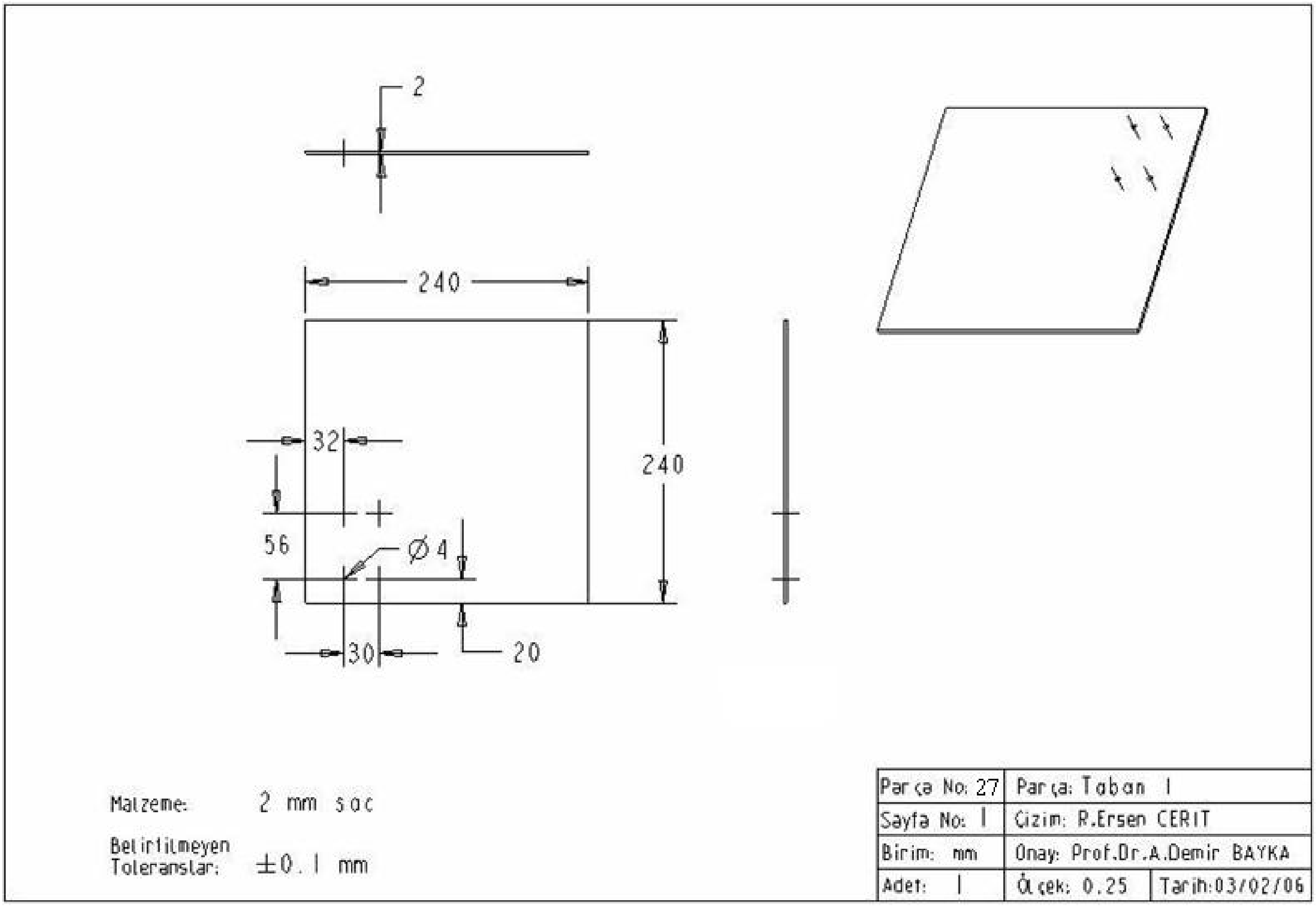


Figure E.20: Technical Drawing of Filter Holder Support Surface.

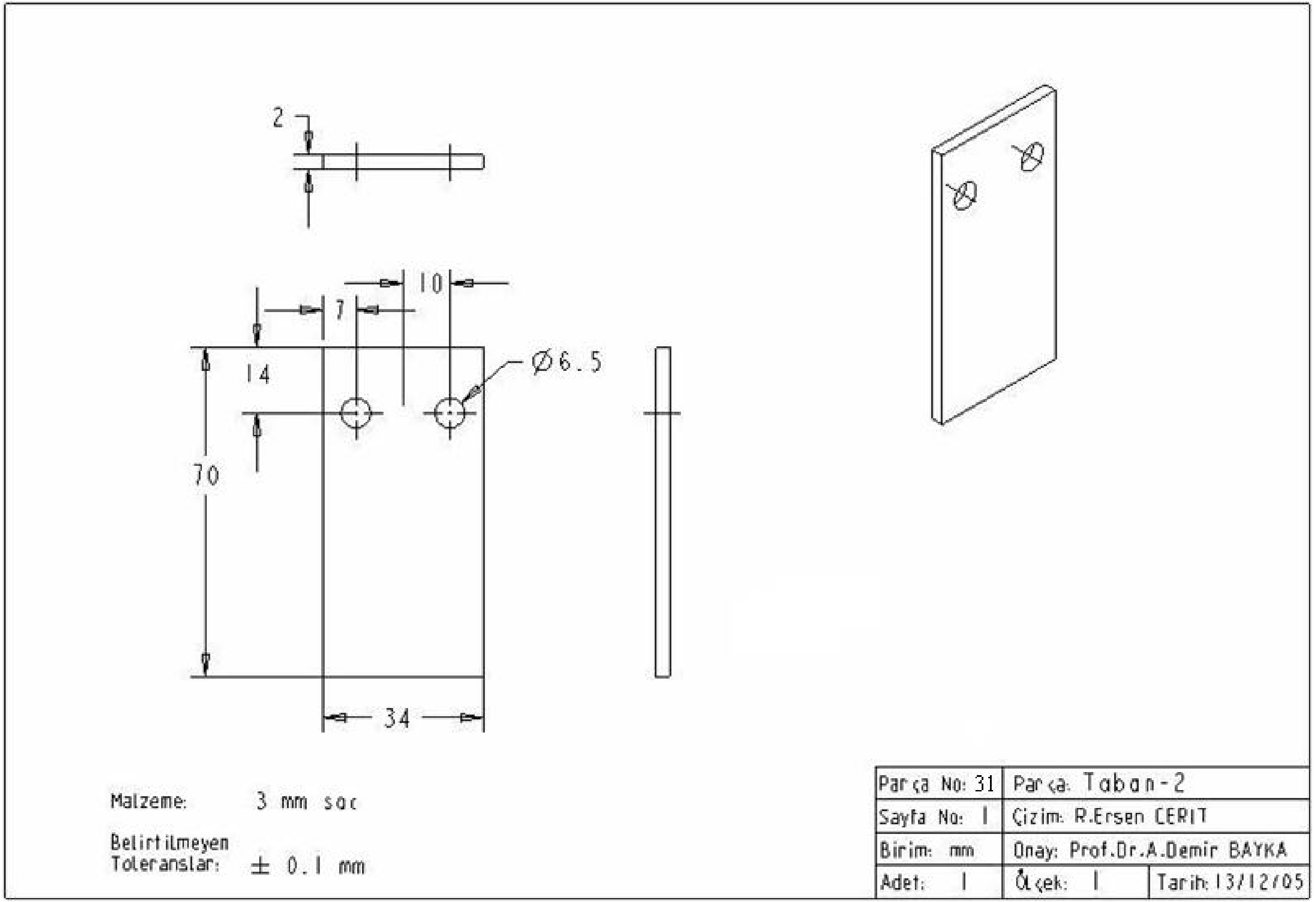


Figure E.21: Technical Drawing of Piston Support on Filter Holder.

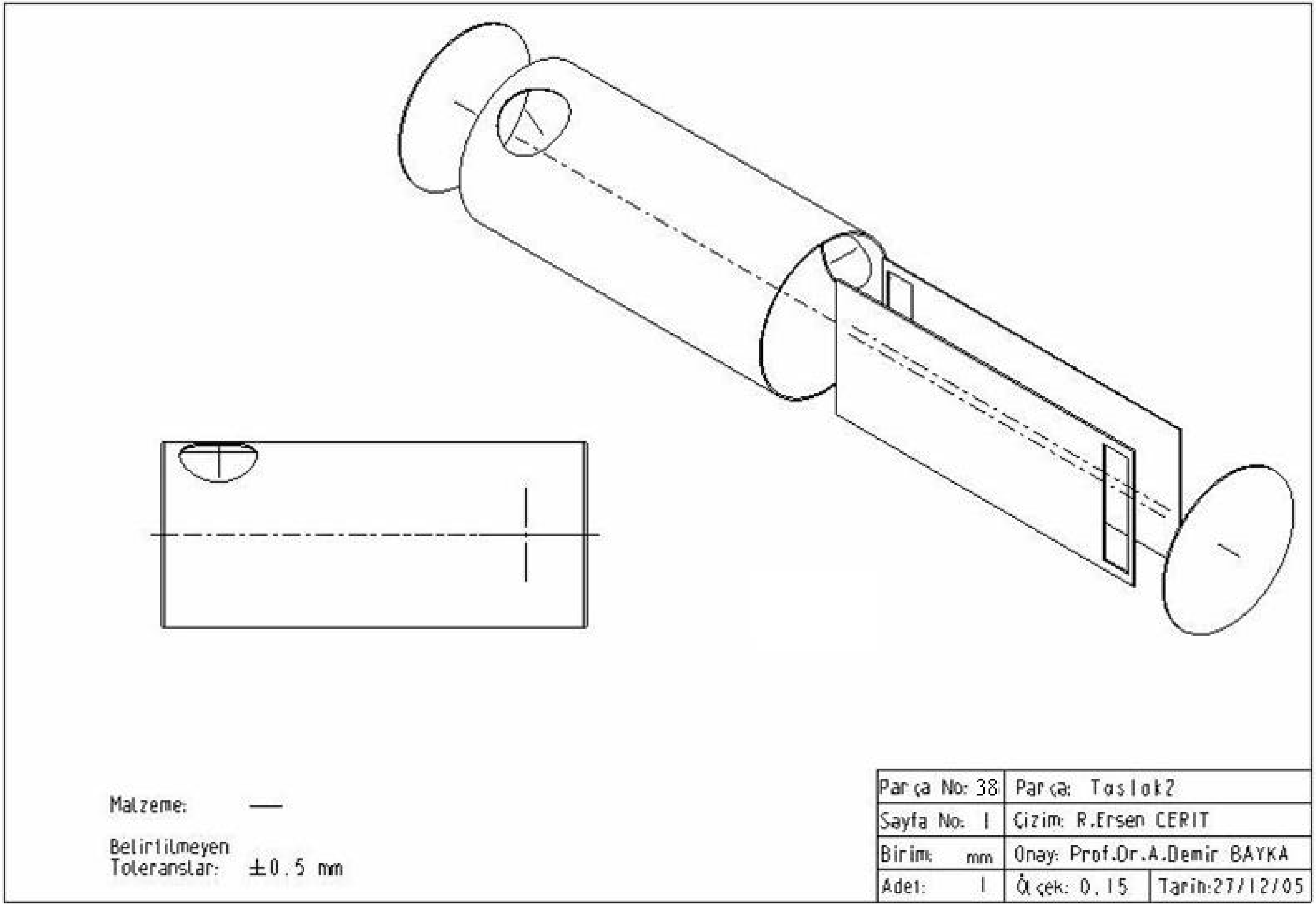


Figure E.22: Technical Drawing of Filter.

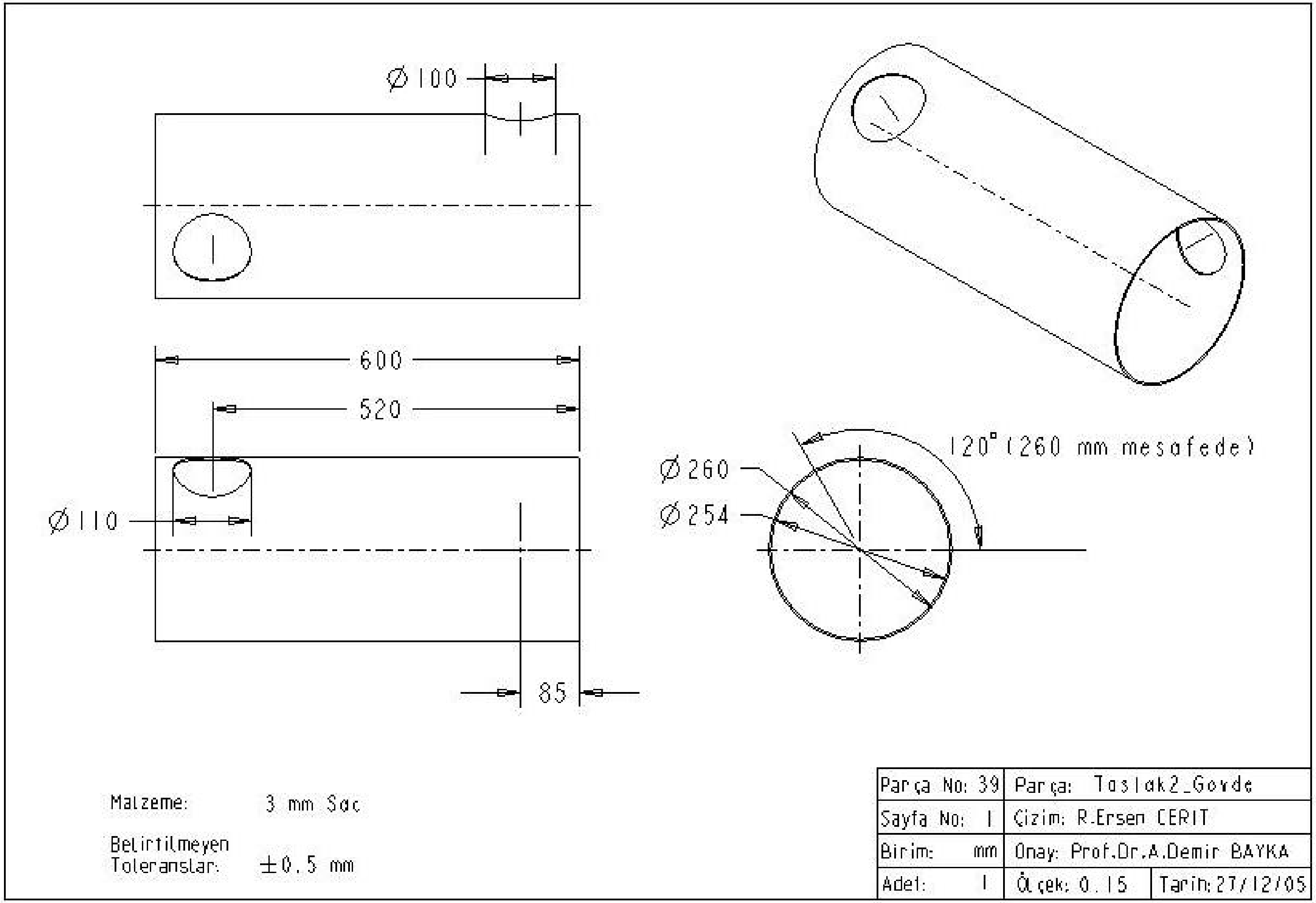


Figure E.23: Technical Drawing of Filter Body.

