BRNO UNIVERSITY OF TECHNOLOGY
VYSOKÉ UČENÍ TECHNICKÉ V BRNĚ

FACULTY OF MECHANICAL ENGINEERING
FAKULTA STROJNÍHO INŽENÝRSTVÍ

INSTITUTE OF AUTOMOTIVE ENGINEERING
ÚSTAV AUTOMOBILNÍHO A DOPRAVNÍHO INŽENÝRSTVÍ

GREEN FUELS FOR SMALL COMBUSTION ENGINES
ZELENÁ PALIVA PRO MALÉ SPALOVACÍ MOTORY

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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BRNO 2023

BRNO UNIVERSITY OF TECHNOLOGY FACULTY OF MECHANICAL ENGINEERING

Assignment Bachelor's Thesis

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Degree program:	Fundamentals of Mechanical Engineering
Branch:	Fundamentals of Mechanical Engineering
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Academic year:	2022/23

As provided for by the Act No. 111/98 Coll. on higher education institutions and the BUT Study and Examination Regulations, the director of the Institute hereby assigns the following topic of Bachelor's Thesis:

Green fuels for small combustion engines

Brief Description:

The target is to obtain information on the availability and properties of green fuels suitable for spark–ignition internal combustion engines. Assessment of their environmental friendliness. Development of a basic model assessing different fuels.

Bachelor's Thesis goals:

Finding the right type and composition of green fuel.
Selecting a suitable green fuel.
Calculation of the existing heat cycle.
Measurement and analysis of the SI–engine on the engine test bench.
Comparison of the existing fuel with the newly selected fuel.

Recommended bibliography:

KIRKPATRICK, Allan T. a Colin R. FERGUSON. Internal combustion engines: applied thermosciences. Third. United Kingdom: John Wiley, 2016. ISBN 978-1-118-53331-4.

BIERNAT, Krzysztof. Alternative Fuels Technical and Environmental Conditions. 1. ExLi4EvA, 2016. ISBN 978-953-51-2269-2.

STONE, Richard. Introduction to internal combustion engines. 4th ed. Basingstoke: Palgrave Macmillan, c2012. ISBN 978-0-230-57663-6.

HEYWOOD, John, HABENICHT, Rudolph E., ed. John Heywood's a dialogue of proverbs. Berkley: University of California, 1963.

Deadline for submission Bachelor's Thesis is given by the Schedule of the Academic year 2022/23

In Brno,

L.S.

prof. Ing. Josef Štětina, Ph.D.	doc. Ing. Jiří Hlinka, Ph.D.
Director of the Institute	FME dean

ABSTRACT

This study confronts the availability and function of various alternative fuels for small two-stroke spark-ignition combustion engines used in sports equipment. Because of rising GHG emissions and the increase in Earth´s surface temperature, alternative sustainable fuels seem indispensable to improve the environment. In the study, available alternative fuels are selected based on their properties and ecology. Firstly, these fuels are experimentally tested on the engine test bench, and individual engine properties are compared. Secondly, a simulation of the heat cycle of the engine is conducted to confirm the results achieved from the experiment. Out of all tested fuels, eco-friendly ethanol seems like the best-performing fuel. However, although it is not fully sustainable, another alternative fuel – E40 mixture – with lower BSFC and slightly lower performance should also be considered. All alternative alcohol-based fuels generally reached lower GHG emissions in both analyses. Based on the results, using alternative fuels in small two-stroke combustion engines can improve their performance and ecology only with small modifications. Nevertheless, more research needs to be done on sustainable alternative fuels to start large-scale serial production and reduce transport´s carbon footprint.

KEYWORDS

Green fuels, E-fuels, Two-stroke engines, SI-engines, Alternative fuels, Biofuels, Ethanol.

ABSTRAKT

Tato práce konfrontuje dostupnost a funkci různých alternativních paliv pro malé spalovací zážehové motory, používané ve sportovním vybavení. Kvůli rostoucím emisím skleníkových plynů a nárustu teploty zemského povrchu, se zdají alternativní udržitelná paliva nezbytná pro zlepšení životního prostředí. V práci je vybráno a vyhodnoceno několik paliv dle jejich vlastností a ekologického vlivu. Nejprve jsou alternativní paliva experimentálně otestována na motorové zkušebně a jednotlivé motorové vlastnosti jsou porovnány. Později je vyhotovena simulace tepelného cyklu motoru k potvrzení výsledků experimentu. Ze všech otestovaných paliv, ekologický ethanol se jeví jako nevhodnější palivo z hlediska výkonových charakteristik. Nicméně, i mixované částečně ekologické palivo E40, které dosahuje nižší měrné spotřeby paliva ale i nižšího výkonu než čistý ethanol, by nemělo být opomenuto. Obecně se dá říct, že všechna alkoholová alternativní paliva dosahují v obou analýzách nižších emisí skleníkových plynů než fosilní paliva. Na základě výsledků z měření je tedy možné tvrdit, že použití alternativního paliva v malých spalovacích motorech bez zásadních úprav může zlepšit jejich výkonnost a ekologii. Je ovšem nezbytné, provést více výzkumu v oblasti alternativních paliv, aby bylo možné zahájit jejich sériovou výrobu a snížit tak dopad dopravního sektoru na ekologii Země.

KLÍČOVÁ SLOVA

Zelená paliva, E-paliva, Dvoutaktní motory. Zážehové motory, Alternativní paliva, Biopaliva, Ethanol.

BIBLIOGRAPHIC CITATION

ZÁHORSKÝ, L. *Green fuels for small combustion engines*. Brno, 2023. Bachelor's thesis. Brno University of Technology, Faculty of mechanical engineering, Institute of automotive engineering. Supervisor of the Bachelor's thesis Josef Štětina. Available also at: https://www.vut.cz/studenti/zav-prace/detail/149584

DECLARATION OF AUTHORSHIP

I hereby declare that this thesis is my own work, which I elaborated individually under Josef Štětina's supervision. All the sources have been quoted and acknowledged by means of a complete list of references in this document.

Brno, May 25, 2023 ……..……..…………………………………………..

Lukáš Záhorský

ACKNOWLEDGMENT

I would like to thank MSR Engines s.r.o. company, and especially Ing. Petr Krečíř, for the material and knowledge support for the experiment on the engine test bench, as well as thesis supervisor prof. Ing. Josef Štětina, Ph.D., and Ing. Michael Böhm for their help during the simulation process, persistence, and patience with my study. My thanks also belong to my closest ones, my, family, and everybody, who somehow supported me.

CONTENTS

INTRODUCTION

Since the Industrial revolution in the mid-19th century, the emission of greenhouse gases (GHG) has been rising rapidly, as many independent scientific studies have shown. This rise led to a global increase in the concentration of several major pollutant gases in the Earth's atmosphere, such as carbon dioxide. The annual carbon dioxide emission per year to the atmosphere has risen from 5 billion tons to 35 billion tons in the last 70 years. As scientists have proved, this effect undoubtedly contributes to the augmentation of Earth's surface temperature – a phenomenon known as global warming. Many have suggested that CO_2 emissions must be reduced significantly to stop this negative effect of global warming on time.

Sources of the emission of GHG vary across the whole industry. Recently, the biggest contributor has been the power production. Still, it is imperative to mention that over 22% of total CO_2 emission belongs to transportation – in a certain way to the combustion engines. Numerous solutions to reducing GHG emissions have been suggested, especially for the transportation sector. The solution must offer a sustainable and easily implementable way to reduce local GHG emissions from transportation. Nowadays, electrification of all kinds of vehicles seems the most suitable way. However, this convention from combustion engines to electric motors has got difficulties. Using hydrogen as a power source seems like another option; nevertheless, the hydrogen distribution network is still to be made, and the production and storage are not as simple as they may seem at first sight.

What may be a turnabout are the green fuels – usually called biofuels or synthetic fuels (e-fuels). They differ from conventional fossil fuels in the production process. While fossil fuels are made from crude oil reserves, green fuels are produced from biomass or artificially from essential chemical substances. Usually, synthetic fuel production requires a large amount of CO_2, hydrogen, and electricity – which can be made from ecological sources. The combustion of synthetic fuel generates, of course, the emission of CO_2. Still, theoretically, it is the same amount used during its production, so the synthetic fuel's life cycle does not add any more CO_2 to the atmosphere. The implementation to the market can be straightforward, as not so many construction changes in an internal combustion unit must be made. The first step of synthetic fuels can be alcohol fuels – ethanol or methanol, which are already being used in fossil form in some countries in South America.

This thesis aims to find a green fuel (biofuel or synthetic fuel) available on the market and to test it by many means against conventional fuel in specific engine in production. This selected fuel will be tested on an engine bench, where many parameters can be observed. The results from the real-life test will also be supported by an analysis of the engine and its different fuels in simulation software. The question is, will the green fuel match the fossil fuel properties, and will the engine maintain its performance?

If the results had favored green fuel, it would be possible that there could exist an easy way to lower GHG emission from small combustion engine (which is tested). The Council of the European Union has adopted a new set of regulations that bans any cars producing CO_2 locally from 2035. As it follows, this could be a death to all ICE if no last-minute update allowed synthetic fuels (e-fuels) instead of fossil fuels. This is why research in this field must be done and implemented in the market as soon as possible, as this thesis tries to demonstrate.

1 GLOBAL ECOLOGICAL SITUATION

Everything from any domain has been rising or expanding in the past century. The world's population has risen from 2,5 billon to 8,0 billon people in just 70 years, and it is estimated to reach 10 billion by the year 2100 [1]. Technological progress has also been on the rise, with more and more innovations intended to simplify human life happening every day. However, everything that the expanding humanity produces impacts nature [2].

The most apparent observed phenomenon is the increase in the global average surface temperature of the Earth. Since the 1950s, the temperature has been rising, as Fig. 1-1 shows.

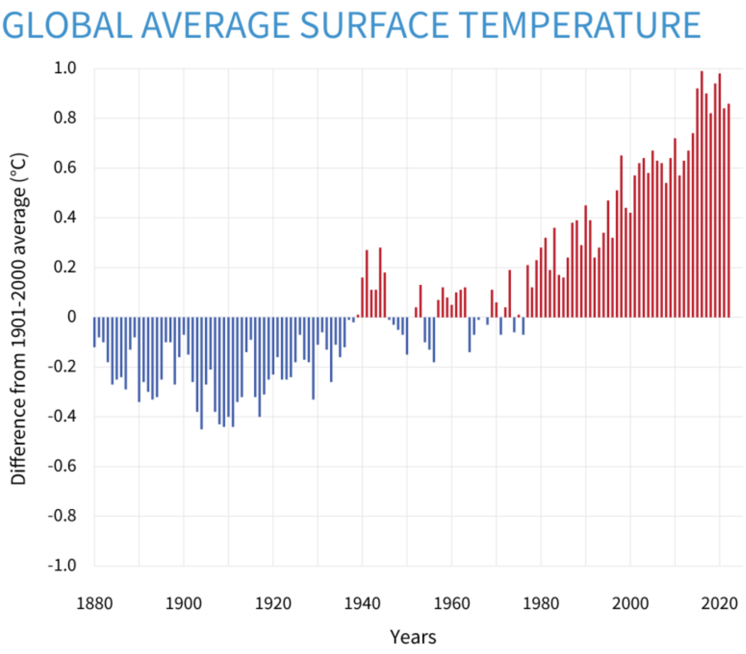


Fig. 1-1 Global average surface temperature over the years [55]

1.1 GREENHOUSE GASES EMISSION

What is the reason behind this annual increase, and why is it happening nowadays? Scientific evidence proves that this negative phenomenon occurs mainly due to human contribution. Primarily because of activities emitting well-known heat-trapping greenhouse gasses (GHG) into the atmosphere [2]. GHG include "*CO_2, methane (CH_4), hydrofluorocarbons (HFCs), perfluorinated compounds (PFCs), and others.*" [3] The first one mentioned is mostly a product of the combustion of fuels in electric power generation, industry, building heating, and transportation. As more GHG are emitted, more heat (from Sunshine) is trapped in Earth's atmosphere, thus raising Earth's temperature.