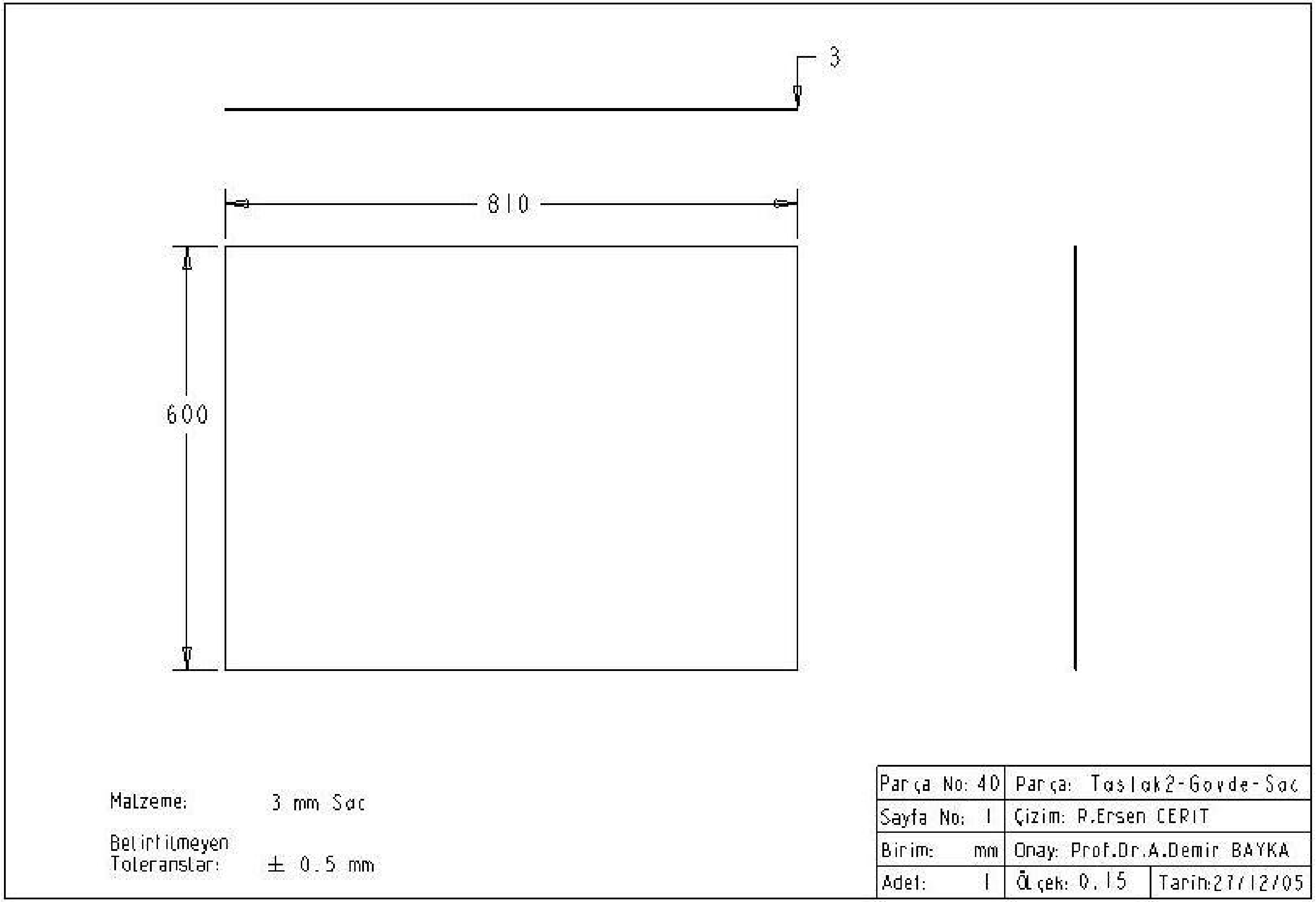


Figure E.24: Technical Drawing of Filter Body Sheet.

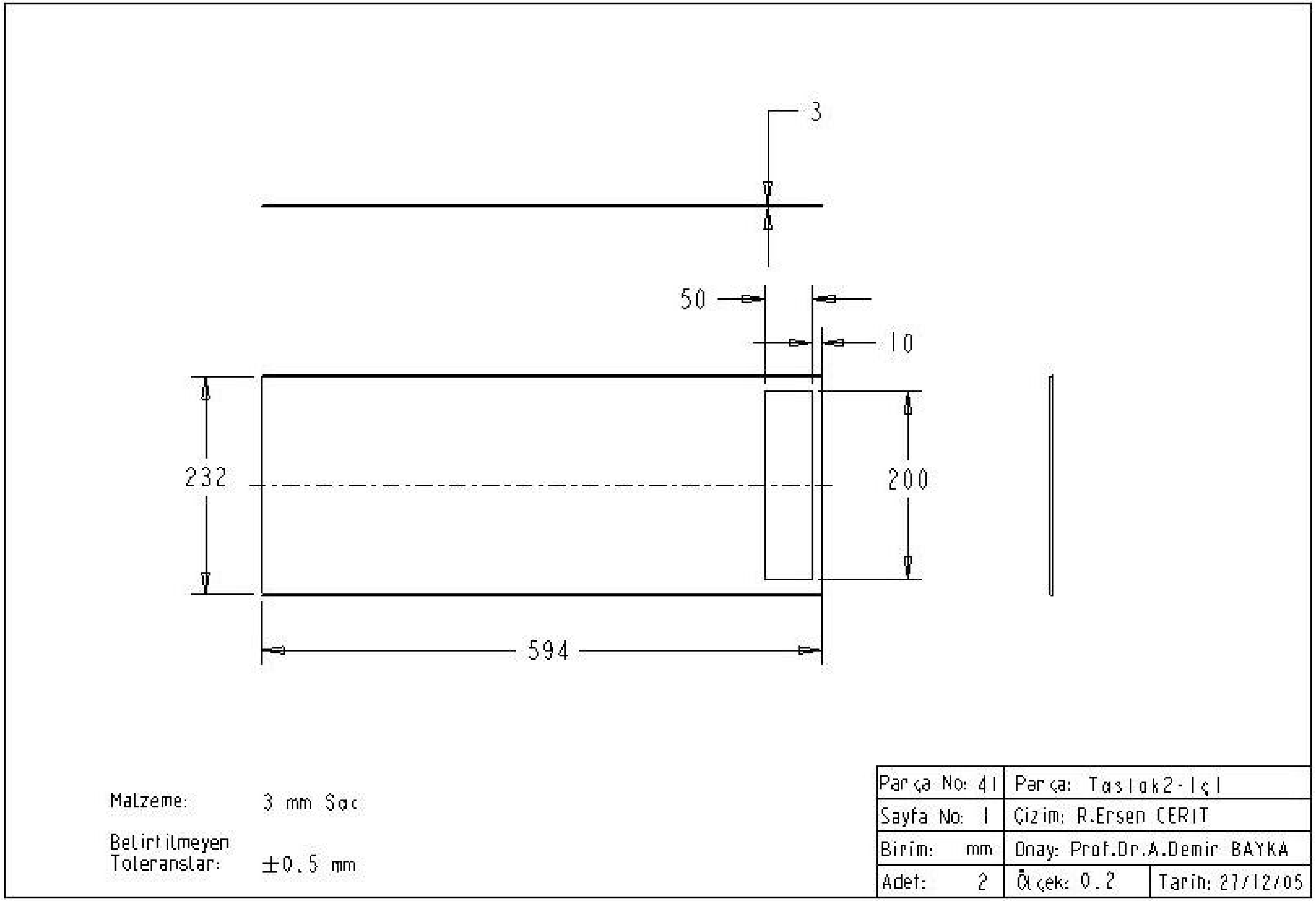


Figure E.25: Technical Drawing of Filter Inside Part

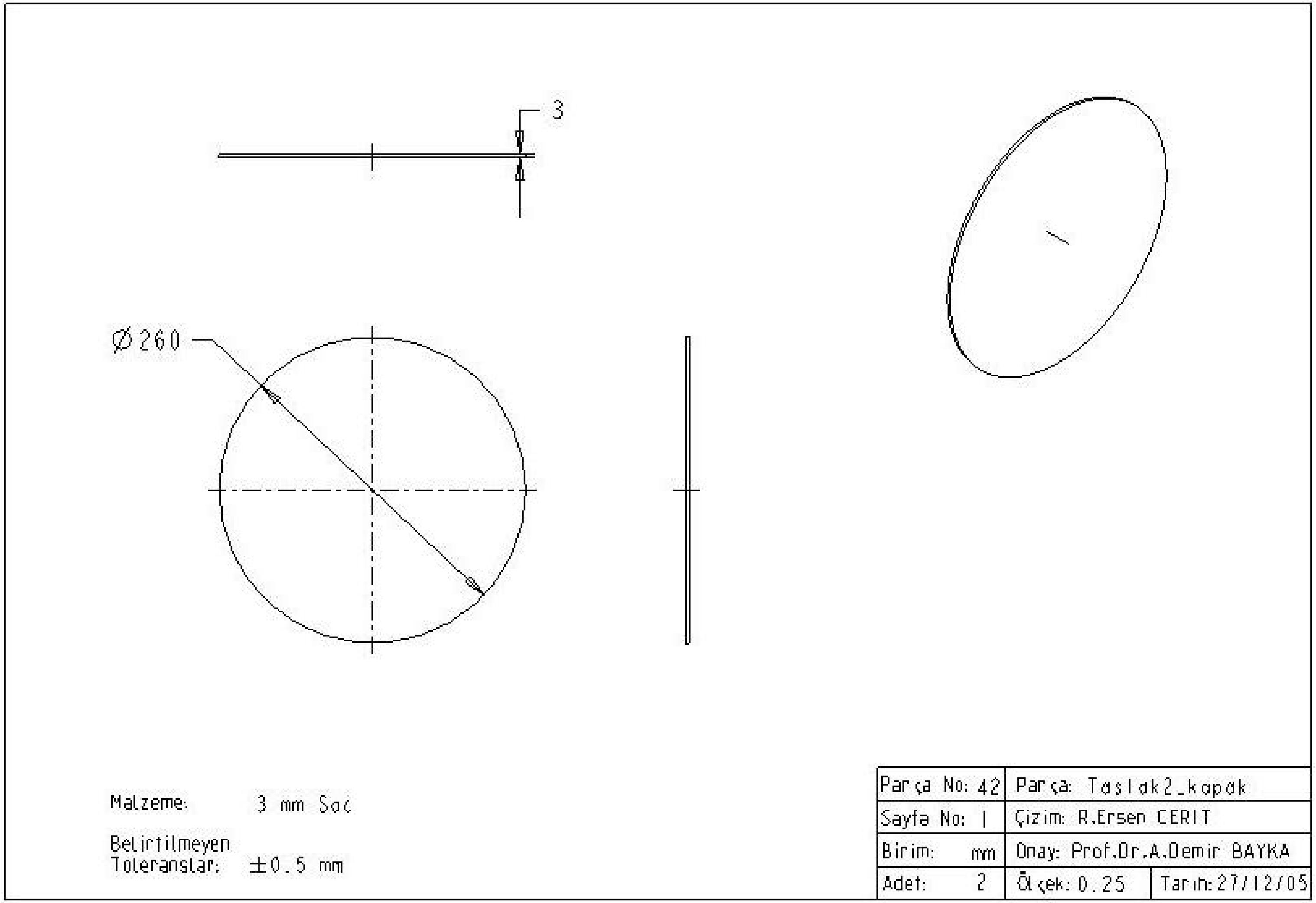


Figure E.26: Technical Drawing of Filter Cover.

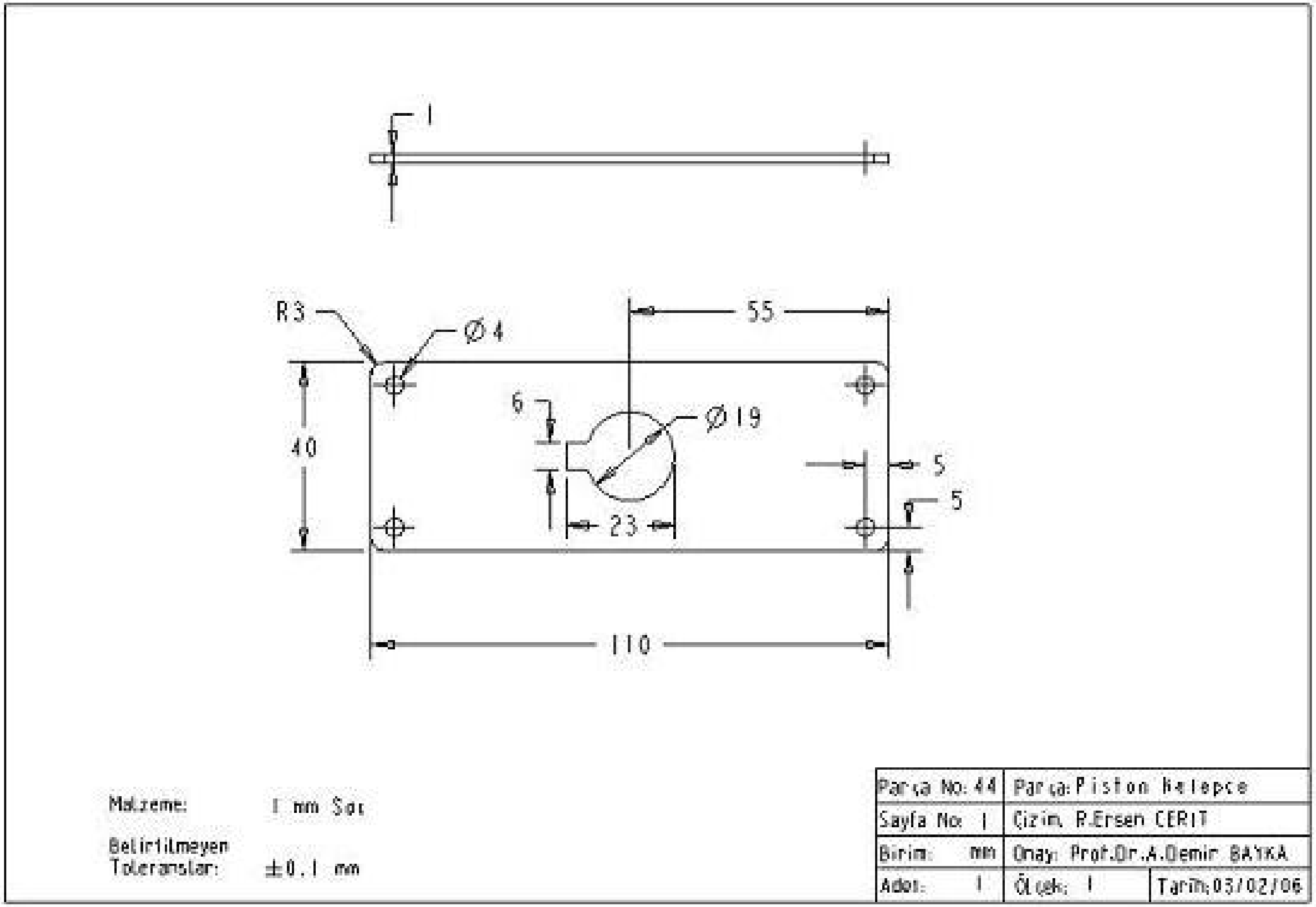


Figure E.27: Technical Drawing of Valve Support on Filter Holder.