As recent data shows [4], the CO_2 annual emissions to the atmosphere have been rising gently from a few gigatons in the early 20th century to approximately 5 gigatons in the first half of the century, until skyrocketing to 30 gigatons in the second half of 20th century. This sudden increase is due to the expansion of the combustion of fuels in the worldwide industry. In hand with the emission, the concentration of carbon dioxide in the atmosphere has been growing up to 410 ppm, which is over 20% more compared to the concentration 50 years ago. Both progresses are shown in Fig. 1-2.

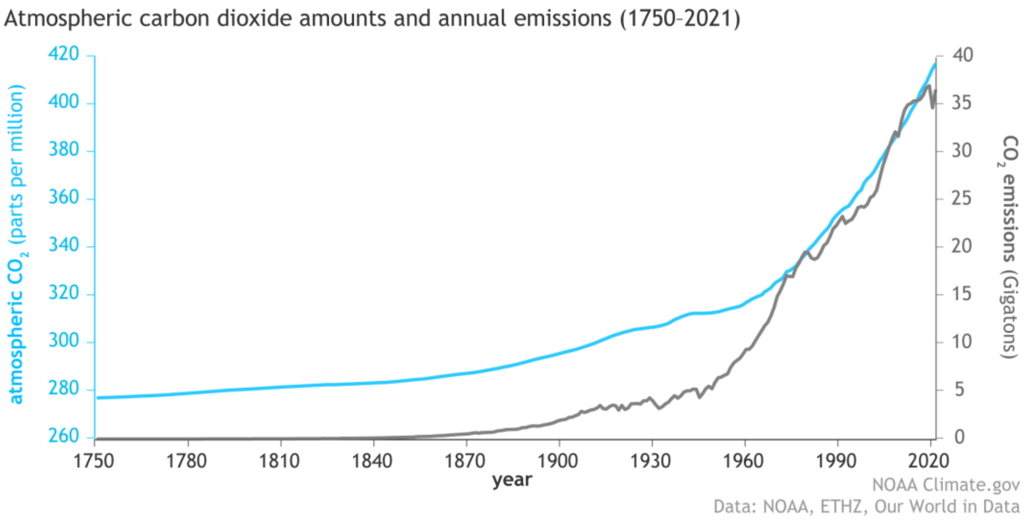


Fig. 1-2 Atmospheric CO_2 concentration and CO_2 emission [4]

Undoubtedly, the planet's temperature and GHG emissions are related. Moreover, "*projections of future climate change indicate that Earth will continue to warm unless significant and sustained actions are taken to limit emissions of GHG.*" [2] Scientists have introduced several global climate models (CMIP5) that predict possible temperature development [5]. In all cases, the magnitude of climate change depends on annual emissions of GHG. The lower the emissions (RCP2.6 and RCP4.5), the greater the chance to slow down the temperature increase. All models and their CO_2 and temperature relation can be found in Fig. 1-3a and Fig. 1-3b, respectively.

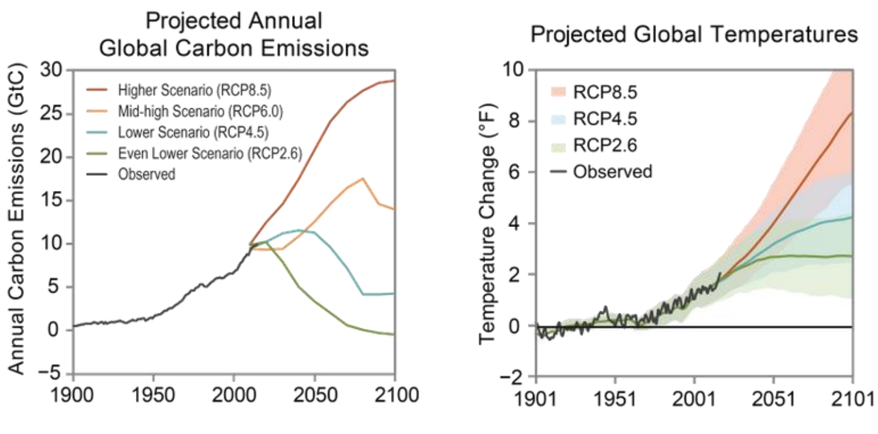


Fig. 1-3a Annual CO2 emission projection models [56]
Fig. 1-3b Related temperature change for different projection models [56]

All the efforts and analyses aim to maintain the global average temperature increase under 2 °C in the following years [6]. If the temperature increase had significantly grown, it would have led to a series of "*multitude of related and interacting changes in the Earth system, including decreases in the amounts of ice stored in mountain glaciers and polar regions, increases in sea level, changes in ocean chemistry, and changes in the frequency and intensity of heat waves, precipitation events, and droughts. These changes pose significant risks to both human and ecological systems*." [7] The need to dramatically reduce GHG emission, in other words, CO_2 emission, has never been higher. The dramatic consequences would have come in tens of years, but actions must now be taken.

1.2 IMPACT OF TRANSPORTATION ON ECOLOGY

Transportation plays a vital role in the global ecology situation. Over 93% of transport is powered by fossil fuel combustion and barely 4% runs on biofuel. [8] Therefore, transportation produced over 22% (7,98 Gt of CO_2) of global CO_2 emissions in 2022. The major contributor to CO_2 emissions remains energy production (14,65 Gt of CO_2), the second largest is industry (9,15 Gt of CO_2), and the smallest is building heating (2,97 Gt of CO_2) [9]. In all the sectors, efforts to lower the emission of CO_2 have been implemented. In energy production, renewable energy sources composed over 28% of total energy production in the world in 2021. Industry and building heating also tend to use renewables. [10]

In transportation, more actions need to be taken to reduce carbon footprint. As described before, the transition to renewables is not as fast as with energy production. Therefore, global and state institutions with juridical and political power or influence must act decisively. Nowadays, the most active element in this radical changeover seems to be the European Union. The recent summit of the European Parliament of the European Union and the Council of the European Union on 28th March 2023 has adopted a new set of regulations (interinstitutional file 2021/0197) to eliminate carbon dioxide emissions from new cars and vans by 2035. [11] This regulation has been approved after months of discussion and based on available analytic data, which proves that road transportation produces the most emissions (5,87 Gt of CO_2) out of the transportation sector [8]. Since any combustion engine produces CO_2 while working, the new restriction means banning cars with internal combustion engines (ICE). However, an exemption has been made for "*sustainable alternative fuels to reach climate neutral mobility*," [12] which translates directly to all kinds of fuels produced in a non-fossil way – so-called green fuels or e-fuels. More importantly, electric-powered vehicles, hybrids, or hydrogen cell vehicles should be favored and preferably produced by car manufactures in the European Union to accommodate the new standards.

The focus is now placed mainly on the road sector of transportation, which means cars, vans, and trucks.

1.3 ALTERNATIVES TO CONVENTIONAL FUEL IN ROAD TRANSPORTATION

Conventional fuel – oil, then refined into different types of fossil fuels, presents the main source of transportation fuel (mentioned before, 97%). Necessary to mention that over 32% of world crude oil production is purified to Gas or Diesel, and over 26% to motor gasoline used in road transportation [13]. Hence, huge amounts of crude oil are used for road transportation, and this explains the high emissions of CO_2 to the atmosphere by the road sector. Needless to say, the world oil reserves are not infinite, and they are fast depleting. Therefore, world governing bodies and local, national governments have supported transitioning from conventional fossil fuels to nonconventional sustainable alternatives. [12]

1.3.1 ELECTRIC VEHICLES

The most significant advantage of an electric vehicle (EV) is its local zero-emission driving mode, which seems a very reliable way to reduce pollution from road transportation. Electrification of transportation can cut dependence on oil reserves and improve the energy independence of countries. [14] Also, EVs powertrain has higher efficiency (60–80%) than the one from vehicles with ICE (20–35%) [15]. The problem with EVs is not their consumer usage but their production. As many studies have shown, the mining of lithium needed for an EV battery and the pollution related to battery production presents a high drawback for EVs [16]. Nevertheless, a model study has proven that EVs are less polluting than ICEVs (internal combustion engine vehicles) only when reaching a lifetime of more than 100 000 km. Longer lifetime also favors EVs. As the average lifetime of a medium-sized saloon car in Europe is 225 000 km, EVs stand a high chance of improving the pollution from road transportation. [17] However, all the energy that EVs use during their life must come from renewable sources, which is hardly feasible due to insufficient electricity distribution networks [18].

1.3.2 HYDROGEN FUEL CELL VEHICLES

Fuel cell electric vehicles (FCEVs) are powered by hydrogen; their only emissions are water vapor and warm air [19]. Another advantage is quick refueling compared to EVs [20]. However, industrial production of pure hydrogen presents the main challenge for this type of vehicle, as a renewable energy source must produce hydrogen to reduce GHG emissions. Another disadvantage is its distribution and storage. Liquid hydrogen seems to be the only possible state for storing this substance, while it must be stored "at *the temperature of 20 K at 2 bars in double-walled insulated cylinders. The liquid hydrogen may be delivered in liquid form or gaseous form based on our requirement."* [21] This may seem like a challenge that must be solved before massive serial production of FCEVs.

1.3.3 ALTERNATIVE FUELS FOR ICEV

The list of alternative fuels for ICE is extensive. Firstly, it can be vegetable oils, which are very good as a substitute for a diesel (compression) engine application, for their chemical composition and properties. They are also environmentally friendly. However, they are in effect, less efficient than diesel fuels, and they are neither cheaper to produce because they depend largely on the seed price and market location. [21]

Another alternative to fossil fuels is biofuels, referred to as biodiesel. It is produced by a reaction of vegetable oil and alcohol in the presence of a catalyst. The biggest drawback is higher NO_x emission and lower energy density in biodiesel, meaning vehicles running on biodiesel usually consume more fuel.

A gaseous alternative for ICEV standard fuel can be Liquefied Petroleum Gas (LPG). This fuel type is commonly used, mostly because it has "*high octane number for spark ignited engines, comparable to gasoline heating value that ensures similar power output*." [21] However, LPG cannot be produced sustainably – it comes from a fossil source. That is why the proposed solutions are not included in reducing CO_2 emissions. [11]

Compressed natural gas (CNG) is also widely used. Even though it is nonrenewable, many studies have shown that CNG produces fewer CO_2 emissions than diesel fuels. Therefore, CNG can contribute to lowering CO_2 emissions globally. [21]

Finally, alcohol fuels can play a major role in the fight against nonrenewable fossil fuels. Alcohol fuels, such as methanol or ethanol, can be produced from natural gas and renewable sources – for example, biomass. Methanol and ethanol are the simplest alcohols, produced as liquids, with high energy density and similar properties as gasoline. Alcohols can be used in already working ICEV, without any major modifications to the engine. Alcohol fuels are good candidates for sustainable alternative fuels of their abundance, and physical and chemical properties, and they could drastically reduce CO_2 emissions from road transportation. [21]

Given the reasons above, this thesis focuses mainly on alternative sustainable alcohol fuels for ICE.

1.3.4 Implementation of an ICE

It is imperative that all kinds of alternative fuels would be tested on a production ICE. Every ICE produces emissions of GHG, especially CO_2, and therefore switching to sustainable alternative fuel is a need for every combustion engine in production by any manufacturer. Types of ICE vary, depending on the engine cycle they are working on. Spark ignition (SI) engines use the Otto cycle for their four-stroke cycle. Diesel engines – compression ignition engines obey the Diesel four-stroke cycle. The types of engines specified above produce power for every other downward stroke. On the contrary, two-stroke engines produce power every revolution, have a higher specific power, have a better-to-weigh ratio, and are usually simpler. Their biggest disadvantage is the scavenging process, which is "*simultaneously exhausting the burnt mixture and introducing the fresh fuel-air mixture into the cylinder*." [22]

Because of the simplicity of the two-stroke engine, this study considers it easier to test different fuels in a two-stroke engine rather than in a four-stroke engine. Several tests and analyses must be conducted to conclude whether the alternative fuel can satisfy consumer needs and reach lower GHG emissions, therefore opening an option towards fuel sustainability.

A specific engine produced by a Czech manufacturer of two-stroke combustion engines – MSR Engines s.r.o., has been selected for the tests. Engine MSR NG 100 (Fig. 1-4) information and specifications can be found in the Tab. 1-1, and Tab. 1-2.

Fig. 1-4 MSR Engines NG 100 cm^3 engine [46]

Type of engine	**the two-stroke internal combustion engine**
Ignition type	spark ignition
Fuel injection type	electric injector controlled by ICU
Fuel injection position	indirect injection before the reed valve
Cooling system	water-cooled engine and exhaust
Exhaust type	reverse expanding double layered cone type
Propulsion type	direct shaft propulsion
Starting mechanism	AC starter with freewheel gear

Tab. 1-1 MSR Engines NG 100 cm^3 specifications

Engine parameter	**value**	**unit**
Combustion chamber volume	100	cm^3
Cylinder bore	50	mm
Cylinder stroke	49.5	mm
Connecting Rod Length	91	mm
Cylinder compression ratio	12.5	-
TDC Clearance Height	0.9	mm
A compression ratio of crankcase volume	1.23	-

Tab. 1-2 MSR Engines NG 100 cm^3 technical parameters

This mentioned engine will present the main observed ICE for the thesis. Every result achieved in the thesis links solely to the mentioned engine.

2 GREEN FUEL TYPES AND PROPERTIES

The notation **green fuels** in this thesis refers to any alternative fuel produced from a sustainable source other than conventional crude oil reserves. Sustainable sources can be biomass, feedstock, chemical reaction, etc. Moreover, it is mentioned in the new set of regulations (interinstitutional file 2021/0197) that one of the possible ways to reach climate neutrality is to consider "*the potential contribution of innovation technologies and sustainable alternative fuels, including synthetic fuels,*" [11] which directly favors all kinds of sustainable alternative fuels.

2.1 BIOFUELS

The first type of alternative fuel is the biofuels. Biofuel is classified into 2 classes, out of which one divides into 4 generations – depending on the production source. The exact classification is shown in Fig. 2-1.

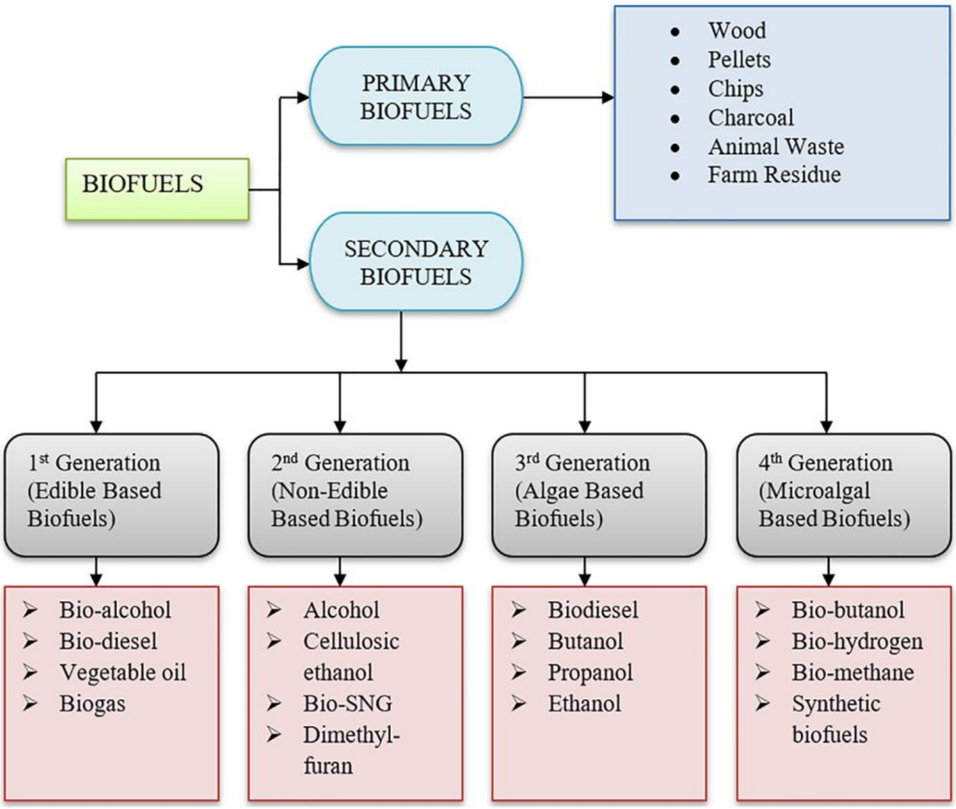


Fig. 2-1 Biofuel types & generations [25]

It is needless to say that many studies have exploited the possibilities of biofuel, and it has been proven that some of them may work very well in ICE as a replacement for conventional fuel. [23]

The first generation is produced from starch, vegetable or animal oil, and sugar. It includes fuels like bio-ethanol, which are produced by extraction with the help of enzymes and microorganisms and later fermentation. [24]

Second-generation fuels "*are manufactured by cellulosic or carbohydrate biomass. These carbohydrates are commonly extracted from non-edible matters of plants and farming.*" [25] For example, a biofuel called cellulosic ethanol can be produced via the fermentation of sugar, which can be derived from polyose and cellulose compounds found in lignocellulose [24].

The third generation is mainly represented by algal oils, which seems like a great option to substitute fossil fuels. It is mostly because algae contain energy-rich oils. However, because of high production prices (due to necessary modern technologies), third-generation biofuel has not made its biggest impact yet. [24]

Unlike third-generation, fourth-generation biofuels are produced with the contribution of genetic engineering. "*The biomass supply in fourth generation biofuels is come from micro algae, macro algae and cyno-bacteria.*" [25]

The biggest advantage of biofuel is arguably lower emission of CO_2 gas, which makes them more environmentally friendly than conventional fuel. During their production, some biofuels consume CO_2 from the atmosphere and return it during use – this can be considered a sustainable way to achieve carbon neutrality. However, biofuel production remains more expensive than fossil fuel production, with an extra need for large areas. In addition, a conflict between fuel and food interest should be noticed, as both require large feedstock supplies. [24]

As mentioned, alcohol fuels (methanol and ethanol) of certain origins may be considered biofuels.

2.2 SYNTHETIC FUELS

"*The term "synthetic fuels" (synfuels, electrofuels) covers several fuels produced in conversion processes like water electrolysis*," [26] mainly conversion processes with hydrogen and its derivatives. The most common source of production of gaseous synthetic fuel is the Sabatier process, where a conversion of hydrogen and CO_2 produces methane. Another means to produce synthetic fuel is Fischer Tropsch synthesis, used to produce liquid fuels such as petrol, diesel, or alcohol fuel. [26]

The major benefit of synthetic fuels is that they are "*potentially suitable for substituting both the energetic use of energy carriers and the use as feedstock."* [27] Because the production of synthetic fuels does not require large areas or big oil supplies, its production may seem easy compared to biofuel. Nevertheless, a massive amount of CO_2 (which must be captured from the atmosphere by a certain modern technology consuming energy) and hydrogen is required to produce synthetic fuel, hand in hand with a need for an extra sustainable energy supply. Thus, the sustainability of synthetic fuels can only be achieved if all the sources are sustainable. Although this seems like the biggest challenge for synthetic fuels nowadays, [28] several studies "*results indicate that the use of synthetic fuels can be expected with a high level of climate protection."* [27]

2.3 TWO-STROKE ENGINE COMPATIBILITY

The two-stroke engine model is a specific type of SI engine, as mentioned in section 1.3.4. Any production two-stroke usually works with a specific mixture of fuel and oil to achieve proper function. Different alternative sustainable fuels (biofuels, synthetic fuels) vary across the industry. Thus, it is imperative to conduct tests of mixing any fuel with different types of oils to discover if this mixture can be used as a source to power the two-stroke engine. Synthetic petrol or diesel can be mixed with conventional oils the same way as with conventional fuels. [29]

However, because of the different polarity of oil and alcohol-based fuels, a major part of production oils is non-soluble in alcohol fuels [29]. Nevertheless, some vegetable oils can be mixed with alcohol fuels, as will be later demonstrated in chapter 5.2.1.

Recently, studies have demonstrated that biofuels can be easily used in a specific type of two-stroke SI engine. For example, a large marine boat powered with a two-stroke SI engine has been converted to biofuel, and it has been concluded that "*biofuel qualities exhibited very similar behavior to the corresponding fossil reference fuels. The given main engine can hence be operated on those new sustainable fuels successfully and without impairing the compliance with the applicable emissions.*" [30] However, to achieve the same or even higher energy output, a few modifications to the engine should be made.

3 WORLD AVAILABILITY OF GREEN FUELS

The availability of green fuels is a very extensive subject. As all biofuels are not produced from crude oil reserves, their production usually requires a large area for feedstock or supplementary energy for chemical processes.

3.1 BIOFUEL AVAILABILITY

The use of biofuel depends solely on its generation. First-generation biofuels are commonly used in Brazil or the United States of America. "*Specifically, the feed stock of corn grain is used in biorefinery facilities to manufacture biofuel or bioethanol*." [31] The production of bioethanol from corn in Brazil has been increasing dramatically every year, as the data of Fig. 3-1 shows [32].