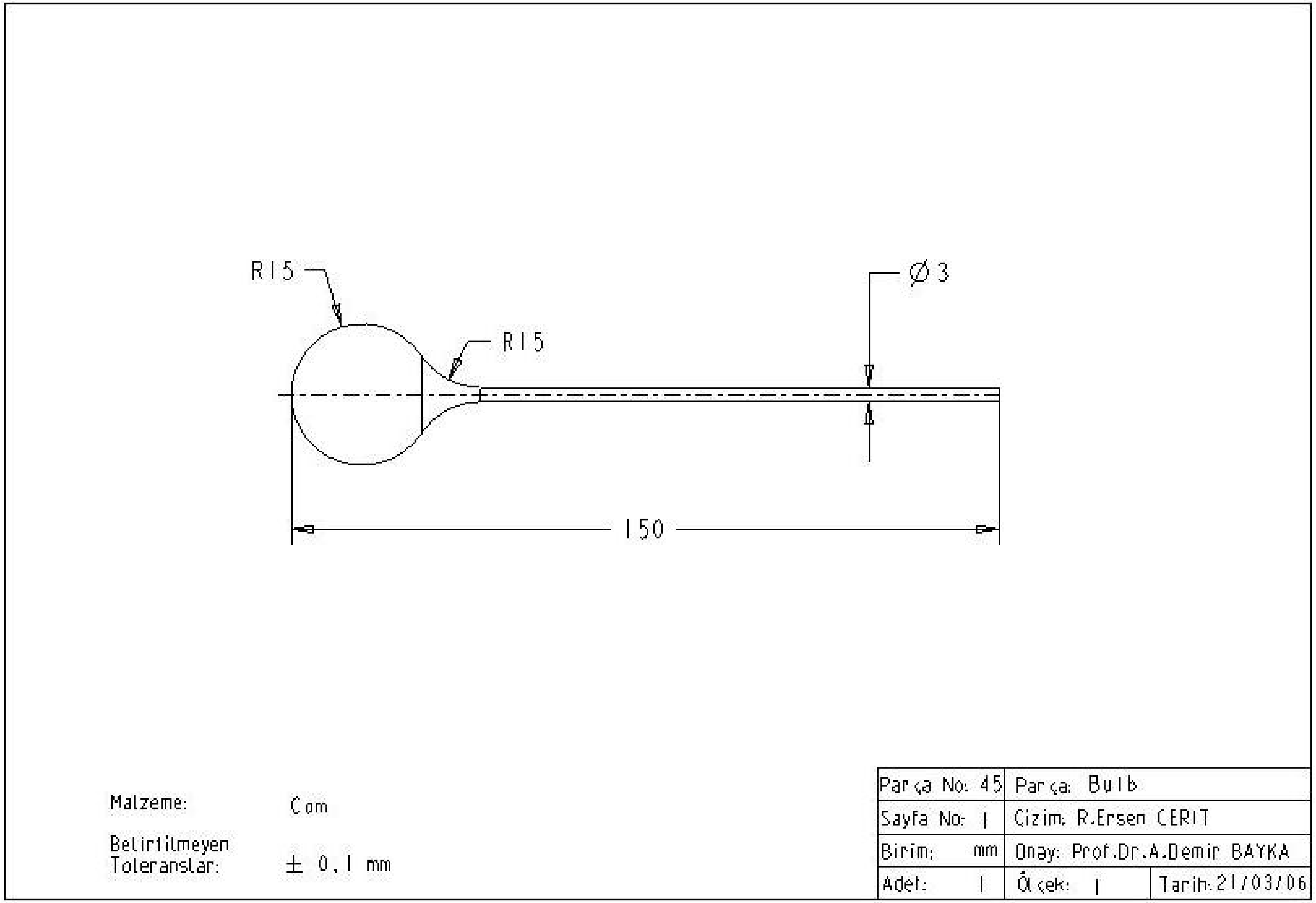


Figure E.28: Technical Drawing of Glass Buoy.

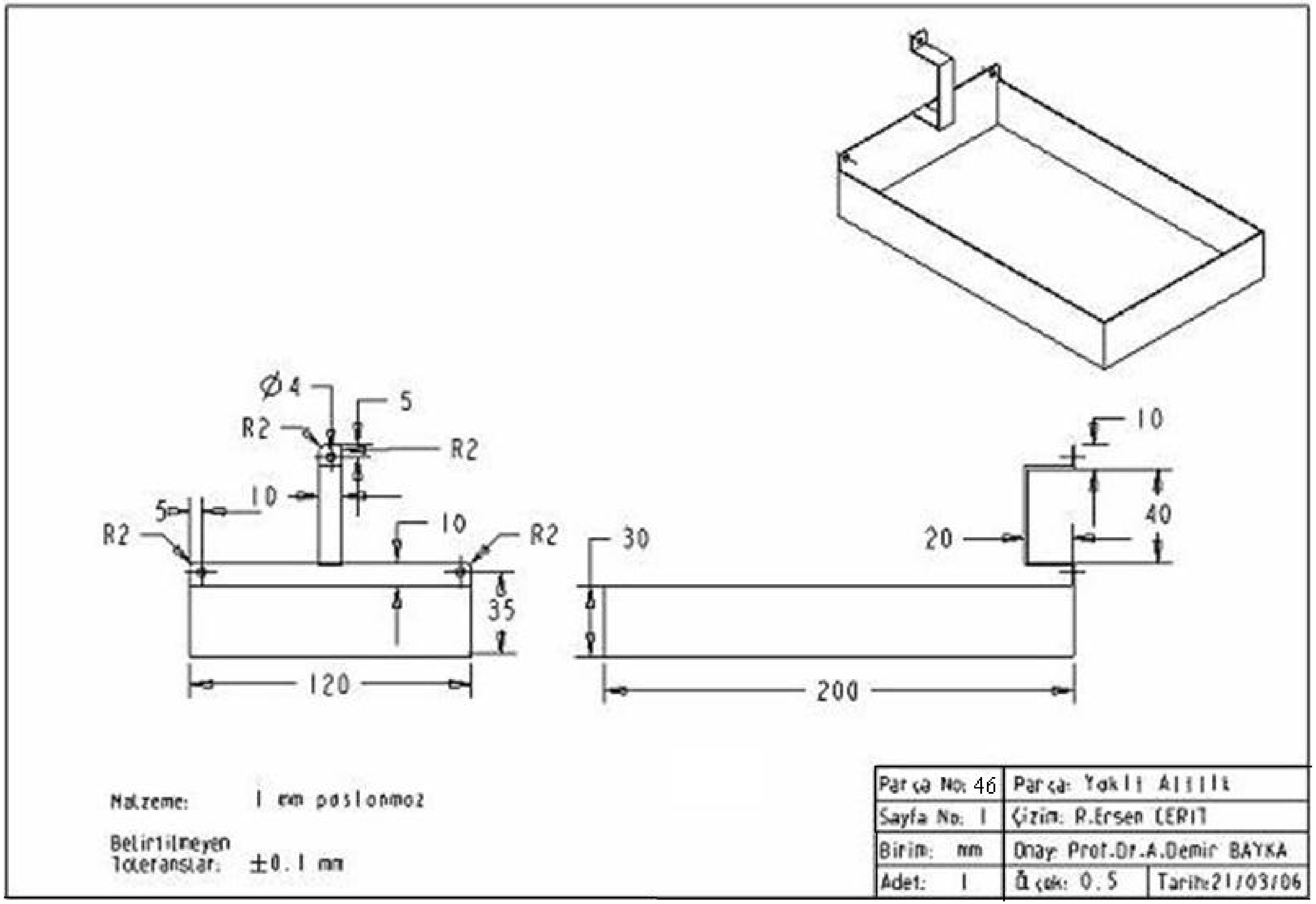


Figure E.29: Technical Drawing of Fuel Container Support..

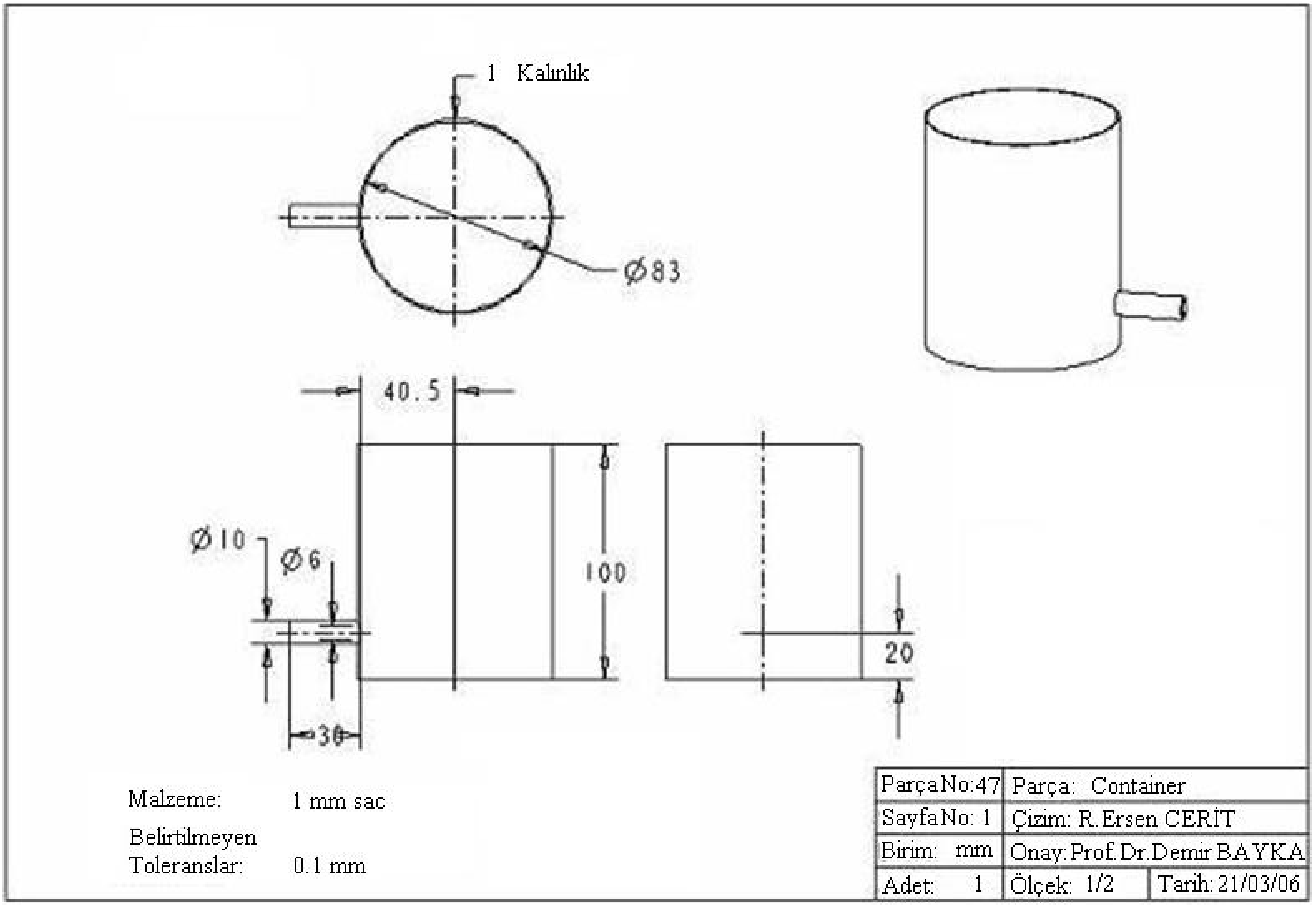


Figure E.30: Technical Drawing of Fuel Container.

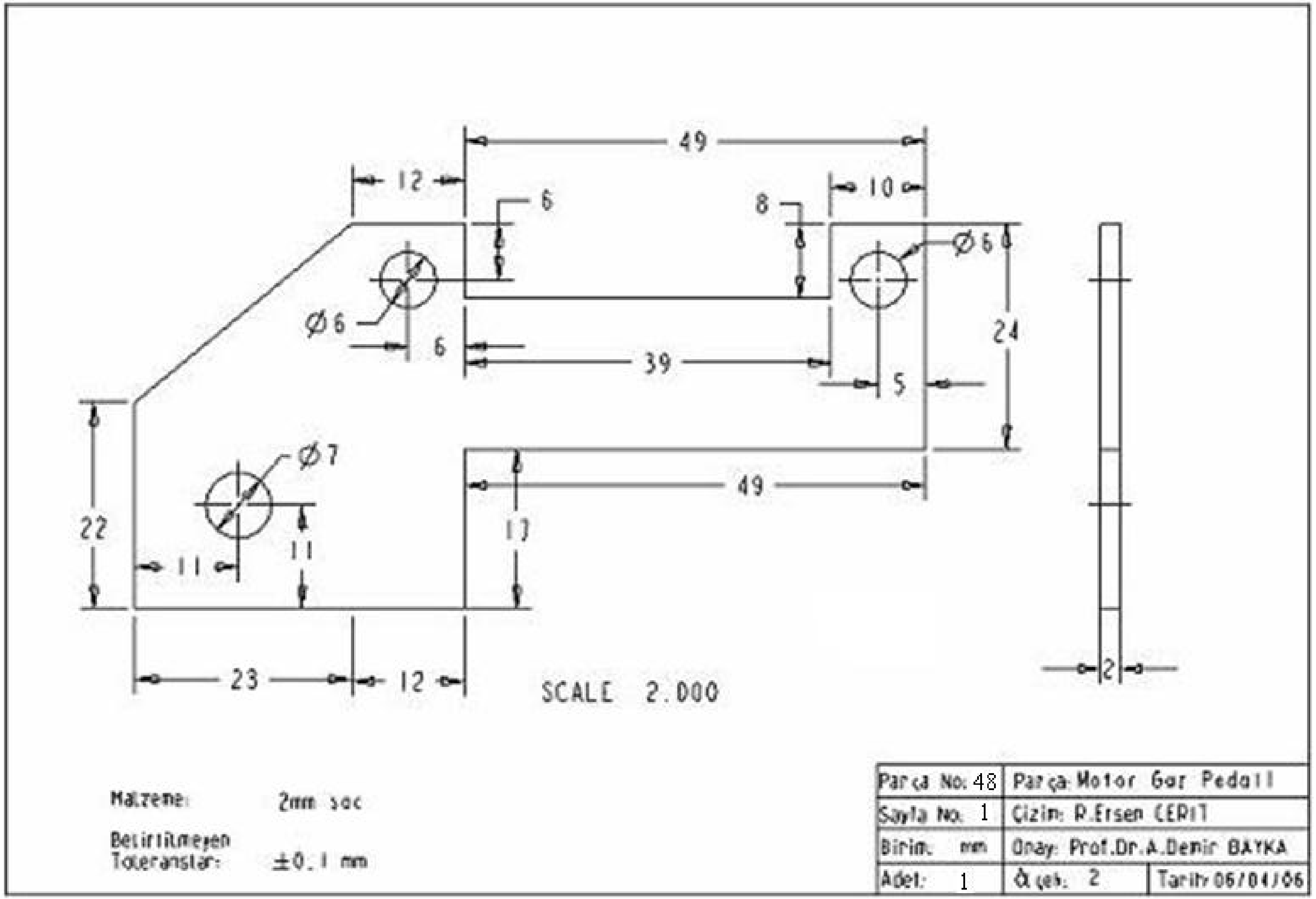


Figure E.31: Technical Drawing of Throttle Support.

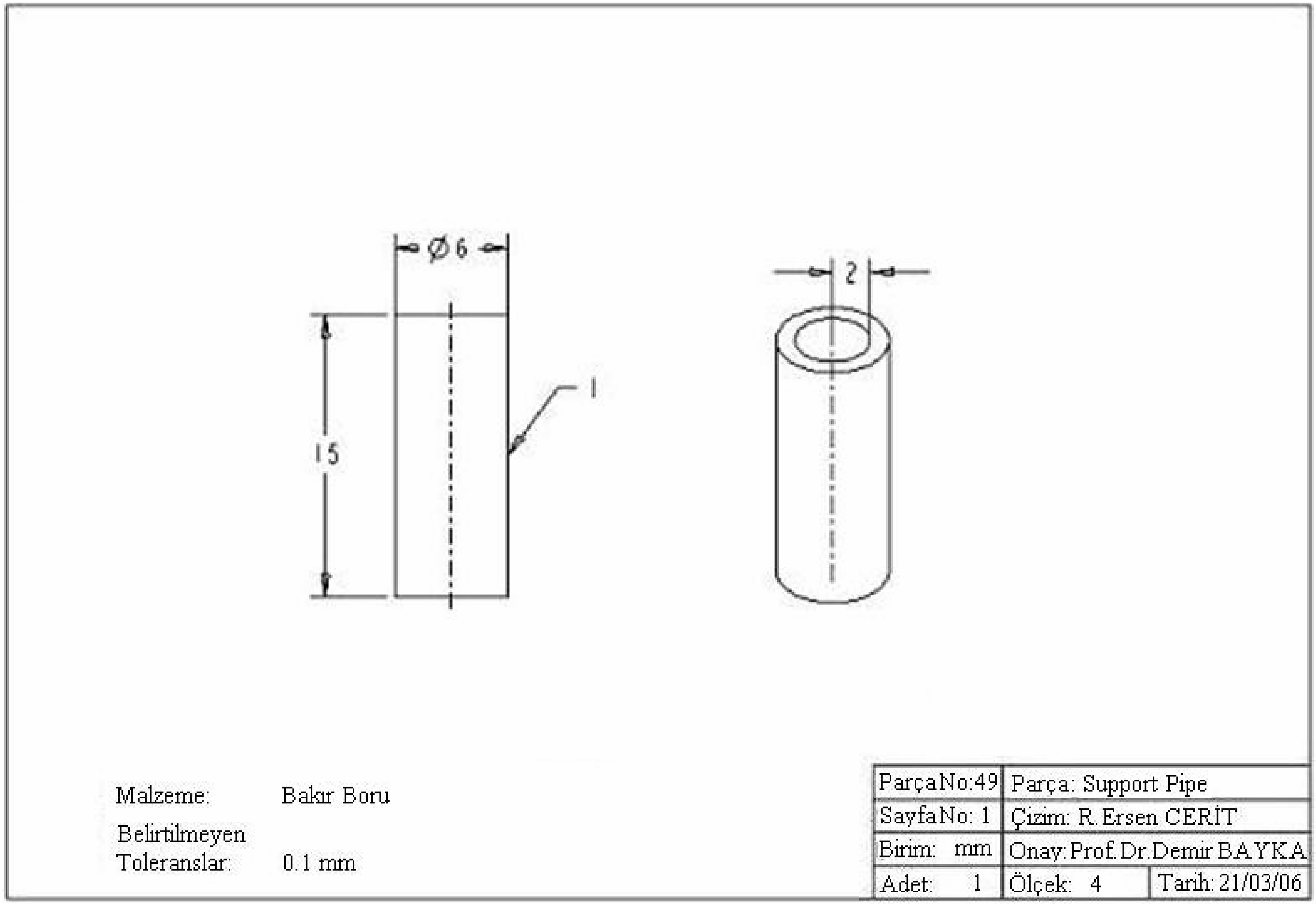


Figure E.32: Technical Drawing of Fuel Glass Buoy Support.

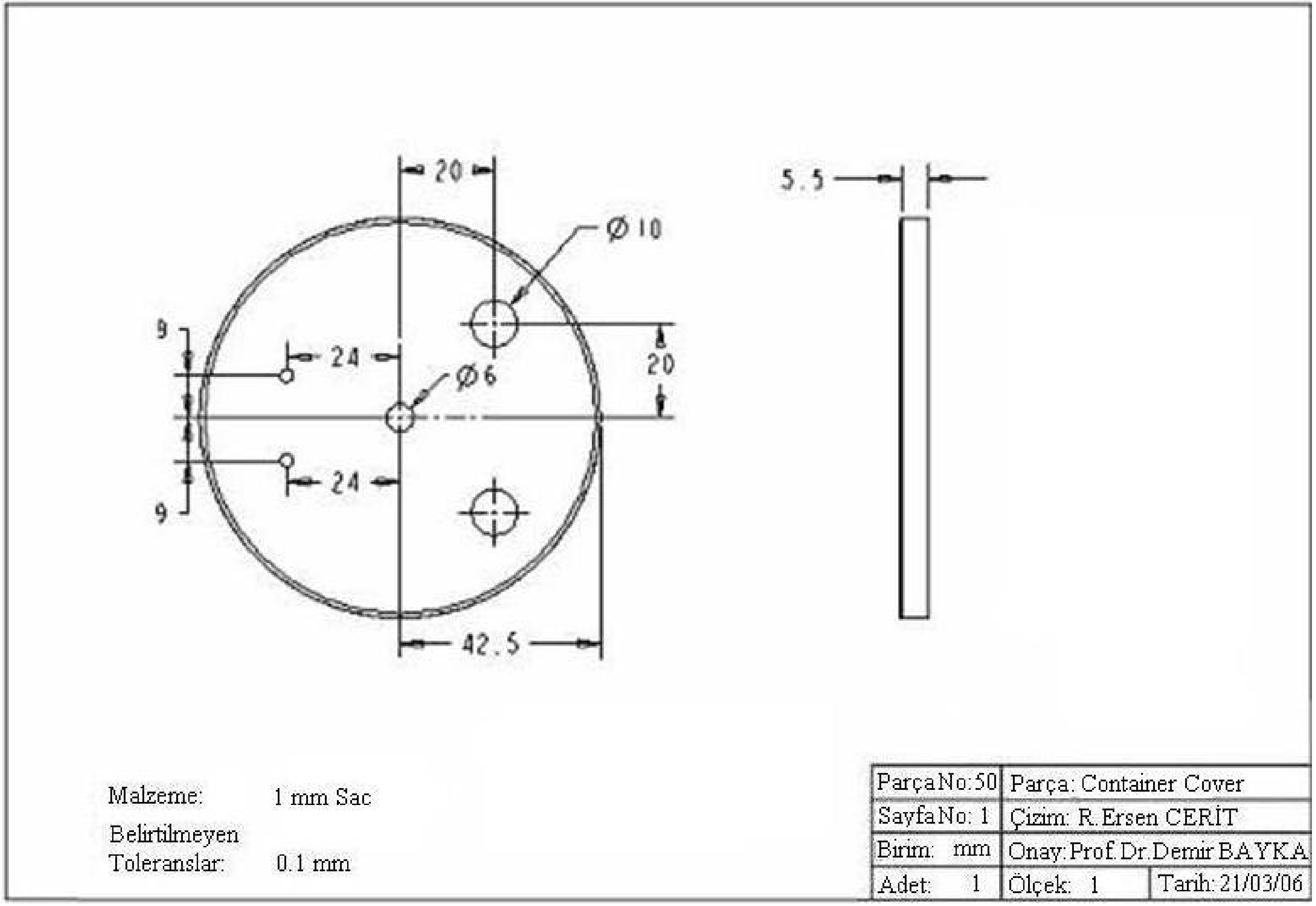


Figure E.33: Technical Drawing of Fuel Container Cover.

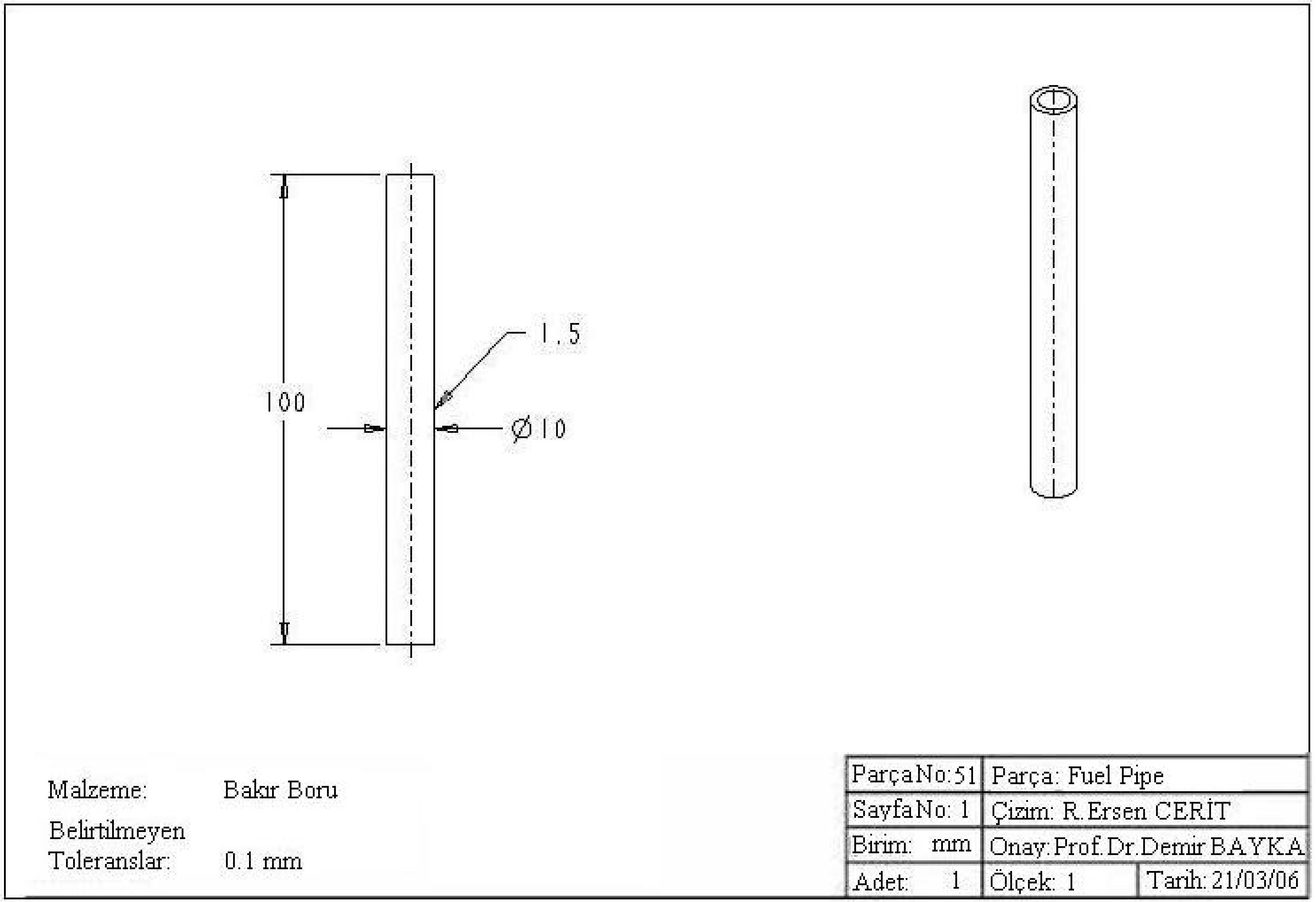


Figure E.34: Technical Drawing of the Pipe in Fuel Container Cover.

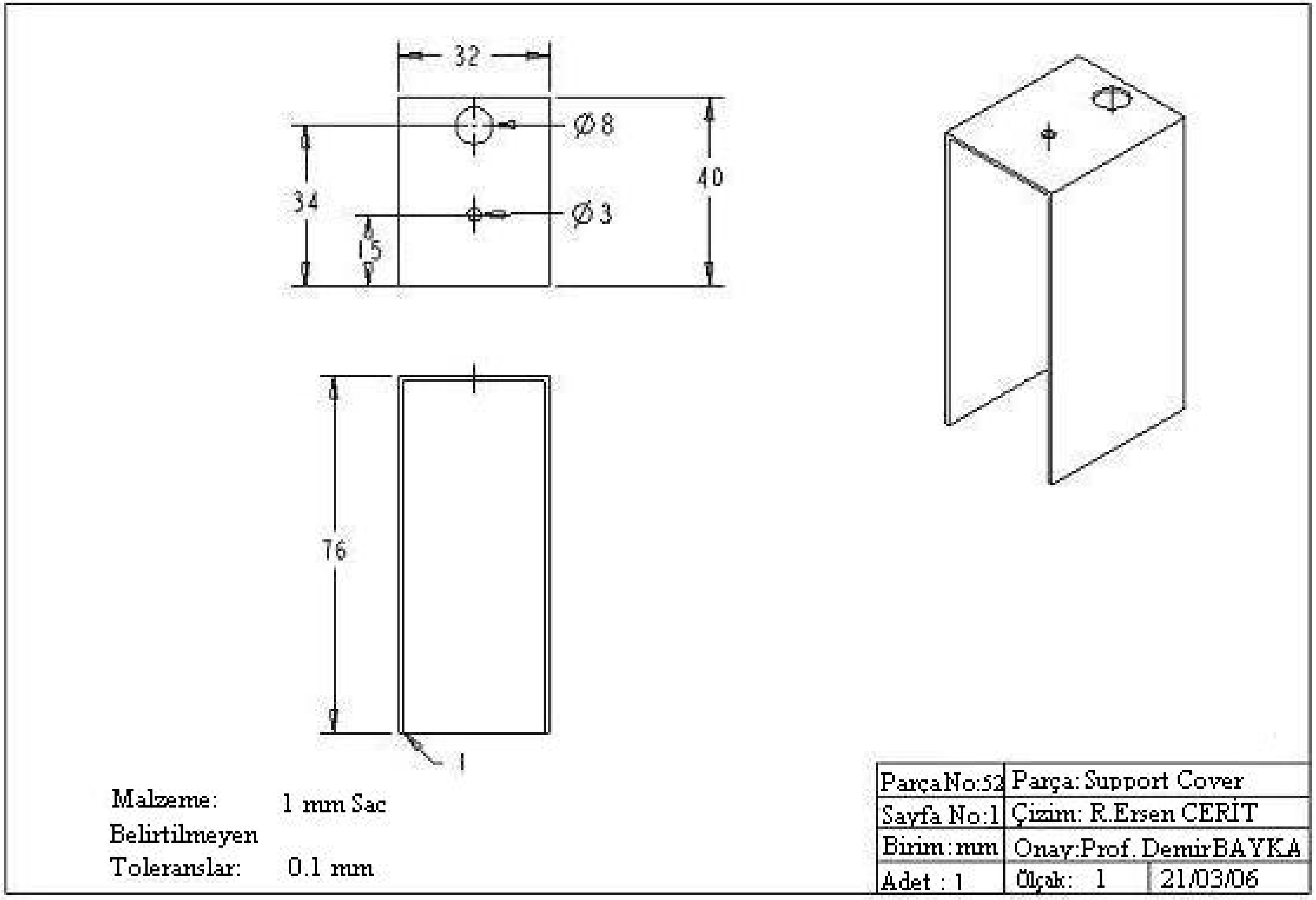


Figure E.35: Technical Drawing of Aluminum Support Cover.