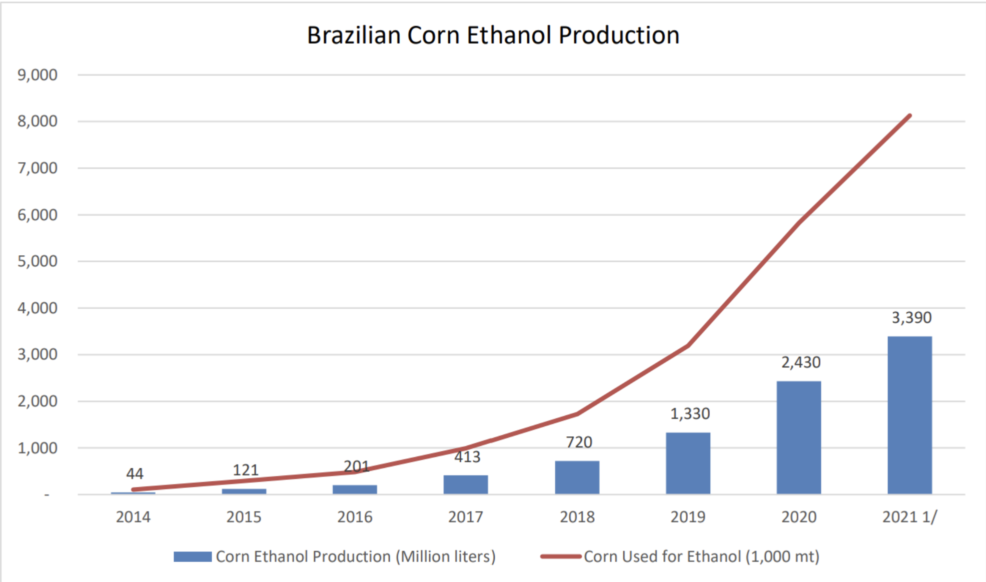


Fig. 3-1 Production of ethanol from corn in Brazil [32]

Yet, the huge amount of ethanol produced from corn in Brazil in 2022 (4500 million liters) is still nothing to compare to solely United States crude oil production in 2021 (690 182 million liters) [33].

Second generations biofuels are also globally produced, but they represent only 0.1% of world biofuel production [34]. Its small share should be enlarged because second-generation biofuel can "*be produced more sustainably than some 1st-generation fuels, and with better land use opportunities, including potential production on marginal lands. However, full commercialization of either biochemical or thermo-chemical conversion routes for producing 2nd-generation biofuels appears to remain some years away*." [35]

Other generations of biofuel are used only on the laboratory level – production plant for 3rd or 4th generation biofuel is still yet to be made.

3.2 SYNTHETIC FUEL AVAILABILITY

As it has been mentioned earlier, liquid synthetic fuels are produced through Fischer-Tropsch synthesis. During this reaction, CO_2 reacts with hydrogen to produce hydrocarbons, which can be later refined in industrial plants into petrol or diesel. It is necessary to mention that all sources of this reaction (chemical end energetic) must be sustainable to create sustainable alternative fuel, commonly called e-fuel. If the new e-fuel does not produce any CO_2 emission during its production but rather consumes it, it becomes CO_2 neutral. [36] This type of fuel will be allowed even from 2035 by the new set of regulations adopted by the European Commission. [11] The production is schematized in Fig. 3-2.

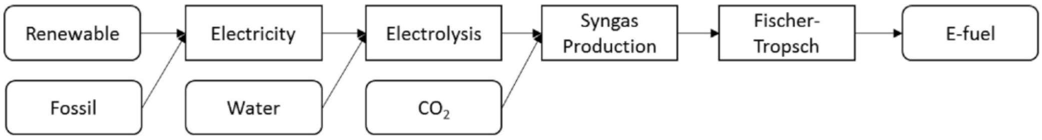


Fig. 3-2 Schematic production of synthetic fuel [36]

Synthetic fuel is not yet commonly available on the market, but some pilot production plants are under construction. German car manufacturer Porsche, owned by VW group, plans to invest about 30 billion $ in its first production plant for synthetic fuels in Chile. The new fuel produced explicitly from renewable and sustainable sources would be CO_2 neutral, and its use or production would not increase the GHG concentration in the atmosphere. The German company intends to run its cars with ICE solely on synthetic fuels from 2035 in the whole world. However, some major economic, logistical, and political challenges are still to be solved. [37]

4 ECOLOGY OF GREEN FUELS

Any hydrocarbon fuel produces CO_2 emissions during the combustion process. The amount of CO_2 produced depends on many variables of specific ICE but generally presents a danger to our climate and environment. Not only ICE produces CO_2, but some other gases like carbon monoxide, nitrous oxide, or methane are emitted as well.

Many factors of the environmental impact of fuels can be considered, but the most important and most mentioned is the amount of CO_2 emitted by an ICE. Today's international standard in the European union, called EURO 6d, sets the maximum limit of emitted CO_2 at the value of 95 gCO_2/km for personal vehicles and 141 gCO_2/km for light commercial vehicles. If the car manufacturer cannot meet these criteria, the manufactures must pay fines for every extra gram. Therefore, car manufacturers seek to find a way to reduce these emissions – and green fuels seem like a favorable option. [38]

Green fuels, or alternative sustainable fuels, can contribute to reducing global CO_2 emissions and therefore improve the environmental situation. "*Alternative fuels are capable of reducing the engine emissions as compared to petroleum products. The molecular structure of alternative fuels (CH_3OH, C_2H_5OH, and CH_4, etc.) is much simpler than gasoline/diesel (mixture of different molecules). Moreover, a low C:H ratio of alternative fuels generates less hydrocarbon emissions on combustion.*" [39] It has been demonstrated on analytic models that the use of bio-alcohol fuels of the first generation of biofuels (bio-methanol or bio-ethanol) can produce approximately 40% fewer emissions than conventional petrol fuel, especially because of a more economical production process. [40]

However, economic factors do not favor environmental requirements in the real world. This applies mainly to synthetic fuels or e-fuels. "*E-fuels can be advantageous in terms of GHG emission compared to fossil fuels but are disadvantageous in terms of production cost.*" [36] A study has demonstrated that CO_2 neutral production cost of an e-fuel is 13,28 € ct/MJ, and its emissions are 64.07 g/MJ. Compared with fossil fuel, produced in a non-sustainable way, with a production cost of 0.61 € ct/MJ and emissions of 83.8 g/MJ, it does not seem that CO_2-neutral fuels can immediately replace fossil fuels until their production is not dramatically reduced. [36] This directly means that more renewable sources of energy should be installed, hand in hand with more innovative and efficient technologies to produce e-fuels artificially.

5 GREEN FUELS APPLICATION IN A PRODUCTION ICE

In this study, several available green fuels should be tested in a production ICE. The goal is to demonstrate the effect of alternative sustainable fuels, available on the local market and suitable for two-stroke SI combustion engines, on engine performance, efficiency, and emissions. The newfound fuel must meet some requirements to be selected for a series of extensive tests, then the results should be analyzed and conclusions brought up.

5.1 LOCALLY AVAILABLE GREEN FUELS ON THE MARKET

As described in the previous chapter, alternative sustainable green fuels are not commonly available on the market, especially in the Czech Republic. Although alternative fuel, labeled E85, is usually available at fuel stations (with 53% to 85% ethanol and the rest regular petrol, according to the norm ASTM 5798), it is still a fossil fuel. No fuel station would provide sustainable alternative fuels for ICE for a personal customer. This is why only a few alternative fuels were considered in the analysis. Newfound fuels and fossil petrol fuels are described in Tab. 5-1.

5.1.1 ETHANOL

Because of the low availability of green fuels, or any biofuels, a special supplier of denatured ethanol C_2H_5OH (CAS number 64-17-5), produced by fermentation of sugar, has been found in the Czech petrochemical industry. This fuel is considered the second generation's biofuel and therefore is considered sustainable and environmentally friendly. Another reason to choose ethanol as an alternative fuel is its higher octane number (108,6 RON) than fossil petrol fuel, allowing it to withstand higher compression in ICE before detonating. This should also positively affect the engine performance. It also has lower vapor pressure, which should lower evaporative emissions. Ethanol has lower flammability than petrol, which means it is harder to start the combustion process in ICE. [41]

5.1.2 METHANOL

Another fuel found on the Czech market is methanol CH_3OH (CAS number 67-56-1). Unfortunately, retrieving sustainable methanol from renewable or organic sources has not been possible. Therefore, fossil methanol has been chosen. Chemical composition remains the same, which should not affect the engine performance, but the emissions can differ from bio methanol. Like ethanol, methanol has a higher octane number (108.7 RON) than conventional petrol fuels. [41]

5.1.3 THE MIXTURE OF PETROL AND ETHANOL (E40)

Additionally, a special mixture of regular fossil petrol and sustainable ethanol was created. The mixing ratio was 60% clear petrol (known as Natural 95, notation E5 by EN 228) and 40% of clear biofuel ethanol (CAS number 64-17-5). This mixture was created to determine whether adding a more considerable amount of ethanol (considered green fuel) would influence the engine performance, economy, and emissions. Based on data from research [39], E40 seems like the best ratio for the mixture of petrol and alcohol. It is proclaimed that "*best increase in thermal efficiency at the E40 mixture was (25.8%) compared to gasoline*." [39] This study aims to achieve similar results with this mixture.

Name	Petrol	Ethanol	Methanol
International standard	ČSN EN 228	CAS number 64-17-5	CAS number 67-56-1
Notation	BA 95 Super	E100, EtOH	MeOH
chemical composition	hydrocarbon chain	C_2H_5OH	CH_3OH
RON number	95	108.6	108.7
density (at 20 °C) [kg/m^3]	720 - 775	810	790
Maximal methanol content [%]	-	-	90
Maximal ethanol content [%]	5	99	0
Maximal oxygen content [%]	2,7	-	-
Vapor pressure (at 20 °C) [kPa]	50 - 80	5.726	12.8

Tab. 5-1 Newfound & conventional fuels [57] properties from GT manual and recommendations for two-stroke engines

5.2 CHALLENGES FOR NEWFOUND FUELS

Newfound alternative fuels have different chemical and physical properties than fossil petrol. Therefore, to use them in a two-stroke SI engine, certain properties must be assured, and a few challenges solved.

5.2.1 MIXABILITY WITH OIL

The selection of alternative fuels is mostly represented by alcohol fuels. A two-stroke SI engine (described in chapter 1.3.4) works only with a fuel that includes a lubricant, in other words, with a mixture of fuel and oil in a specifically recommended ratio. Because alcohols have different polarity than most of the available two-stroke oils, it is necessary to determine if some oil can be dissolved in the new fuel. All examined fuels were thus tested with different types of oils, which basic properties are listed below in Tab. 5-2. The results of mixability from conducted tests can be found in Tab. 5-3.

Oil name	Oil base	Quality level	Certifications	Density at 20 °C [kg/m^3]	Flash point [°C]	Boiling point [°C]	Viscosity index [-]	Color
IPONE TC-W3 100% Synthetic 2T	ester	synthetic	API TD, TC-W3	911	264	-33	138	dark red
Fuchs Silkolene Pro KR2	ester	castor & synthetic	SAE 30	944	200	-35	101	dark yellow
Xeramic Castor Evolution 2T Kart Racing	ester	castor	FIA CIK	941	235	-24	-	light yellow
Total Prosylva 2T SYN	ester	synthetic	API TC	869	-	-21	132	blue
Motorex Cross Power 2T	ester	synthetic	API TC	874	< 110	-54	156	red
Denicol Scoot Racing 2T	ester	synthetic	API TC	868	85	-40	138	yellow
Denicol Kart Powerlube 2-stroke Castor	ester	castor	FIA CIK	955	-	-	-	clear

Tab. 5-2 Different oil types and properties (from the manufacturers)

	Mixable with			
Oil name	**Ethanol**	**Methanol**	**Petrol**	**Mixture (60% petrol, 40% Ethanol, or E40)**
IPONE TC-W3 100% Synthetic 2T	NO	NO	YES	NO
Fuchs Silkolene Pro KR2	YES	YES	YES	YES
Xeramic Castor Evolution 2T Kart Racing	NO	NO	YES	NO
Total Prosylva 2T SYN	NO	NO	YES	NO
Motorex Cross Power 2T	NO	NO	YES	YES
Denicol Scoot Racing 2T	NO	NO	YES	NO
Denicol Kart Powerlube 2-stroke Castor	YES	YES	YES	YES

Tab. 5-3 Results of test of mixability of fuels with different oils

As the results indicate, regular petrol can be mixed with any two-stroke oil. The mixture (E40) can be mixed only with castor oils or one fully synthetic oil (Motorex Cross Power 2T). The alcohol-based fuels, methanol, and ethanol, are only mixable with specific castor two-stroke oils (Fuchs Silkolene Pro KR2 and Denicol Kart Powerlube 2-stroke Castor). The main reason for this effect is probably due to the different chemical compositions of synthetic or castor oils, which directly affects their mixability with alcohol fuels. The difference between properly mixed and improperly mixed samples is visible in Fig. 5-1 and Fig. 5-2.