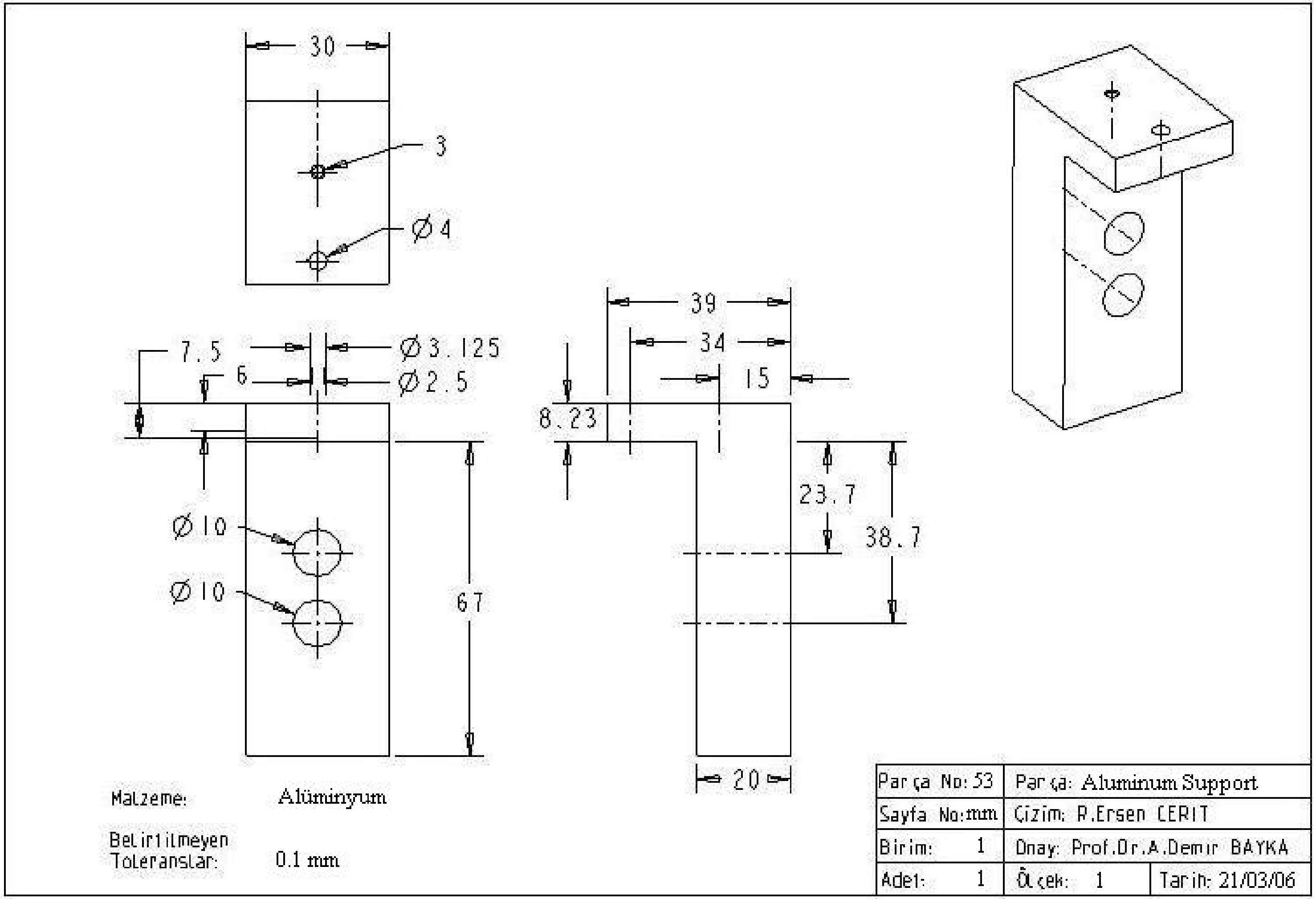


Figure E.36: Technical Drawing of Aluminum Support for Fuel Container.

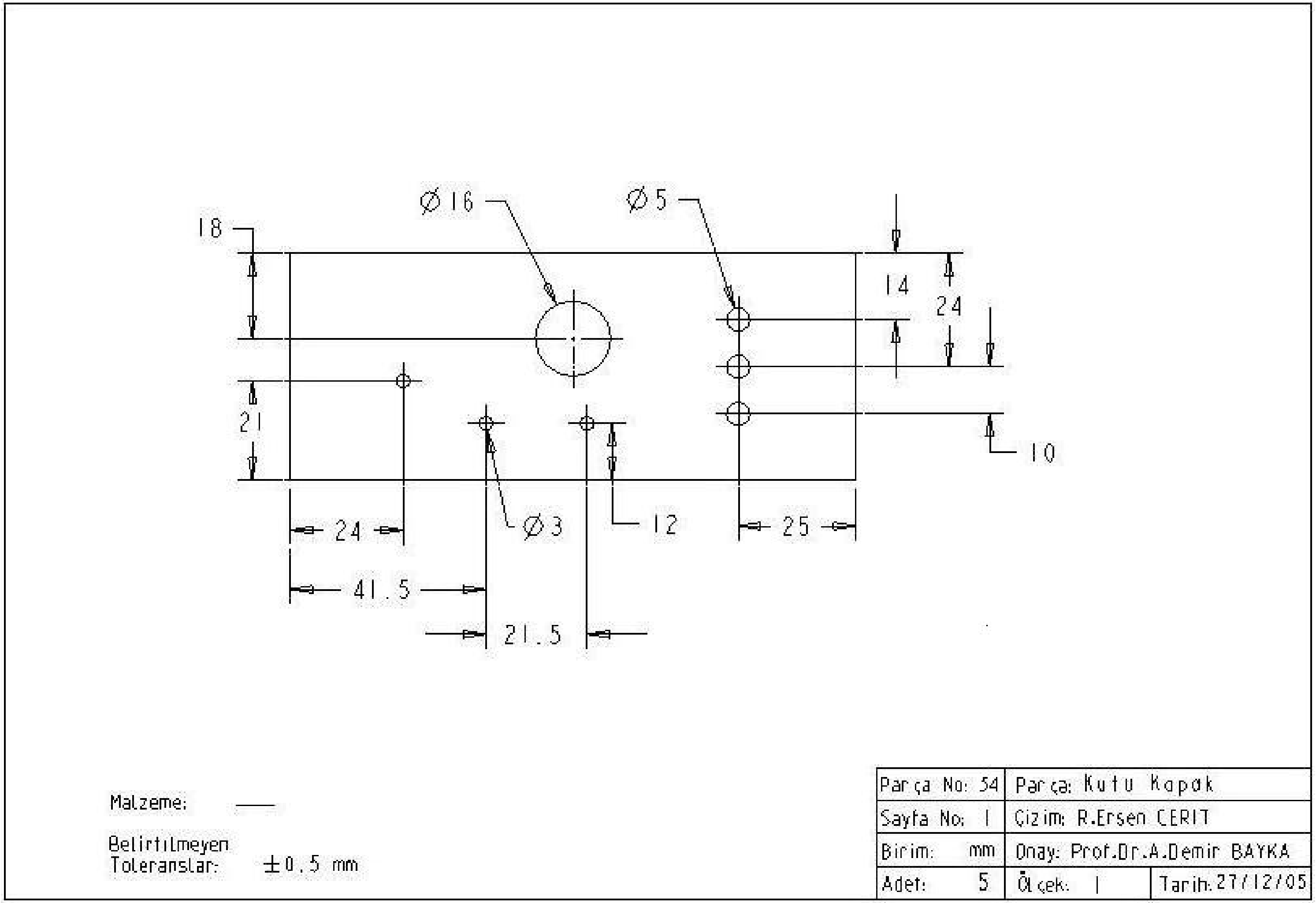


Figure E.37: Technical Drawing of Amplifier Front Cover.

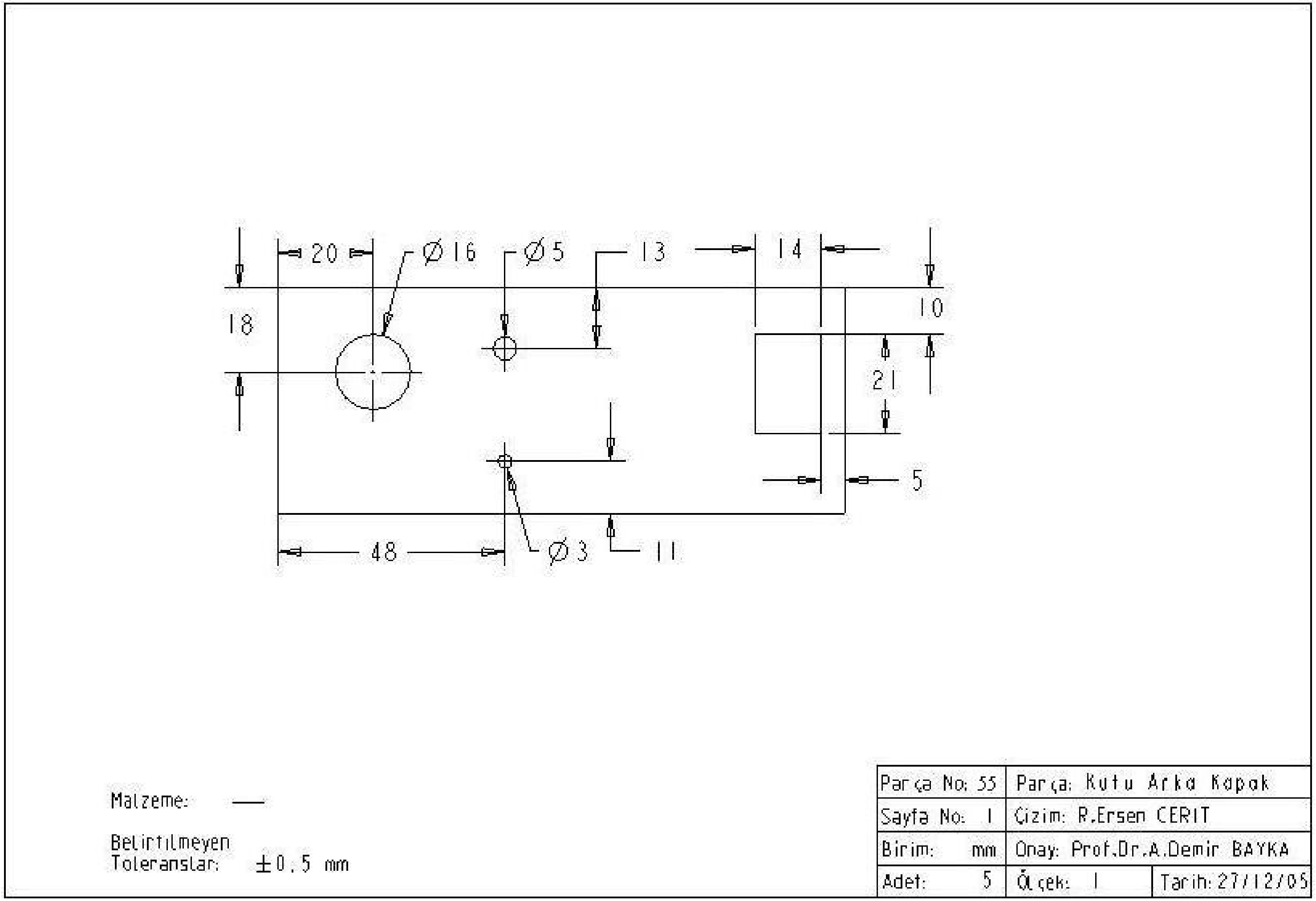


Figure E.38: Technical Drawing of Amplifier Back Cover.

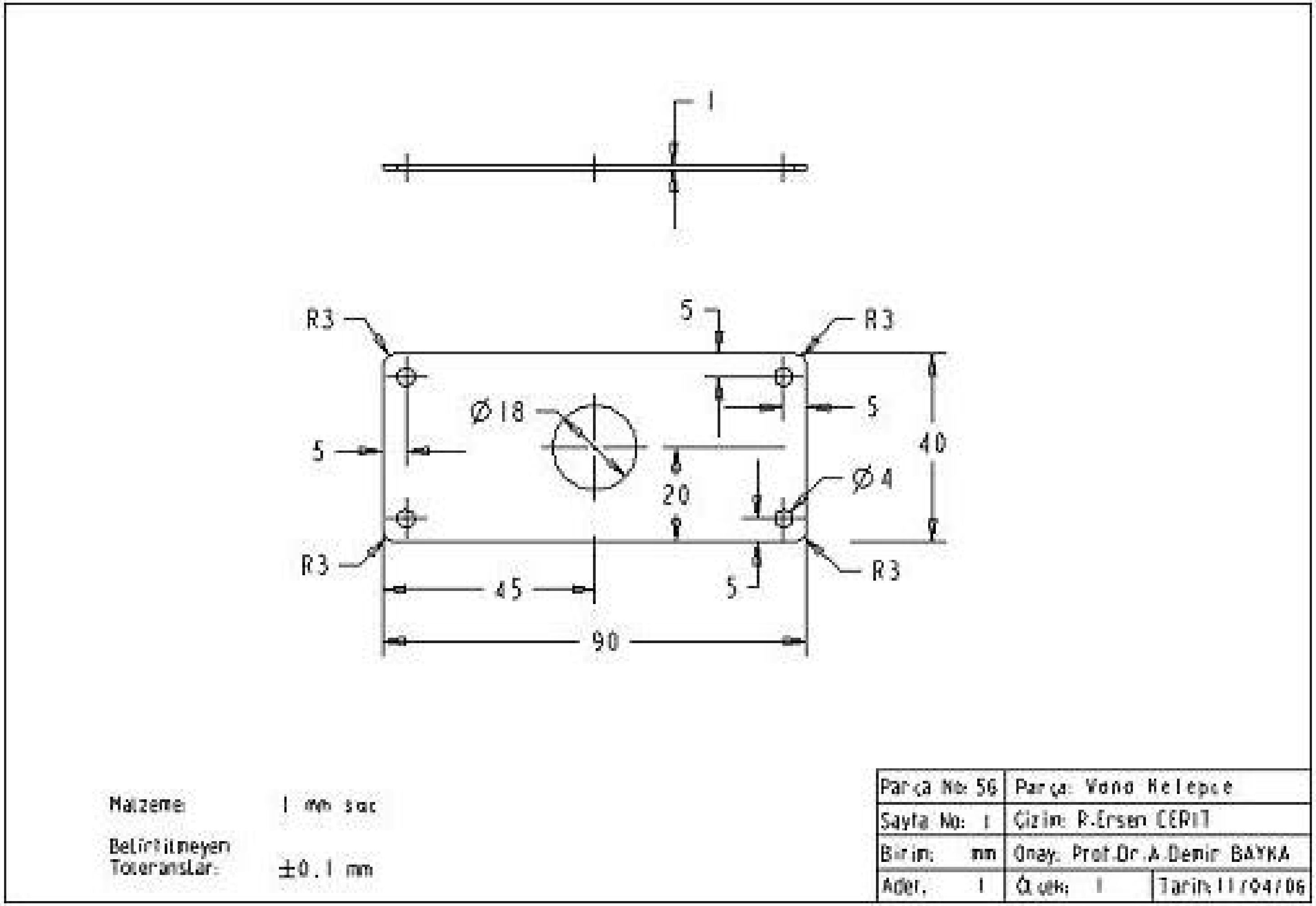


Figure E.39: Technical Drawing of Valve Support on Indicator Board.

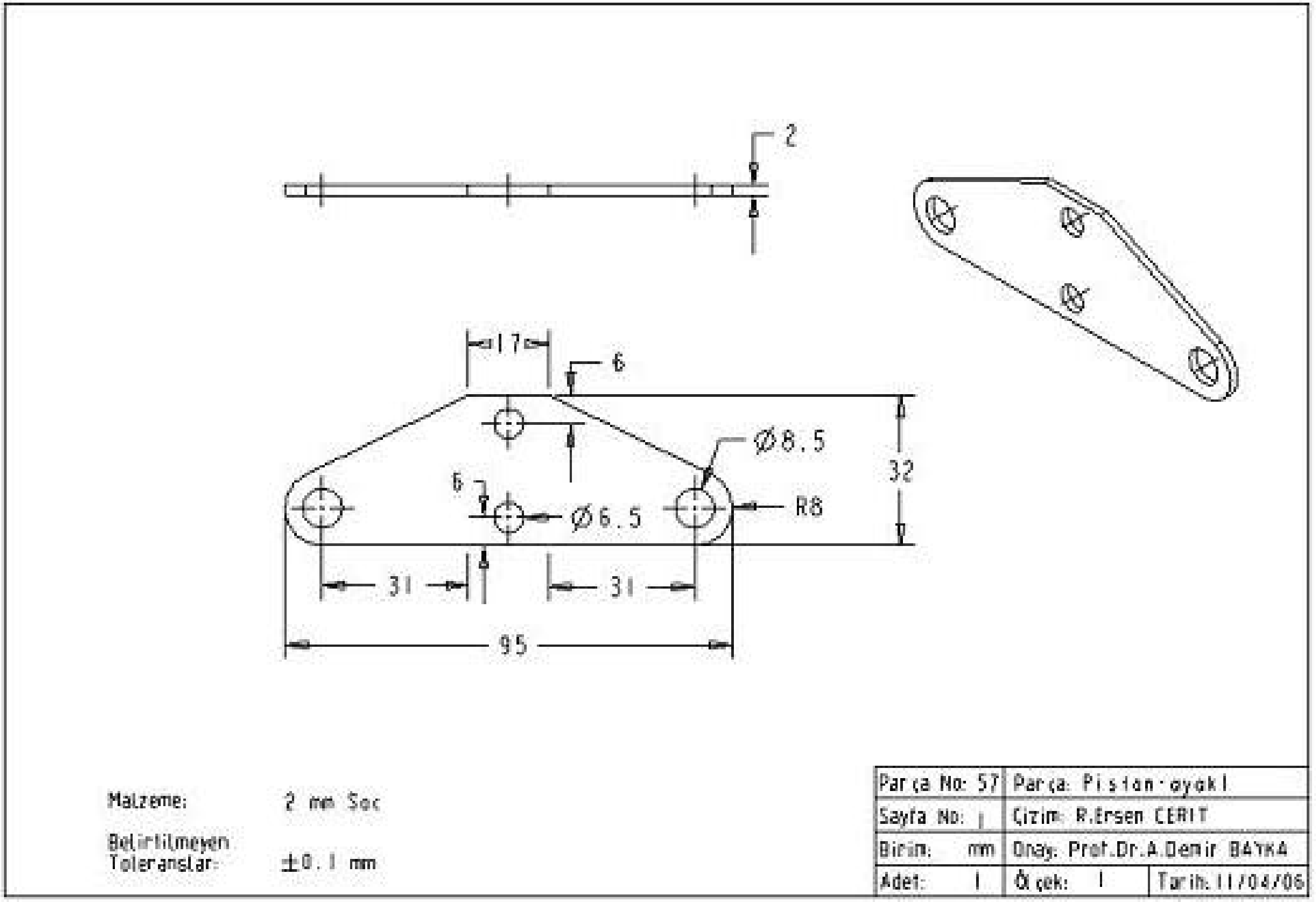


Figure E.40: Technical Drawing of Piston Support.

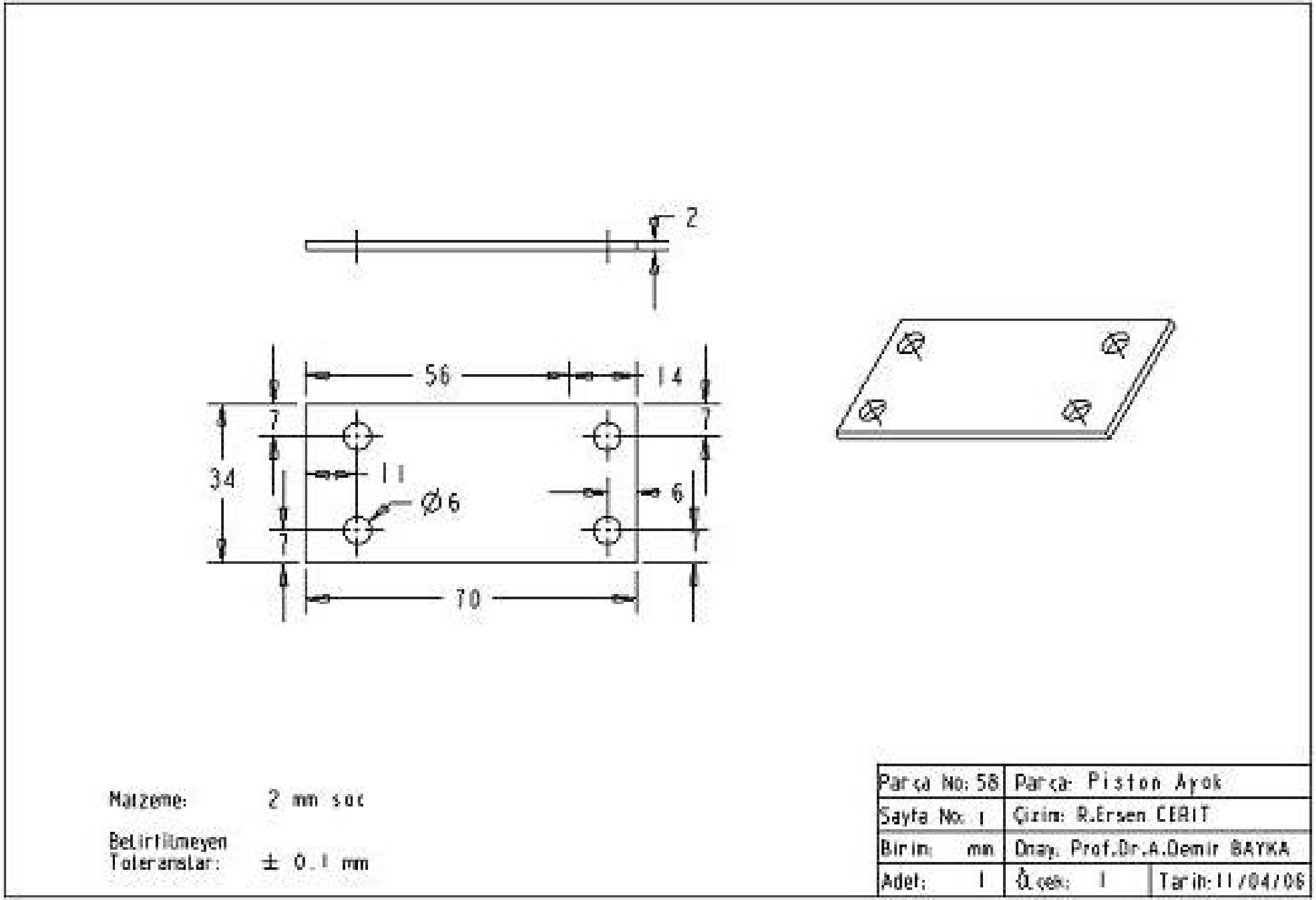


Figure E.41: Technical Drawing of Piston Support on Indicator Board.

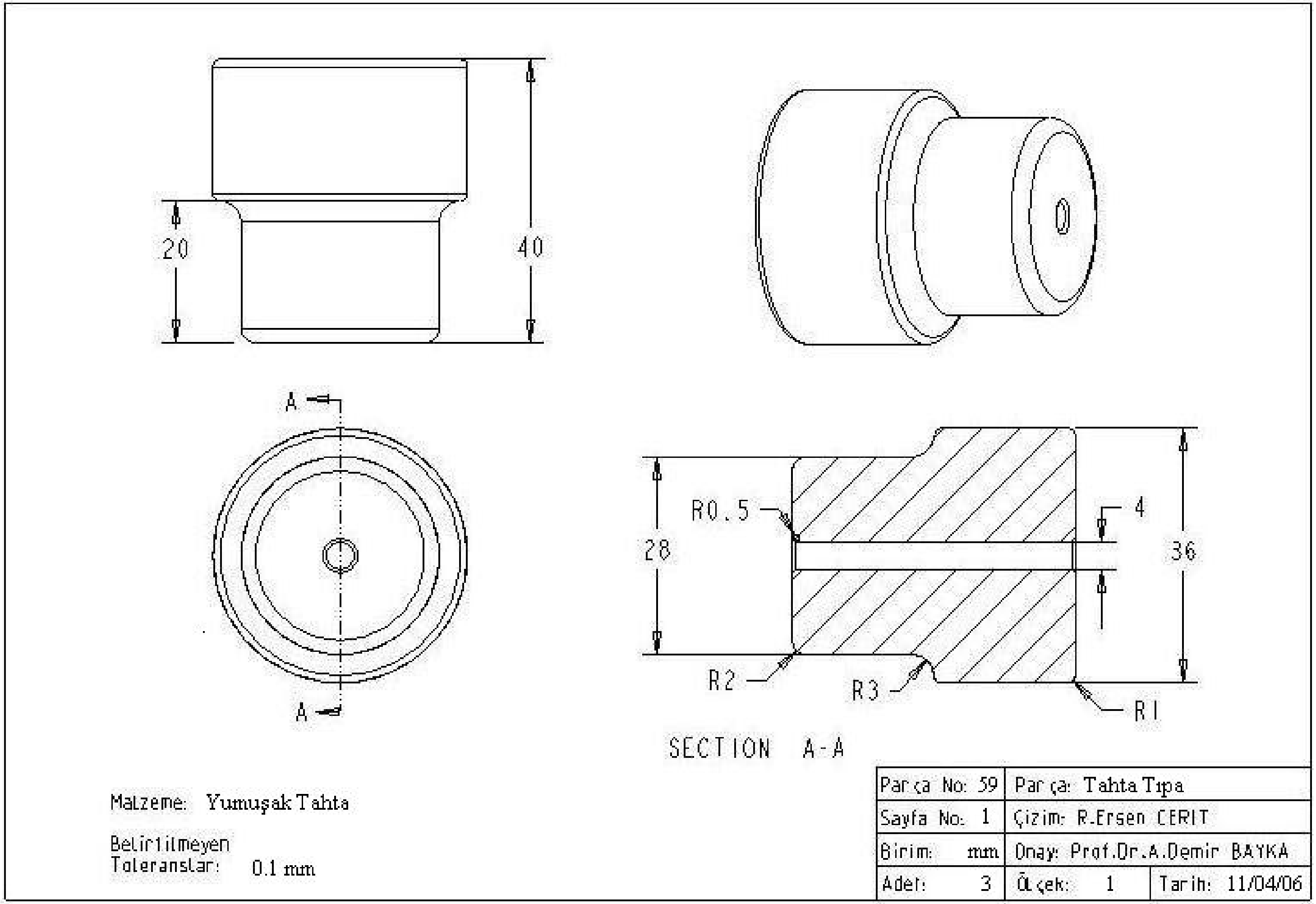


Figure E.42: Technical Drawing of Wooden Stopple.

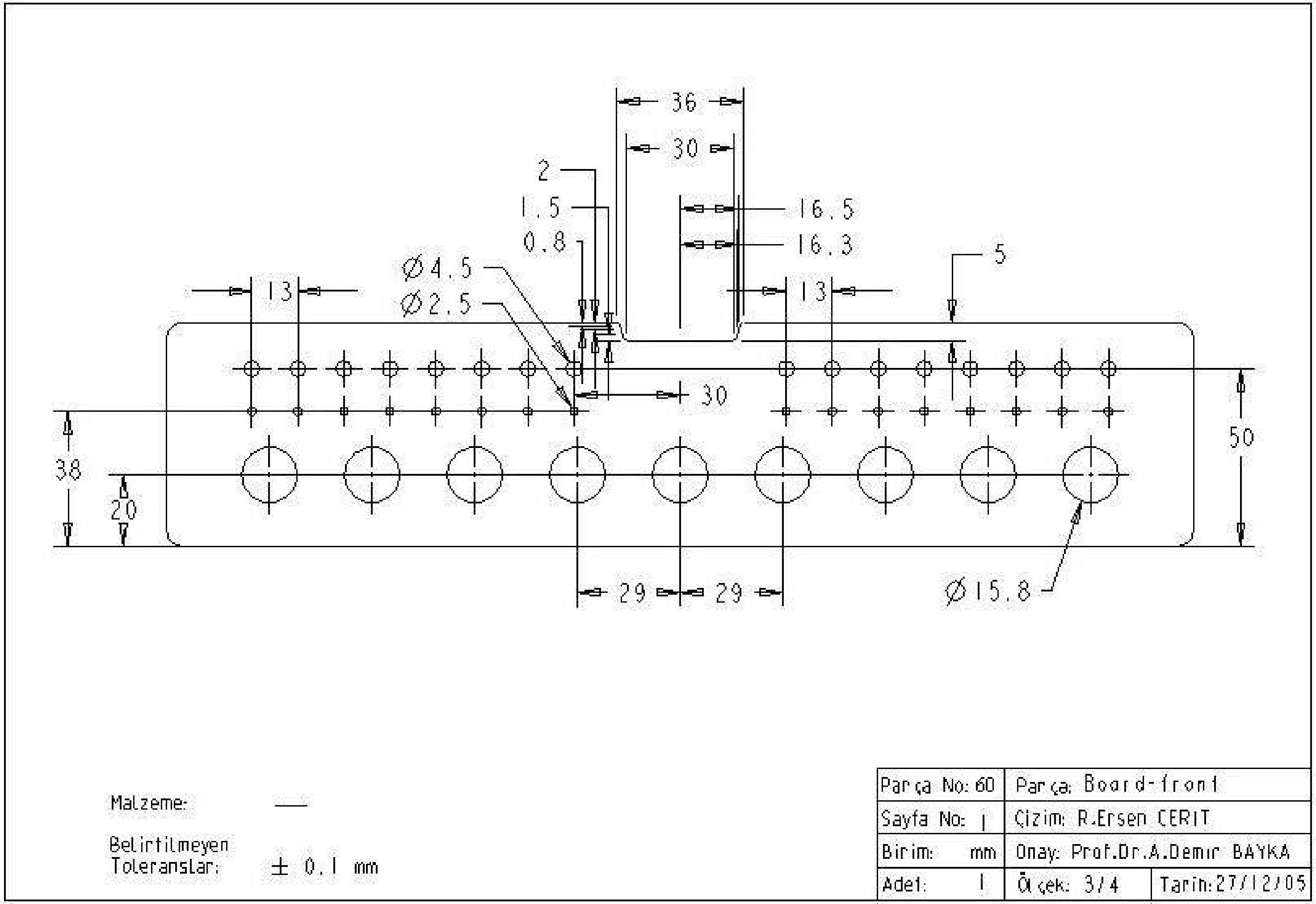


Figure E.43: Technical Drawing of Input-Output Box Front Cover.