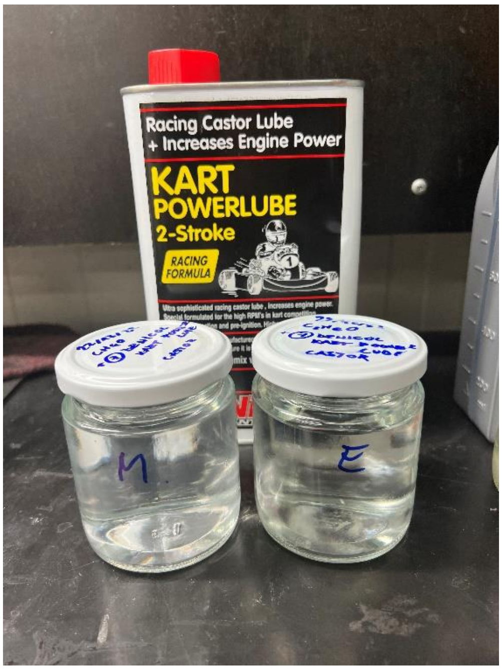


Fig. 5-1 Properly mixed fuel (Methanol – left, Ethanol – right) and oil (Denicol Kart Powerlube 2-stroke Castor)

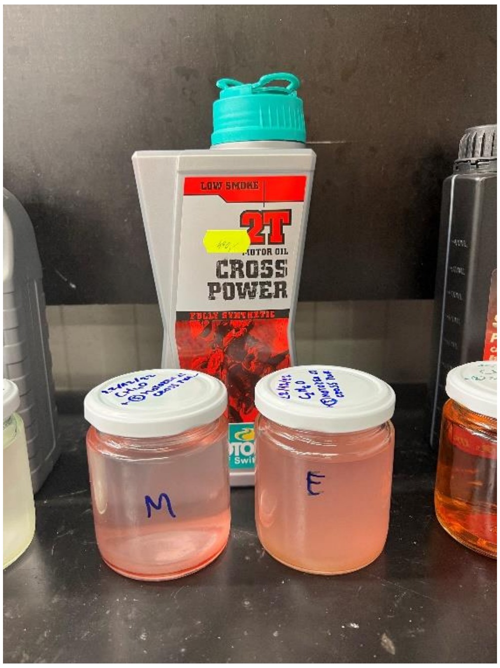


Fig. 5-2 Improperly mixed fuel (Methanol – left, Ethanol – right) and oil (Motorex Cross Power 2T synthetic)

Based on the results from the experiment, all alcohol-containing fuels are mixed with Denicol two-stroke Castor oil, in fuel to oil ratio of 25/1, given the information from the engine manufacturer. Petrol fuel is mixed with Motorex's two-stroke fully synthetic fuel in fuel to oil ratio of 50/1, as the engine manufacturer suggests for petrol. Four different fuels, mixed with different oils, will be considered in all the analyses and experiments from now on. A list of tested fuels can be found in Tab. 5-4.

Fuel	Oil	Fuel/Oil Ratio
Petrol	Motorex Cross Power 2T	50/1
Methanol	Denicol Kart Powerlube 2-stroke Castor	25/1
Ethanol	Denicol Kart Powerlube 2-stroke Castor	25/1
Mixture (E40)	Denicol Kart Powerlube 2-stroke Castor	25/1

Tab. 5-4 Tested fuels and used oils

5.2.2 Castor oil

Castor oil is a special type of vegetable oil produced from castor plants, which grows mostly in tropical areas. "*It is a natural, viscous, pale yellow, nonvolatile, and nondrying oil with a bland taste. Castor oil like all other plant oils is a vegetable triglyceride*." [42] Its advantages are mostly good renewability and low environmental impact. Moreover, it is produced without dependence on any petrochemicals, and its chemical properties, like low density, desirable fiber aspect ratio, or relatively high tensile and flexural modulus, favor its use in alcohol fuels. [42]

Given the reasons above, it is recommended to use alcohol fuels with castor-type oils.

5.2.3 MATERIAL AND FUEL SYSTEM REQUIREMENTS

The chemical composition of alcohol is different compared to petrol. Ethanol is an alcohol that reacts well with sodium metal or potassium metal. Ethanol or methanol can also act aggressively against aluminum or copper. The biggest problem is that ethanol or methanol can cause swelling or hardening of rubber components – such as fuel pipes used in the observed engine. Plastic components – the engine's fuel tank – can also be impacted by alcohol. [41]

For the purpose of the test, neither the engine block material nor the fuel line pipes have not been modified. Nevertheless, using stainless steel or caoutchouc rubber for alcohol-working systems is recommended.

The fuel pump used for the test is a standard fuel pump from the manufacturer (AISAN 1100-01370), working with a fuel pressure regulator of 350 kPa and a fuel strainer. The manufacturer does not recommend using this fuel pump with alcohol fuels because of alcohol hygroscopic action, which produces a lot of water on the bottom of the fuel tank during rest. In addition, alcohol is not a good lubricant for fuel pumps. This can be improved by using a fuel/oil mixture. During tests, a standard fuel pump is used, but once again, it is not recommended to use this fuel pump in a production ICE.

5.2.4 ENGINE MODIFICATIONS

Necessary engine modifications are described in chapter 6.3.3. This chapter presents only expected theoretical modifications of the engine based on the different characteristics of each fuel.

CONSTRUCTION MODIFICATIONS

No construction modifications are made to the experimental engine, even though the use of alcohol fuels allows to increase the compression ratio. [41] The reason behind this is to observe differences solely in the used fuel. However, to ensure the proper function of the engine running on methanol fuel, different injectors (with higher flow rates) and different sparkplugs must be used.

INTERNAL CONTROL UNIT MODIFICATIONS

Electronical modifications are made to meet ideal fuel combustion parameters. Each fuel has got different theoretical Air-to-Fuel ratio (AFR), as described in Tab. 5-5 [43]. The difference in AFR is caused by different oxygen content in the fuels. As the provider indicates, gasoline or petrol fossil fuel used for the tests has an oxygen content of 0.25%. In contrast, apparent ethanol can comprise almost 35% of oxygen because it contains a hydroxyl group (–OH) bound to the carbon atom. Methanol can contain even more oxygen (up to 50% of its chemical composition), naturally reducing the need for oxygen for methanol fuel and lowering the AFR. [44] The engine has fuel injection before the reed valve (indirect injection) and is controlled by the fuel-mapping internal control unit (ICU). Different fuel maps were set up to meet the required stoichiometric AFR based on verified information from the petrol fuel map from the current ICU [43]. These maps were changed in the ICU hand in hand with the fuels. For blended fuel (E40), stochiometric AFR was calculated as an ideal ratio of each AFR in the mixing ratio. [45]

AFR	Lean	Stoich.	Rich
Gasoline	17.6	14.7	11.8
Ethanol	10.8	9	7.2
Methanol	7.8	6.5	5.2

Tab. 5-5 Air-to-Fuel Ratio of different fuels for SI engines [43]

The fuel map for each set up was later modified during the experiment based on the retrieved data.

Another modification was made to the timing of the ignition. Because of the higher octane number and lower flammability, methanol can be ignited earlier during a single engine cycle, resulting in higher power output. [41]

5.3 RESEARCH METHODS TO EXAMINE GREEN FUELS IN PRODUCTION ICE

To determine if the selected alternative fuel is suitable for the production two-stroke SI combustion engine, two major studies are conducted.

5.3.1 EXAMINATION OF PROPERTIES OF ICE ON THE ENGINE TEST BENCH

A real-life test of the SI combustion engine on the engine test bench is conducted as a first step of the examination. Naturally, during the test, several important data (ex. Torque, RPM, emissions, consumption, etc.) are recorded and then evaluated for every fuel. The result should demonstrate the performance and emission properties of the engine running on different types of fuels and should present the main output from the tests.

5.3.2 SIMULATION OF HEAT CYCLE USING SIMULATION SOFTWARE

As a next step in the study, the simulation of the selected engine's heat cycle in the GT Suite computer program is realized. In this 1D study, an exact model of the engine, including engine dimensions, thermal properties, fuel information, and combustion information, is created in the software. After verifying that the virtual engine model is comparable to the real engine, which is measured on the engine test bench, the model will be modified to another type of fuel. Therefore, the simulation should comply with the real behavior of alternative fuels in IS combustion engines.

Both analyses, practical and computational, are compared based on several parameters defined later in chapter 6.4 – major differences between each fuel should be visible and analyzed.

5.4 OBJECTIVES OF THE TESTS AND FURTHER GOALS

The study sets a series of objectives that must be fulfilled in order to proclaim that the alternative fuel can be used in the analyzed SI combustion engine.

TORQUE OUTPUT

The torque output from the engine with alternative fuel should remain the same as with fossil petrol fuel. Studies indicate that the torque should increase while using alcohol fuels. In addition, torque characteristics serve as a benchmark for the analysis.

EMISSIONS

The new alternative fuels should reduce engine emissions of CO_2, CO, NO_X, and other gases. However, used measurement method does not allow precise examination of the emissions, so the study focuses only on CO_2 and CO; also, the results can be only comparative, not objective.

FUEL ECONOMY

During the test, fuel economy indicated in brake-specific fuel consumption (BSFC) should be measured, and a conclusion should be made. Because alcohols lower AFR, it is assumed that alcohol fuels have higher BSFC. However, if the power output from alternative fuels can grow significantly higher, it may keep the BSFC at close values to the petrol fuel.

GLOBAL IMPACT OF THE STUDY

The manufacturer of the ICE is a supplier of engines for petrol-powered motorized surfboards (brand name Jetsurf) [46]. The manufacturer produces over 1000 engines unit a year, and therefore, changing the fuel of the surfboard to sustainable renewable fuel would make even the ICE surfboard CO_2 neutral. In this case, the manufacturer would become the first-ever producer of climate-neutral combustion engines powering surfboards.

Moreover, these engine-equipped surfboards are used in international competitions, such as world championship series, taking place all over the world [47]. Because of current emission regulations, the promoter of the series wants to lower the emissions of CO_2 from the engines. A new class of electric-powered surfboards has been invented, but petrol-powered boards still represent the biggest interest between competitors and spectators. Therefore, to save the ICE class, alternative sustainable fuel, like ethanol, could be used instead of fossil petrol to power all the boards in the world championship. This change would represent significant contribution to the world championship series to reach climate neutrality [47].

6 COMPARISON OF ALTERNATIVE FUELS ON ENGINE TEST BENCH

To be able to compare alternative fuels in the production ICE, several testing methods are available. The most precise method of measurement of the ICE is a practical simulation of an engine run on an engine test bench. This experiment, where a real production engine with all the equipment is fitted on the bench, allows one to measure all necessary data from the engine run, such as engine speed, torque, power output, several temperatures, and emissions. The behavior of the engine on the test bench should be the same as in real use; therefore, the results from this experiment create the foundation for the comparison of the fuels.

6.1 ENGINE TEST BENCH DESCRIPTION

The producer of the MSR NG 100 engine has in its factory own testing laboratory (Fig. 6-1), which features an engine test bench – dynamometer from US company DYNOmite™ dynamometers Land & Sea, designed for kart and small engines (Fig. 6-2) [48]. This engine test bench is water brake type. [49] This type works with water flow, turbine, or propeller inside the housing on free mounting, which can turn a few degrees freely. The engine is connected directly to the dynamometer with a shaft. When the engine turns, the propeller inside the dynamometer starts spinning. Water is constantly pumped under pressure (via a pressure regulator) inside the housing in the stator pockets, and then the water leaves at the bottom of the housing. As the water flows from the stator pockets inside propeller turning pockets, the radial force is generated by the shock of water on the sides of stator pockets. This radial force generates a moment that tries to spin the freely mounted stator case. But this motion is prevented with a large lever, attached on one side to the stator housing and on the other side to the tensiometer. Knowing the force (F) acting on a distance (r), torque (M_K) can be calculated (Eq. 6-1). Using a different type of torque meter is also possible. The device also measures rotation speed (n_{RPM}); therefore, engine output power (P) can be determined (Eq. 6-2). It is necessary that water always flows through the housing because it is heated up during the shock and must not evaporate during the cycle. Fig. 6-3 presents a schematic drawing of the water brake dynamometer. [49] In this drawing, the difference between the rotor and stator is visible. The gap width in the drawing presents the water inlet and also the outlet.

$$M_K = F \cdot r \qquad \text{Eq. 6-1}$$

$$P = M_K \cdot \omega = M_K \cdot 2\pi n = M_K \cdot 2\pi\left({}^{n_{RPM}}/_{60}\right) \qquad \text{Eq. 6-2}$$

Fig. 6-1 Engine test bench laboratory at MSR Engines Factory

Fig. 6-2 DYNOmite™ dynamometers Land & Sea, designed for kart and small engines [48]

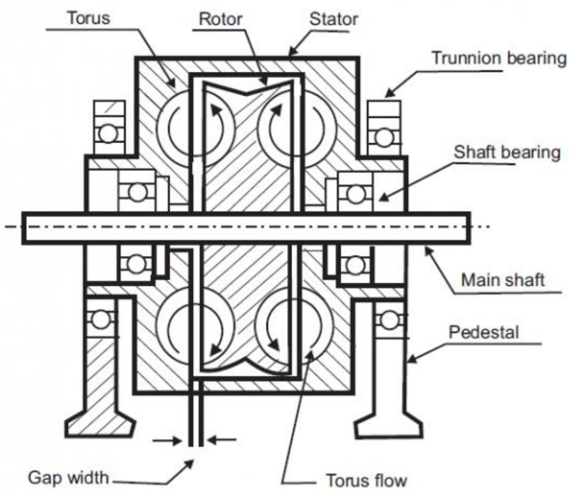


Fig. 6-3 Water brake schematic drawing [50]

Data from the dynamometer is acquired with DYNO-MAX™ Software from the same company. This software measures and records torque, and engine speed and records several analog or digital input signals. The control unit of the dynamometer can variate rotation speed or load when the working engine is connected. Thus, this software is used to control engine rotation speed and, therefore, to measure the torque or power of the engine.

6.2 MEASURING DEVICES ON THE ENGINE TEST BENCH

6.2.1 WATER TEMPERATURE SENSORS

The temperature of inlet and outlet water to the dynamometer housing is recorded to ensure that water flowing through the system does not evaporate. The water at room temperature (approx. 23 °C) from a large tank (approx. 400 l) is pumped to the dynamometer housing and warmed up to 50 °C when it leaves the housing. This water is cooled down in another water tank and later pumped back to the first large tank.

6.2.2 ROOM CONDITIONS SENSORS

Room air temperature, room air pressure, and air humidity are measured on meteorological stations. In addition, the air temperature in front of the engine air intake is also measured.

6.2.3 EMISSION ANALYSIS STATION

To measure exhaust gas emissions, AVL DiTEST MDS 250 (Fig. 6-4) emission analysis station for petrol engines are used. [50] Its gas measuring unit AVL DiTEST Gas 2301 can measure CO_2, CO, NO_x, O_2, and HC concentration in the exhaust gas mixture. These measured values can be read and recorded on a computer program AVL.

Fig. 6-4 AVL DiTEST MDS 250 [50]

6.2.4 DATA ACQUISITION UNIT

Because different data from different measuring devices is recorded, it is necessary to unite all records into a single data-logging device for easier control. During this experiment, Cosworth Badenia 2 data logger is used (Fig. 6-5). [51] This logger supports all types of communication and vehicle buses – analog, digital, and CAN (Controller Area Network). All the information can be later displayed on the computer in the software Pi Toolbox from Cosworth. This software is used to analyze all types of fuels on the engine test bench. Badenia is powered by a 12 V DC (direct current) source.

Fig. 6-5 Cosworth Badenia 2

6.3 PREPARATION OF THE ENGINE FOR THE EXPERIMENT

Engine MSR NG 100 technical parameters are described in chapter 1.3.4. This specific engine is mounted on the engine test bench along with the exhaust, ICU, and external sensors, as Fig. 6-6 shows.

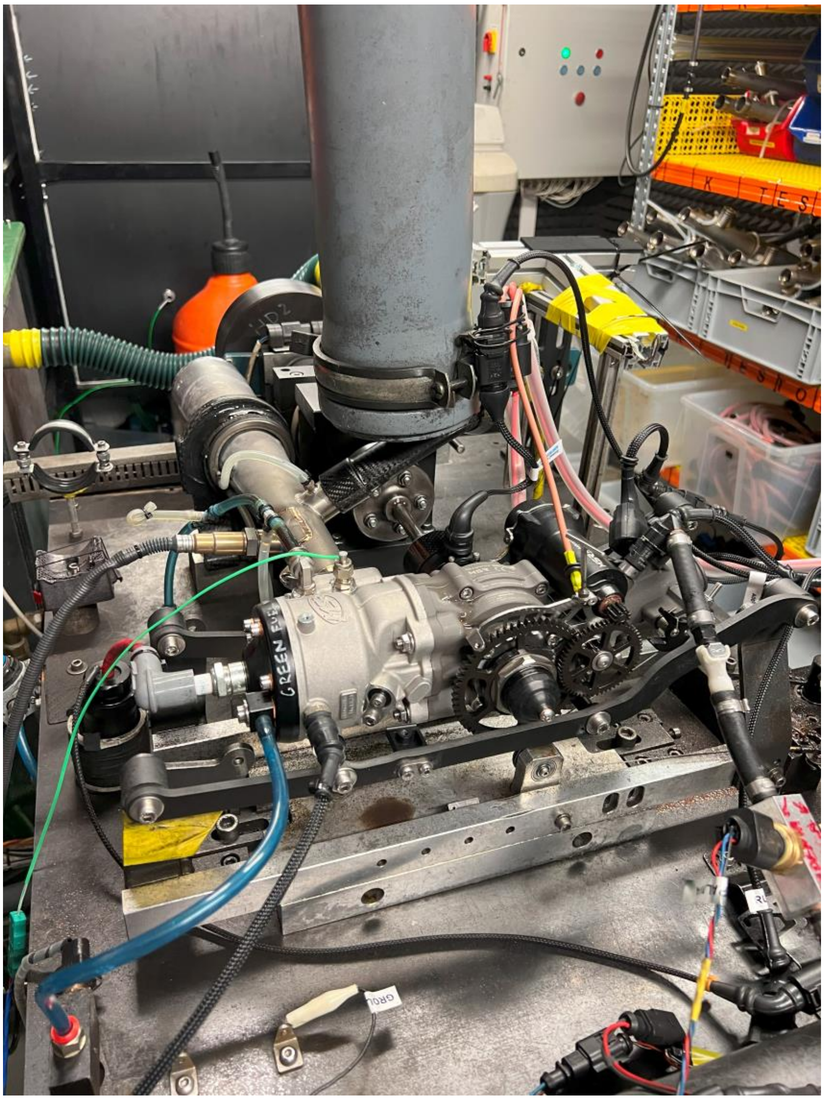


Fig. 6-6 MSR NG 100 Engine on the engine test bench

The engine is connected to the dynamometer with a shaft with rubber bushing vibrator isolators. The bushing ensures that both shafts (from the engine and from the dynamometer) are spinning without any unwanted radial force when the connection is not coaxial. This bushing is also externally air-cooled. MSR NG 100 engine is water cooled type of engine. Therefore, water flows through the engine’s cooling system is realized with a water pump.

The connection of the engine to the dynamometer, the position of engine components and sensors, and the location of measuring devices are shown in Fig. 6-7, with a description in Tab. 6-1. The final selection of fuels for the experiment is written in Tab. 5-4.

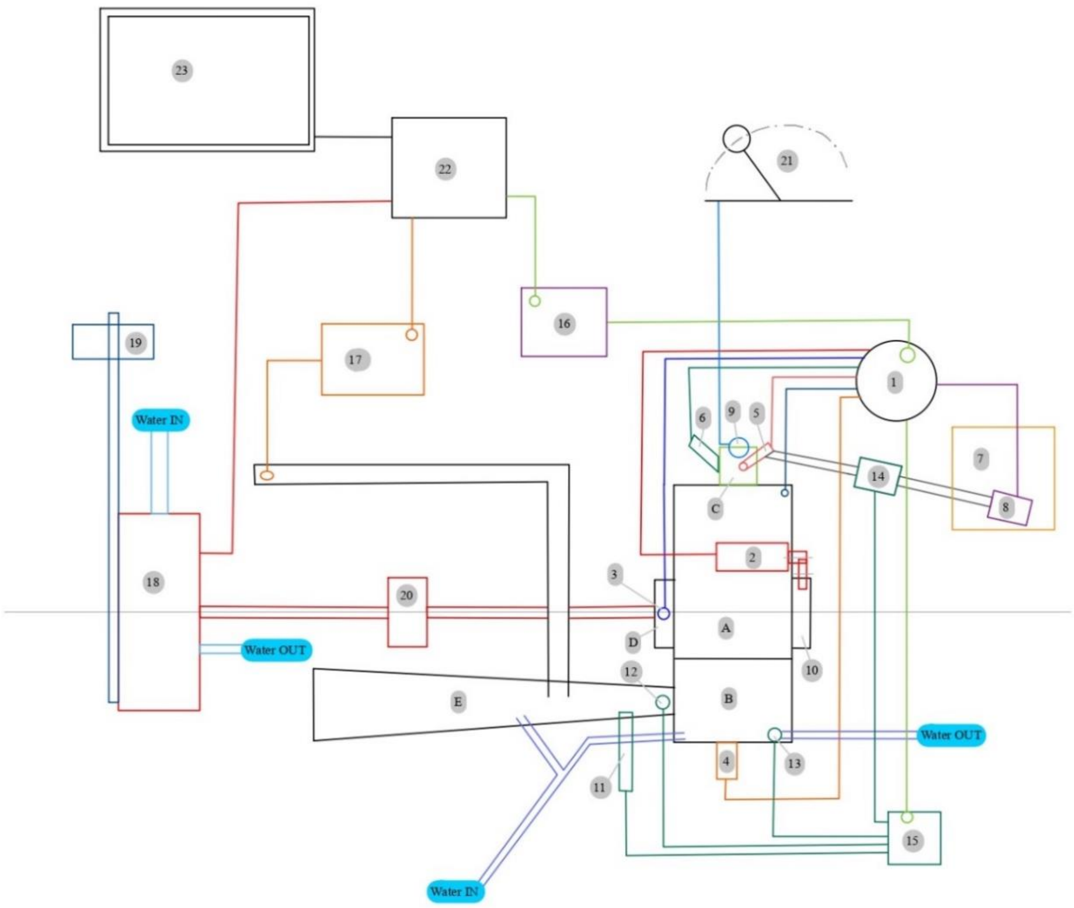


Fig. 6-7 Drawing of the complete connection of the engine, dynamometer, and sensors