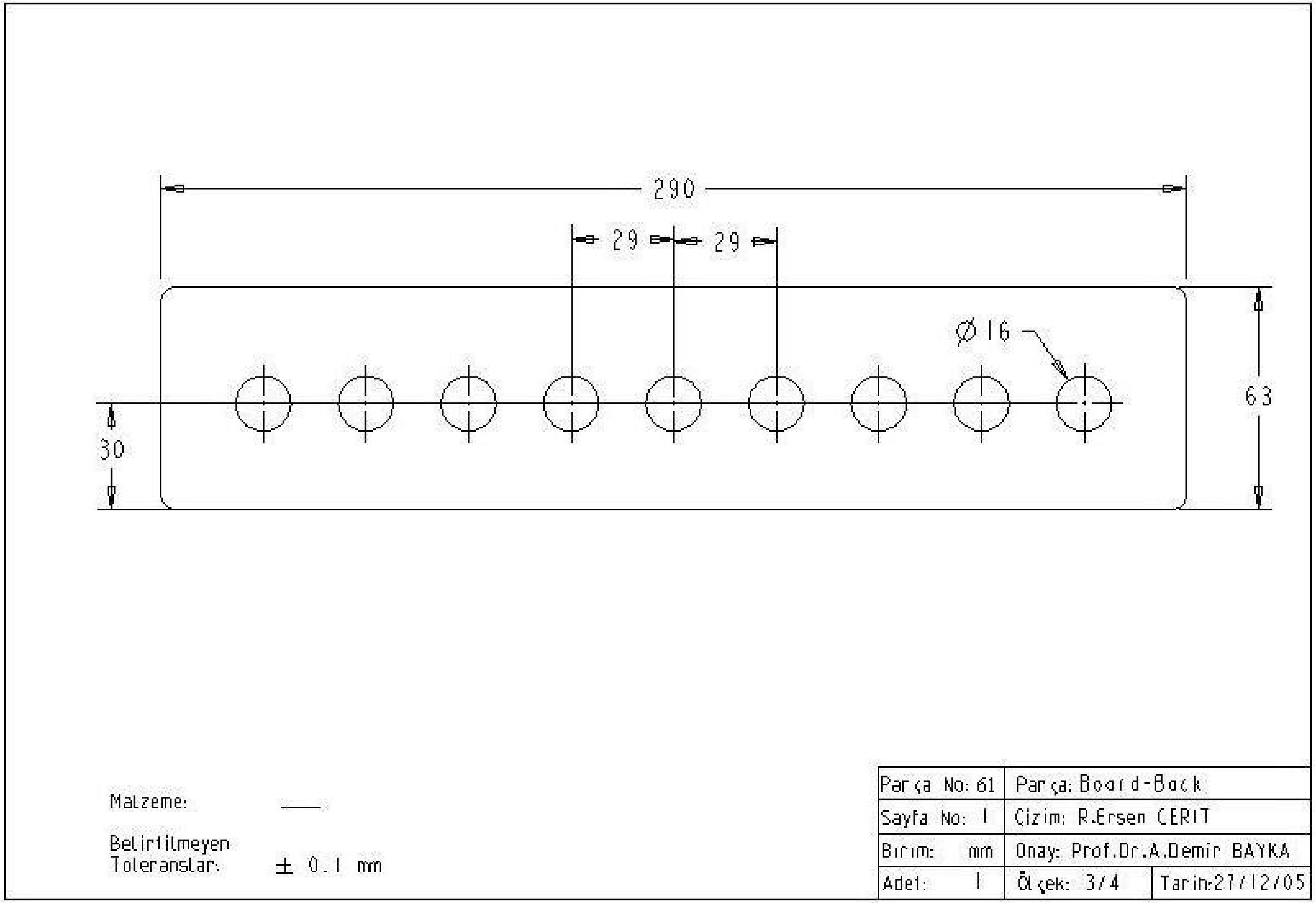


Figure E.44: Technical Drawing of Input-Output Box Back Cover.

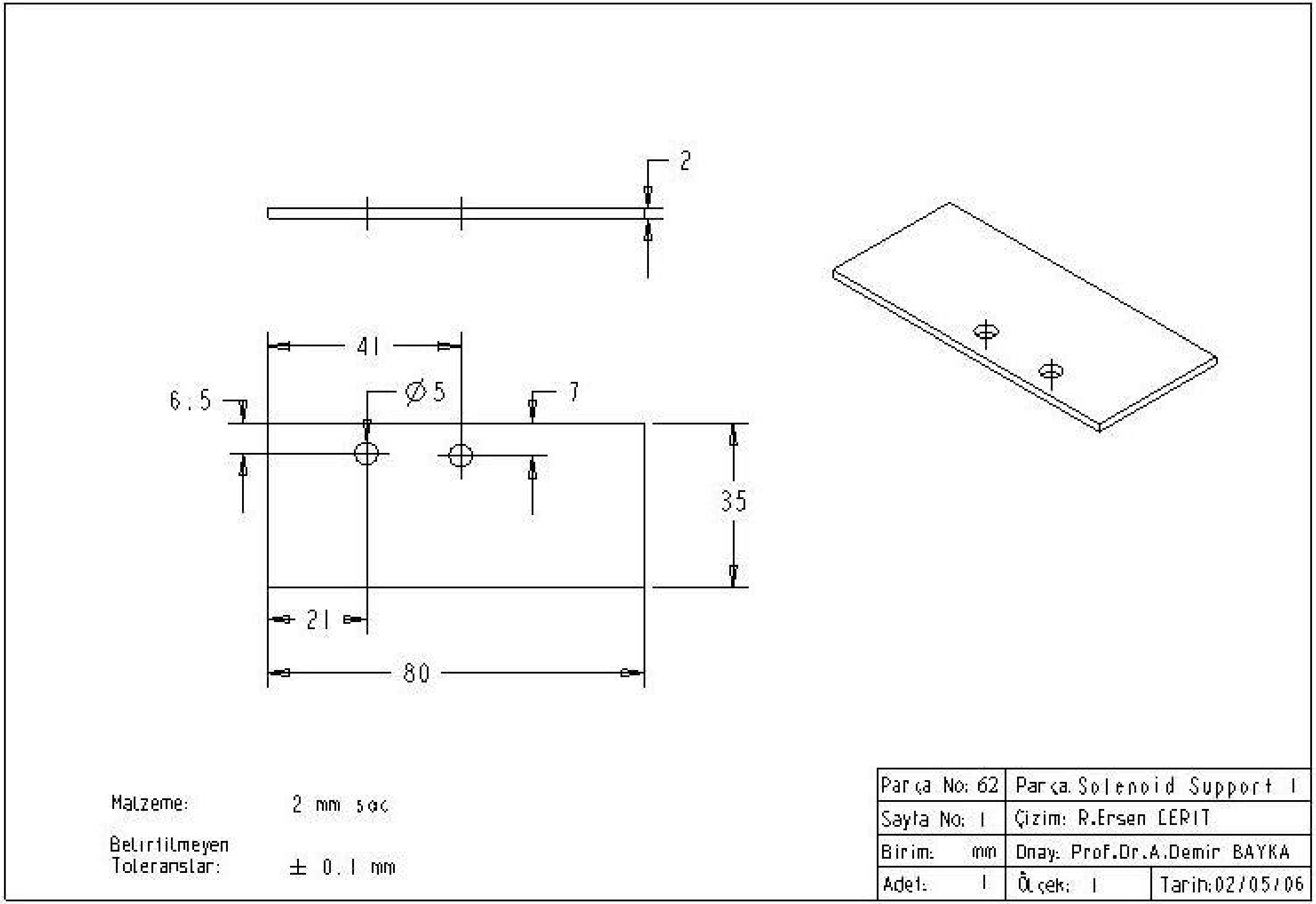


Figure E.45: Technical Drawing of Solenoid Support-1.

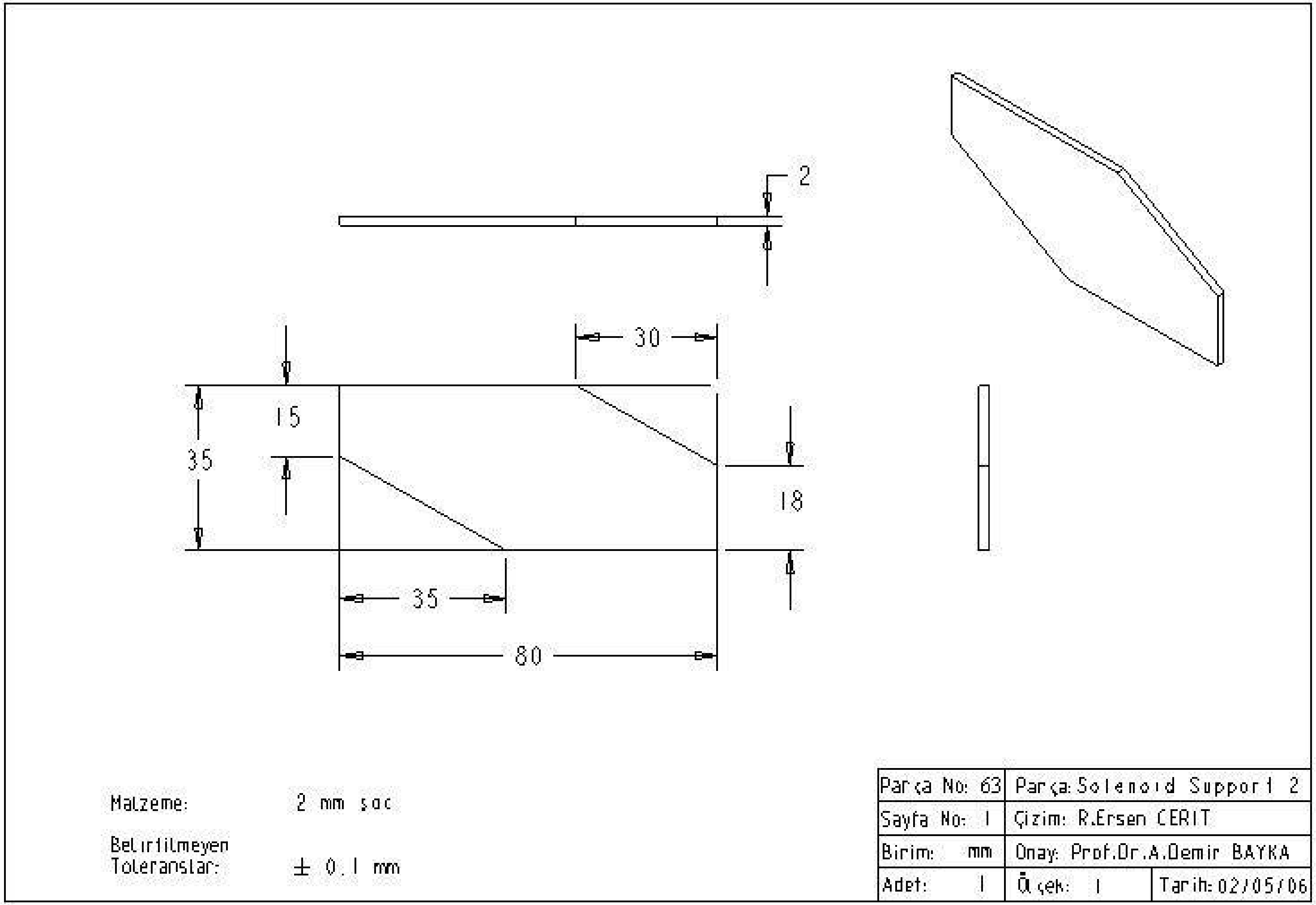


Figure E.46: Technical Drawing of Solenoid Support-2.

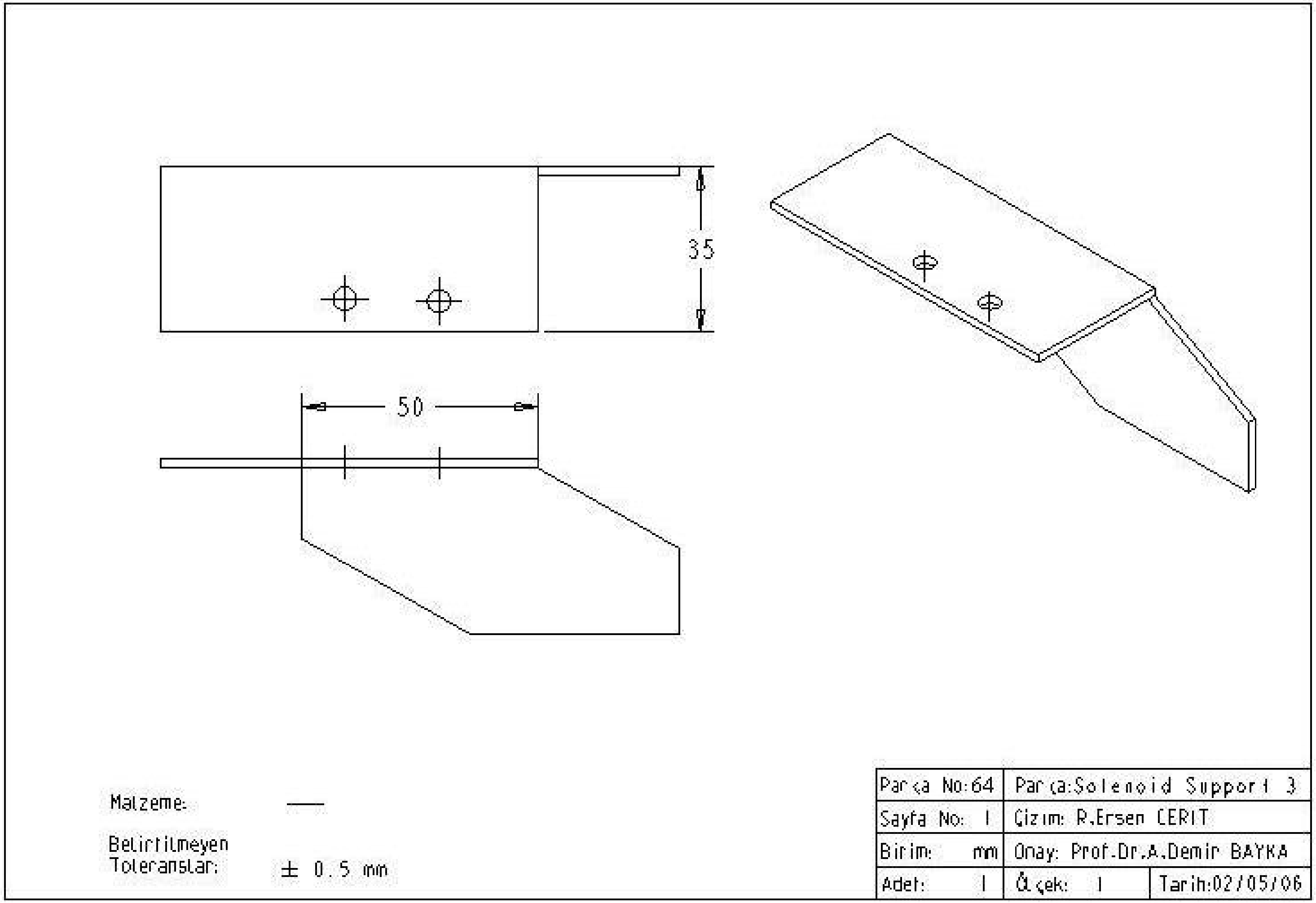


Figure E.47: Technical Drawing of Solenoid Support Body.

APPENDIX F

OPTIC SENSORS CONNECTION

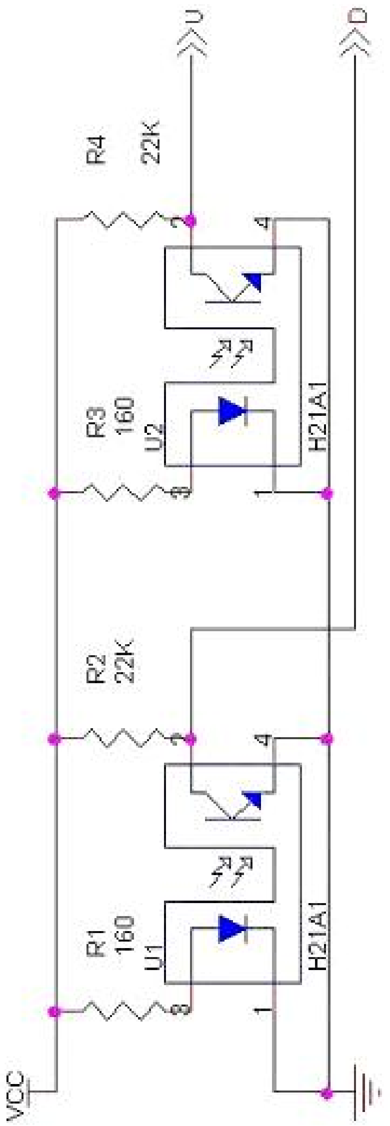


Figure F.1: Optic sensors connection.

APPENDIX G

ERROR ANALYSIS

In this appendix, error analysis of the each formula used in calculations and data read will be supplied. The analysis is being performed for following data.

Filter Material	: Cu
Ambient Temperature	: 30 ^{0}C
Ambient Relative Humidity	: 56 %
Ambient Pressure	: 738 mmHg
Engine Speed	: 1600 rpm
Dynamometer Reading	: 4.8
Load	: 100 %
Go Power Reading	: 0.86 inWater
Fuel Flow rate	: 2.66 g/s
Backpressure	: 11 mmHg
Tunnel Pressure	: 0.62 inWater
Sampling Rate	: 0.7 scfm
AVL HC	: 5 ppm
AVL Opacity	: 79.3 %
Filter Weight #1	: 201.920 mg
Filter Weight #2	: 202.195 mg
Weight factor	: 8 %
Duration	: 2 minute
Water Vapor Pressure	: 31,82 mmHg (at 30 ^{0}C)

Assuming that,

Error in Ambient Temperature	: 0.5 ^{0}C then 1.7 % for 30 ^{0}C
Error in Ambient Relative Humidity	: 0.5 % for 56 %
Error in Ambient Pressure	: 0.5 mmHg then 0.07 % for 738 mmHg
Error in Engine Speed	: 10 rpm then 0.6 % for1600 rpm
Error in Dynamometer Reading	: 0.05 then 1 % for 4.8
Error in Go Power Reading	: 0.005 inW then 0.6 % for 0.86 inWater
Error in Fuel Flow rate	: 0.005 g/s then 0.2 % for 2.66 g/s
Error in Backpressure	: 0.2 mmHg then 1.8 % for 11.0 mmHg
Error in Tunnel Pressure	: 0.005 inW then 0.8 % for 0.62 inWater
Error in Sampling Rate	: 0.02 scfm then 2.8 % for 0.70 scfm
Error in AVL HC	: 0.5 % (AVL Gas Analyzer)
Error in AVL Opacity	: 0.2 % (AVL Gas Analyzer)
Error in Filter Weight #1	: 0.002 mg then 0.001 % for 201.920 mg
Error in Filter Weight #2	: 0.002 mg then 0.001 % for 202.195 mg
Error in Duration	: 0.1 s then 0.08 % for 120 second

Using:

$$z = f(x_1, x_2, x_3 \ldots x_n)$$

$$\delta_z = \sqrt{\left[\frac{\partial z}{\partial x_1} \times \delta x_1\right]^2 + \left[\frac{\partial z}{\partial x_2} \times \delta x_2\right]^2 + \ldots + \left[\frac{\partial z}{\partial x_n} \times \delta x_n\right]^2}$$

G.1 Error in Brake Power (HP)

$$\delta_d = \sqrt{(\delta_{atm})^2 + (-\delta_{RH} \times P_v)^2}$$

$$\delta_d = \sqrt{(0.5)^2 + (-0.5 \times 31.82)^2}$$

δ_d = 15.9 mmHg then error is 2.2 % for 720.2 mmHg.

$$\delta_{K_d} = \sqrt{\left(\left(\frac{742.56^{0.65}}{298^{0.5}} \times (-0.65) \times T_{atmK}{}^{0.5} \times P_d{}^{-1.65}\right) \times \delta_{P_d}\right)^2 + \left(\left(\frac{742.56^{0.65}}{298^{0.5}} \times 0.5 \times P_d{}^{-0.65} \times T_{atmK}{}^{-0.5}\right) \times \delta_{T_{atmK}}\right)^2}$$

$$\delta_{K_d} = \sqrt{\left(\left(\frac{742.56^{0.65}}{298^{0.5}} \times (-0.65) \times 303^{0.5} \times 720.2^{-1.65}\right) \times 15.9\right)^2 + \left(\left(\frac{742.56^{0.65}}{298^{0.5}} \times 0.5 \times 720.2^{-0.65} \times 303^{-0.5}\right) \times 0.5\right)^2}$$

δ_{K_d} = 0.015 then error is 1.5 % for 1.029

$$\delta_{BP} = \frac{Torque\ \text{Re}ading\ x\ N_{speed} x\ K_d}{200} \sqrt{\left(\frac{\delta_{TR}}{TR}\right)^2 + \left(\frac{\delta_{N_{speed}}}{N_{speed}}\right)^2 + \left(\frac{\delta_{K_d}}{K_d}\right)^2}$$

$$\delta_{BP} = \frac{4.8\ x 1600 x\ 1.029}{200} \sqrt{\left(\frac{0.05}{4.8}\right)^2 + \left(\frac{10}{1600}\right)^2 + \left(\frac{0.015}{1.029}\right)^2}$$

δ_{BP} = 0.75 HP then error is 1.9 % for 39.5 HP

G.2 Error in Engine Torque (Nm)

$$\delta_T = \frac{60000}{2 \times \pi \times 1.36} \times \sqrt{\left(\frac{\delta_{BP}}{N_{speed}}\right)^2 + \left(\frac{-BP \times \delta_{N_{speed}}}{N_{speed}{}^2}\right)^2}$$

$$\delta_T = \frac{60000}{2\times\pi\times1.36}\times\sqrt{\left(\frac{0.75}{1600}\right)^2+\left(\frac{-39.5\times10}{1600^2}\right)^2}$$

δ_T = 3.5 Nm then error is 2 % for 173.4 Nm

G.3 Error in Fuel Consumption (kg / h)

$$\delta_{m_{fuel}} = \frac{-86\ x\ \rho_f\ x\ 3.6}{t_f^{\ 2}}\times\delta_{t_f}$$

$$\delta_{m_{fuel}} = \frac{86\ x\ \rho_f\ x\ 3.6}{120^2}\times0.1$$

$\delta_{m_{fuel}}$ = 0.0022 g/s then error is 0.08 % for 2.66 g/s

G.4 Error in Brake Specific Fuel Consumption (kg / HP h)

$$\delta_{BSFC} = 3.6\times\sqrt{\left(\frac{\delta_{m_{fuel}}}{BP}\right)^2+\left(\frac{-m_{fuel}\times\delta_{BP}}{BP^2}\right)^2}$$

$$\delta_{BSFC} = 3.6\times\sqrt{\left(\frac{0.0022}{39.5}\right)^2+\left(\frac{-2.66\times0.75}{39.5^2}\right)^2}$$

$\delta_{BSFC} =$ 0.0046 kg/HPh then error is 1.9 % for 0.242 kg/HPh

G.5 Error in Air Flow Rate (kg / h)

$$\delta_{m_{air}} = (6\times(-11.549)G^5+5\times114.6G^4-4\times450.38G^3+$$
$$3\times903.24G^2-2\times1009G+755.31)\times\delta_G$$

$$\delta_{m_{air}} = (6\times(-11.549)\times 0.86^5 + 5\times 114.6\times 0.86^4 - 4\times 450.38\times 0.86^3 + 3\times 903.24\times 0.86^2 - 2\times 1009\times 0.86 + 755.31)\times 0.005$$

$\delta_{m_{air}} = 0.795$ Ibs/hr = 0.36 kg/h then error is 0.3 % for 127.5 kg/h

G.6 Error in Air / Fuel Ratio

$$\delta_{A/F} = \sqrt{\left(\frac{\delta_{m_{air}}}{m_{fuel}}\right)^2 + \left(\frac{-m_{air}\times\delta_{m_{fuel}}}{m_{fuel}{}^2}\right)^2}$$

$$\delta_{A/F} = \sqrt{\left(\frac{0.36}{9.576}\right)^2 + \left(\frac{-127.5\times 0.0022}{9.576^2}\right)^2}$$

$\delta_{A/F} = 0.038$ then error is 0.3 % for 13.32

G.7 Error in Excess Air Coefficient

$$\delta_{\lambda} = \frac{\delta_{(A/F)}}{(A/F)_{stc}}$$

$$\delta_{\lambda} = \frac{0.038}{14.389}$$

$\delta_{\lambda} = 0.0026$ then error is 0.28 % for 0.93

$$\delta_{\Phi} = (1/\lambda^2)\times\delta_{\lambda}$$

$$\delta_{\Phi} = (1/0.93^2)\times 0.0026$$

$\delta_{\Phi} = 0.003$ then error is 0.28 % for 1.08

G.8. Error in Volumetric Efficiency (%)

$$\delta_{m_{ath}} = \frac{\rho_{std}\ x\ V_s\ x\ i\ x\ 2}{jx60} \times \delta_{N_{speed}}$$

$$\delta_{m_{ath}} = \frac{1.205\ x\ (9.76\ \text{x}\ 10^{-4})\ x\ 4\ x\ 2}{4x60} \times 10$$

$\delta_{m_{ath}} = 1.4$ kg/h then error is 0.6 % for 225.9 kg/h

$$\delta_{\eta_v} = \sqrt{\left(\frac{\delta_{m_{air}}}{m_{ath}}\right)^2 + \left(\frac{-m_{air} \times \delta_{m_{ath}}}{m_{ath}^{\ 2}}\right)^2}$$

$$\delta_{\eta_v} = \sqrt{\left(\frac{0.36}{225.9}\right)^2 + \left(\frac{-127.5 \times 1.4}{225.9^2}\right)^2}$$

δ_{η_v} = 0.0038 then error is 0.67 % for 0.5645 or 56.5 %

G.9. Error in Thermal Efficiency (%)

$$\delta_{\eta_{th}} = \frac{1000}{Q_c \times 1.36} \times \sqrt{\left(\frac{\delta_{BP}}{m_{fuel}}\right)^2 + \left(\frac{-BP \times \delta_{m_{fuel}}}{m_{fuel}^{\ 2}}\right)^2}$$

$$\delta_{\eta_{th}} = \frac{1000}{42000 \times 1.36} \times \sqrt{\left(\frac{0.75}{9.576}\right)^2 + \left(\frac{-39.5 \times 0.0022}{9.576^2}\right)^2}$$

$\delta_{\eta_{th}} = 0.0014$ then error is 0.54 % for 0.26 or 26 %

G.10. Error in Dilution Ratio (%)

$$\delta_{Q_{exh}} = \sqrt{\delta_{Q_{air}}{}^2 + (770 \times \delta_{Q_{fuel}})^2}$$

$$\delta_{Q_{exh}} = \sqrt{0.36^2 + (770 \times 0.0022)^2}$$

$\delta_{Q_{exh}} = 1.73$ m^3/h then error is 1.60 % for 107.9 m^3/h

$$\delta_{Q_{exd}} = \sqrt{\delta_{Q_{air}}{}^2 + (-750 \times \delta_{Q_{fuel}})^2}$$

$$\delta_{Q_{exd}} = \sqrt{0.36^2 + (-750 \times 0.0022)^2}$$

$\delta_{Q_{exd}} = 1.69$ m^3/h then error is 1.63 % for 103.8 m^3/h

$$\delta_{Q_{se}} = \delta_{Q_{exh}} \left(\frac{D_{se}}{D_{exh}} \right)^2$$

$$\delta_{Q_{se}} = 1.73 \left(\frac{13}{60} \right)^2$$

$\delta_{Q_{se}} = 0.08$ m^3/h then error is 1.57 % for 5.1 m^3/h

$$\delta_{Q_{dt}} = (84,8454 - 2 \times 0,802568 P_{dt}) \times \delta_{P_{dt}}$$

$$\delta_{Q_{dt}} = ((84,8454 - 2 \times 0,802568 \times 0.62) \times 0.005) \times (60/1000)$$

$\delta_{Q_{dt}} = 0.025$ m^3/h then error is 0.1 % for 41.5 m^3/h

$$\delta_{DR} = 100 \times \sqrt{\left(\frac{\delta_{Q_{se}}}{Q_{dt}}\right)^2 + \left(\frac{-Q_{se} \times \delta_{Q_{dt}}}{Q_{dt}^{\ 2}}\right)^2}$$

$$\delta_{DR} = 100 \times \sqrt{\left(\frac{0.08}{41.5}\right)^2 + \left(\frac{-5.1 \times 0.025}{41.5^2}\right)^2}$$

$\delta_{DR} = 0.19$ % then error is 1.56 % for 12.2 %

G.11 Error in Particulate Emissions (g/HPh)

$$\delta_{M_p} = \frac{m_p \text{ x } \mathrm{Q_{exh}} \text{ x } 100 \,/\, \mathrm{DR}}{Q_{vp} \text{ x } \mathrm{t_s} \text{ x } \mathrm{BP}} \times \sqrt{\left(\frac{\delta_{m_p}}{m_p}\right)^2 + \left(\frac{\delta_{\mathrm{Q_{exh}}}}{\mathrm{Q_{exh}}}\right)^2 + \left(\frac{-\delta_{\mathrm{DR}}}{\mathrm{DR}}\right)^2 + \left(\frac{-\delta_{Q_{vp}}}{Q_{vp}}\right)^2 + \left(\frac{-\delta_{\mathrm{t_s}}}{\mathrm{t_s}}\right)^2 + \left(\frac{-\delta_{\mathrm{BP}}}{\mathrm{BP}}\right)^2}$$

$$\delta_{M_p} = \frac{(0.275/1000) \text{ x } 107.9 \text{ x } 100\,/12.2}{(0.7 \text{ x } 28.317 \text{ x } 60/1000) \text{ x } (2/60) \text{ x } 39.5} \times$$
$$\sqrt{\left(\frac{(0.002/1000)}{0.275}\right)^2 + \left(\frac{1.73}{107.9}\right)^2 + \left(\frac{0.19}{12.2}\right)^2 + \left(\frac{0.02}{0.7 \text{ x } 28.317 \text{ x } 60/1000}\right)^2 + \left(\frac{0.1/3600}{2/60}\right)^2 + \left(\frac{0.75}{39.5}\right)^2}$$

$\delta_{M_p} = 0.005$ g/HPh then error is 2.5 % for 0.2 g/HPh

G.12 Error in Gas Emissions (g/HPh)

$$\delta_{M_{THC}} = \frac{Q_{exd} \text{ x } \rho_{\mathrm{HC}} \text{ x } \mathrm{C}_{\mathrm{HC}} \text{ x } 10^{-3}}{BP} \times \sqrt{\left(\frac{\delta_{\mathrm{Q}_{exd}}}{Q_{exd}}\right)^2 + \left(\frac{\delta_{\mathrm{C}_{\mathrm{HC}}}}{\mathrm{C}_{\mathrm{HC}}}\right)^2 + \left(\frac{-\delta_{BP}}{BP}\right)^2}$$

$$\delta_{M_{THC}} = \frac{103.8 \text{ x } 0.619 \text{ x } 5 \text{ x } 10^{-3}}{39.5} \times \sqrt{\left(\frac{1.69}{103.8}\right)^2 + \left(\frac{0.025}{5}\right)^2 + \left(\frac{-0.75}{39.5}\right)^2}$$

$\delta_{M_{THC}} = 0.0002$ g/HPh then error is 2.5 % for 0.008 g/HPh