Number	Component / sensor	Number	Component / sensor	Number	Component / sensor	Number	Component / sensor
A	engine crankcase	3	Hall effect sensor	10	freewheel	17	AVL DiTest Emission Analyser
B	engine cylinder	4	sparkplug	11	lambda sensor	18	DYNOmite dynamometer
C	engine air intake valve	5	fuel injector	12	EGT sensor	19	level with tensiometer
D	carrier for drive shaft	6	TPS	13	outlet cooling water temperature sensor	20	bushing on drive shaft
E	exhaust system	7	fuel tank	14	fuel pressure sensor	21	control of the opening angle of the air intake valve
1	ICU	8	fuel pump	15	external control unit	22	PC
2	starter	9	air intake valve	16	Cosworth badenia 2	23	monitor

Tab. 6-1 Description of the drawing Fig. 6-7 of the complete connection of the engine, dynamometer, and sensors

6.3.1 Standard components and sensors of the engine

MSR NG 100 has several components which allow precise control of the engine. The complete connection between the engine itself and all the components on the engine test bench is described in Fig. 6-7.

The internal control unit (ICU)

The brain of the engine is the Internal Control Unit (ICU) developed by the manufacturer itself. ICU is secured inside a waterproof case, together with Li-On batteries, with a nominal voltage of 12.6 V. This battery pack powers with higher voltage the starter of the engine, fuel pump, and all other low-voltage electronic components. ICU control information is transferred via CAN vehicle bus and can be read on a computer with a CAN communicator. Information about ICU-controlled parameters (like injection timing, ignition timing, voltage of battery pack, etc.) is displayed in the software JEFFIS Control from the manufacturer. This information is also transferred and stored in Cosworth Badenia 2, which was mentioned earlier.

Starter

This type of engine has got an electric starter. A small AC (alternative current) motor with a 12.6 V supply is used to start the engine cycle with the use of gear to match the engine's working rotation speed.

Hall effect sensor

To precisely control the injection of the fuel, ICU needs to know the exact engine rotation speed. This is ensured by using a Hall effect sensor on the drive shaft.

Sparkplug

To commence the ignition, sparkplug type BPR7HS from manufacturer NGK is needed. The ignition timing is controlled through ICU.

Fuel Injector

MSR NG 100 engine uses electrical fuel injection with BOSCH injector 0 280 158 251, with a static flow rate of fuel equal to 116 g/min (Q_1), at 300 kPa (p_1). The amount of fuel injected is determined by the opening time of the injector, which is controlled by the ICU. Because the engine is working with a pressure regulator on 350 kPa (p_2), the flow rate (Q_2) must be recalculated using Eq. 6-3.

$$Q_2 = Q_1 \cdot \sqrt{\frac{p_2}{p_1}} \qquad \text{Eq. 6-3}$$

The flow rate at 350 kPa is equal to 119.8 g/min.

THROTTLE POSITION SENSOR (TPS)

To determine the correct position of the air intake opening valve, TPS connected to the ICU is used. Both injection and ignition timing depend on data from TPS and Hall effect sensor.

FUEL TANK AND FUEL PUMP

Each fuel is poured into a different fuel tank from the manufacturer. Inside the fuel tank, there is a fuel pump AISAN 1100-01370 with a pressure regulator of 350 kPa and a fuel pump strainer. During the test, it will be experienced that the fuel pump does not withstand long-term use with alcohol fuels, and therefore the fuel pumps have been changed several times.

6.3.2 EXTERNAL ENGINE SENSORS

In addition to all standard sensors of the engine in production, several more sensors were added to obtain all necessary information for alternative fuel comparison. Data from all the sensors is transferred to the External control unit, which can have analog, digital, or CAN bus input and transfers everything to a single CAN bus output, which is later transmitted to Cosworth Badenia 2.

EXHAUST GAS TEMPERATURE SENSOR (EGT SENSOR)

EGT sensor is working on the principle of thermocouples. It can measure a high range of temperatures up to 1000 °C, as the manufacturer of the sensor states. This is specifically good for EGT because the temperatures can reach almost 800 °C.

OUTLET COOLING WATER TEMPERATURE

A different type of temperature sensor, this time a thermistor, is used to measure outlet cooling water temperature inside the engine. Thermistor electrical resistance depends strongly on its temperature. It used to temperature ranges under 90 °C (given the information from the manufacturer), which suits nicely to current use.

FUEL PRESSURE SENSOR

To ensure the proper function of the fuel pump inside the fuel tank, a pressure sensor is used in the fuel pipe. The fuel pressure value is transmitted to the External control unit. It is necessary always to ensure that the fuel pressure is correct during the experiment because lower pressure could result in lower mass flow and, therefore, negatively influence the measurement.

LAMBDA SENSOR

A lambda sensor is a device that measures the proportion of oxygen in the exhaust gas. Lambda refers to air to fuel equivalence ratio in the exhaust gases. [52] The value of lambda (λ) is the most important information while optimizing the timing of injection and ignition of the air-fuel mixture. Lambda value can be read on a computer, and depending on its value, changes in timings can be made to improve engine performance. The ideal stoichiometric proportion of the mixture of air-fuel in the exhaust gas indicates a lambda value equal to one. The lower the value of lambda is, the richer the fuel mixture is combusted. When lambda reaches higher values, the mixture is lean.

6.3.3 NECESSARY ENGINE MODIFICATIONS FOR DIFFERENT FUELS ON THE ENGINE TEST BENCH

As it was mentioned earlier in chapter 5.3.4, different fuel maps (injection and ignition timing of the mixture) must be used with different fuels. The modification of injection timing is made based on stoichiometric AFR. The modification in ignition timing is made solely for methanol fuel, which has got very high RON number and low flammability [41]. Therefore, the mixture must be ignited earlier to ensure complete combustion of the mixture. [45]

DIFFERENT FUEL INJECTOR FOR METHANOL FUEL

Because of the low AFR of methanol, more fuel must be injected inside the engine with each revolution. The injector in standard MSR NG 100 engines has a static flow rate of fuel equal to 116 g/min at 300 kPa. After editing the fuel injection timing, it was discovered that the duty cycle of the fuel injector is above 100%. This means that the current injector cannot, even during one complete revolution, satisfy the engine's need for fuel. Thus, a different injector BOSCH 0 280 158 038 is used. This injector has got flow rate of fuel equal to 237 g/min at 300 kPa. After recalculating the flow rate at 350 kPa using Eq. 6-3. The new flow rate is equal to 244.8 g/min – which can satisfy the needs of the engine for fuel.

DIFFERENT SPARKPLUG FOR METHANOL FUEL

Because methanol fuel has got higher RON number than gasoline fuel [45], it can deliver almost complete combustion. This means that more heat is generated during the combustion process; therefore, colder sparkplug is needed to transfer more heat from the combustion chamber. [53] Sparkplug NGK BP6HS is chosen to fulfill these new criteria. [54]

6.4 Experiment procedure and its limitations

During each experiment with different fuels, two main analyses are conducted.

6.4.1 Performance test

At first, torque and power characteristics are measured. Working warmed-up engine (in steady state) is subjected to a predefined test by the engine bench software. During this test, the throttle inlet valve is opened at 100% (TPS indicates 100%), and the engine bench releases the load from a rotational speed of 5000 RPM up to 8800 RPM [1] while the engine is generating torque. During one test, this cycle is repeated three times. The software then calculates average values of torque during different rotational speeds and deducts the engine power. The result of the test is two curves in a graph of torque and power as a function of engine rotational speed. Knowing this whole characteristic allows to compare different torque outputs of different fuels. To make this experiment more accurate, more tests are made for each fuel (usually three tests at different times and conditions).

6.4.2 Efficiency test

When the engine performance with different fuels is known, it is necessary to compare its efficiency with different fuels. Because this analysis is not continuous in time and it is not possible to measure wanted parameters immediately with the time change, only several engine rotational speeds are analyzed. Based on the recommendation from the manufacturer, four measure points are selected (Tab. 6-2). These points should be in proximity to real engine jet pump propeller characteristics.

Point	Rotational speed [RPM]
1	5500
2	6500
3	7500
4	8500

Tab. 6-2 Points of measure for efficiency test

When the running engine reaches desired rotational speed, a measure of several parameters commences. BSFC is measured by a decrease in fuel mass during a certain period, knowing the engine power output at this point. While this measure is conducted, emission parameters are registered. Once again, the test for each point is repeated several times to reduce the chance of the accidental nature of the measurement. This test should demonstrate the effectiveness and economy of each fuel.

[1] lower rotational speeds are not possible because the engine would stall

During each point, the throttle opening valve stays open on the same level, as values of TPS indicate. Outer conditions are described by two temperature sensors, one (T air) in the proximity of the engine and the second in the weather station (room temperature sensor), placed over one meter away from the testing bench. Engine temperature is measured at the cooling water outlet port, while EGT is measured directly at the beginning of the exhaust pipe. The ICU shows the current injection timing. Emissions of CO, HC, CO_2, and O_2 are measured with AVL DiTEST in Fig. 6-4. However, this measure can be only comparative and not objective because the emission station can only measure the volumetric percentage of each compound in the exhaust gas. It is not possible to measure exact emissions in part per million for the known volume of the exhaust gas. This fact reduces the chances of acquiring precise emission values. The lambda sensor at the exhaust pipe can determine the after the initial warm-up exact lambda value. Room conditions, like humidity and pressure, are measured with a small weather station. The fuel pressure is measured with a pressure sensor shown in Fig. 6-8. BSFC is manually calculated with fuel mass change during a known period while knowing the exact power output of the engine during the test.

Fig. 6-8 fuel pressure sensor

6.4.3 LIMITATIONS

As it was mentioned before, the most important parameters to compare are torque, power, emissions, and BSFC. Torque and power values are compared based on the performance test. The rest of the values can be withdrawn from the efficiency test. BSFC values are relatively precise and can be compared directly. However, all emissions cannot be compared directly because, during the efficiency test, AVL DiTEST measuring device did not seem to measure the values correctly for alcohol fuels. The reason may be the higher oxygen content in the alcohol fuels, which is not suitable for the station in its basic settings. The results could be more precise if the device were set up differently using the control software. This could be only reached with laboratory experiments on an advanced scientific level, which is not possible due to practical limitations of the engine test bench and its testing laboratory in the manufacturers factory. Therefore, only values of CO and CO_2 are compared in this study.

Both elements usually have consistent values and present an important part of general exhaust gas emissions from SI engines.

After each fuel is separately examined, it is individually described. In the end, all alternative fuels are compared on performance and efficiency level.

6.5 CONVENTIONAL FUEL – PETROL

Firstly, the engine is set up on the engine test bench with conventional fossil petrol fuel (indicated in Tab. 5-4). This standard fuel presents the benchmark of all alternative fuels – which will be directly compared with this regular fuel. Set up of the engine is prepared by Fig. 6-7, with a fuel tank filled with a mixture of Petrol and oil in a given ratio (Tab. 5-4).

6.5.1 PERFORMANCE TEST OF PETROL FUEL

Three tests of the engine performance are realized at different times and conditions. From the test data, the average of torque and power are calculated and brought up in Fig. 6-9, which shows the progress of engine torque and power in function of engine rotational speed while the engine is running on conventional Gasoline. Both maximal torque and maximal power are marked in the figure.

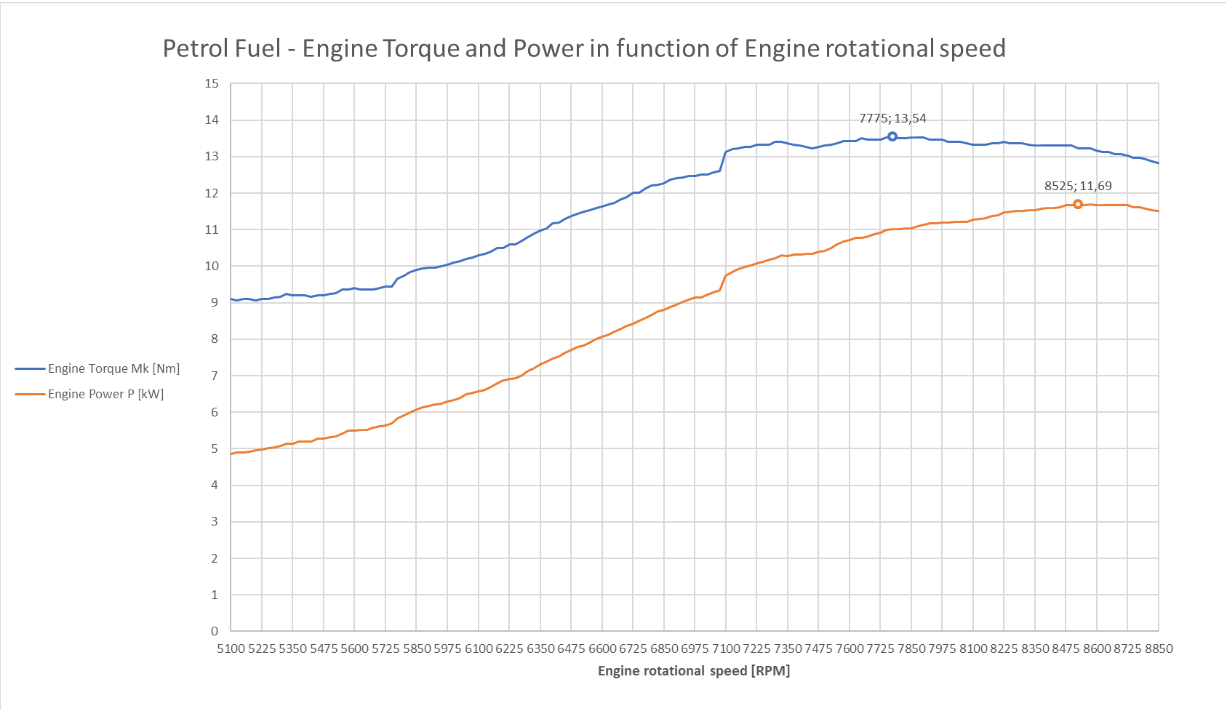


Fig. 6-9 Engine torque and power in function of engine rotational speed for petrol fuel

The behavior of torque and power is continuous, partially increasing function as predicted for a two-stroke single-gear engine. The result depends on the geometric dimensions and ICU parameters.

Engine torque starts at 9 Nm and reaches over 13.5 Nm, while engine power goes from 4.8 kW to 11.69 kW. After reaching maximum values, both functions decrease with higher rotational speeds.

6.5.2 EFFICIENCY TEST OF PETROL FUEL

In the efficiency test, all 4 points are measured three times at different day times. This should rule out the possibility of the accidental nature of the experiment. Several values, described in chapter 6-3, are recorded, and stored. To make this measure more accurate, mean values are calculated along with standard deviation and standard error. Results from the efficiency test are shown in Tab. 6-3.

Point	Engine rotational speed [RPM]	Date of measure or statistic value	Mk [Nm]	Power [HP]	Power [kW]	TPS [%]	T air [°C]	T motor [°C]	T INJ akt [ms]	EGT akt [°C]	CO [%vol]
1	5500	21.04.2023 10:30	4.20	3.30	2.46	40.00	25.00	40.00	2.22	516.00	2.12
		22.04.2023 8:40	4.40	3.40	2.54	40.00	29.00	41.00	2.27	512.00	2.14
		23.04.2023 2:06	4.40	3.40	2.54	40.00	34.00	40.00	2.38	492.00	3.27
		Mean value	**4.33**	**3.37**	**2.51**	**40.00**	**29.33**	**40.33**	**2.29**	**506.67**	**2.51**
		Standard deviation	0.12	0.06	0.04	0.00	4.51	0.58	0.08	12.86	0.66
		Standard error	0.07	0.03	0.02	0.00	2.60	0.33	0.04	7.42	0.38
2	6500	21.04.2023 10:30	7.30	6.80	5.07	50.00	27.00	46.00	2.73	524.00	2.02
		22.04.2023 8:40	7.40	6.90	5.15	50.00	29.00	44.00	2.78	522.00	1.79
		23.04.2023 2:06	7.40	6.80	5.07	50.00	34.00	44.00	2.76	524.00	1.48
		Mean value	**7.37**	**6.83**	**5.10**	**50.00**	**30.00**	**44.67**	**2.76**	**523.33**	**1.76**
		Standard deviation	0.06	0.06	0.04	0.00	3.61	1.15	0.03	1.15	0.27
		Standard error	0.03	0.03	0.02	0.00	2.08	0.67	0.02	0.67	0.16
3	7500	21.04.2023 10:30	11.50	12.20	9.10	70.00	28.00	55.00	3.56	580.00	2.73
		22.04.2023 8:40	11.50	12.10	9.03	70.00	29.00	51.00	3.61	580.00	2.63
		23.04.2023 2:06	11.50	12.10	9.03	70.00	36.00	51.00	3.68	585.00	1.73
		Mean value	**11.50**	**12.13**	**9.05**	**70.00**	**31.00**	**52.33**	**3.62**	**581.67**	**2.36**
		Standard deviation	0.00	0.06	0.04	0.00	4.36	2.31	0.06	2.89	0.55
		Standard error	0.00	0.03	0.02	0.00	2.52	1.33	0.03	1.67	0.32
4	8500	21.04.2023 10:30	12.70	15.30	11.41	100.00	29.00	58.00	4.02	587.00	3.28
		22.04.2023 8:40	12.90	15.60	11.64	100.00	30.00	53.00	4.12	590.00	3.24
		23.04.2023 2:06	12.70	15.20	11.34	100.00	27.00	54.00	4.31	592.00	4.05
		Mean value	**12.77**	**15.37**	**11.46**	**100.00**	**28.67**	**55.00**	**4.15**	**589.67**	**3.52**
		Standard deviation	0.12	0.21	0.16	0.00	1.53	2.65	0.15	2.52	0.46
		Standard error	0.07	0.12	0.09	0.00	0.88	1.53	0.09	1.45	0.26

Point	Engine rotational speed [RPM]	Date of measure or statistic value	HC [ppm]	CO2 [%vol]	O2 [%vol]	Lambda [-]	Room temperature sensor [°C]	Air humidity [%]	Air pressure [kPa]	fuel pressure [kPa/100]	BSFC [g/(kW*h)]
1	5500	21.04.2023 10:30	2130.00	8.40	6.34	0.93	24.00	34.00	101.70	4.40	378.79
		22.04.2023 8:40	1830.00	7.96	6.87	0.93	24.30	36.00	101.70	4.40	420.88
		23.04.2023 2:06	2830.00	9.09	4.48	0.91	27.80	32.00	101.40	4.42	438.78
		Mean value	**2263.33**	**8.48**	**5.90**	**0.92**	**25.37**	**34.00**	**101.60**	**4.41**	**412.82**
		Standard deviation	513.16	0.57	1.26	0.01	2.11	2.00	0.17	0.01	30.80
		Standard error	296.27	0.33	0.72	0.01	1.22	1.15	0.10	0.01	17.78
2	6500	21.04.2023 10:30	2190.00	9.20	5.20	0.93	25.00	34.00	101.60	4.40	347.89
		22.04.2023 8:40	2043.00	9.38	5.12	0.93	24.20	34.00	102.50	4.40	360.09
		23.04.2023 2:06	2645.00	10.35	4.29	0.95	28.20	32.00	101.70	4.41	327.37
		Mean value	**2292.67**	**9.64**	**4.87**	**0.94**	**25.80**	**33.33**	**101.93**	**4.40**	**345.12**
		Standard deviation	313.86	0.62	0.50	0.01	2.12	1.15	0.49	0.01	16.53
		Standard error	181.21	0.36	0.29	0.01	1.22	0.67	0.28	0.00	9.55
3	7500	21.04.2023 10:30	1863.00	9.48	4.35	0.93	26.00	36.00	101.50	4.40	333.80
		22.04.2023 8:40	1720.00	9.58	4.20	0.93	24.30	36.00	101.90	4.40	325.97
		23.04.2023 2:06	1977.00	10.45	3.95	0.97	29.00	32.00	101.30	4.40	315.26
		Mean value	**1853.33**	**9.84**	**4.17**	**0.94**	**26.43**	**34.67**	**101.57**	**4.40**	**325.01**
		Standard deviation	128.77	0.53	0.20	0.02	2.38	2.31	0.31	0.00	9.31
		Standard error	74.35	0.31	0.12	0.01	1.37	1.33	0.18	0.00	5.37
4	8500	21.04.2023 10:30	2247.00	8.76	4.75	0.93	26.00	36.00	101.50	4.40	345.12
		22.04.2023 8:40	2076.00	8.90	4.57	0.93	24.20	36.00	101.70	4.40	344.39
		23.04.2023 2:06	2240.00	8.88	3.98	0.92	29.90	32.00	101.60	4.39	346.59
		Mean value	**2187.67**	**8.85**	**4.43**	**0.93**	**26.70**	**34.67**	**101.60**	**4.40**	**345.37**
		Standard deviation	96.77	0.08	0.40	0.01	2.91	2.31	0.10	0.01	1.12
		Standard error	55.87	0.04	0.23	0.00	1.68	1.33	0.06	0.00	0.65

Tab. 6-3 Measured values during efficiency test of petrol fuel

As Tab. 6-3 shows, in each point, the engine torque and power values are lower than during the performance test. This is because the engine behaves differently when increasing the load (accelerated state) and when the load is stable (steady state). However, the engine torque and power are increasing with higher rotational speeds. BSFC remains almost constant during all measures, with the lowest value at 7500 RPM. Emissions of CO and CO_2 are also almost constant. A good observation is that the emissions are not skyrocketing with increasing rotational speed. This means that the engine operates very effectively at all speeds.

6.6 ALTERNATIVE FUEL – MIXTURE E40

After the test of standard conventional fuel, the mixture of fossil petrol and sustainable ethanol is measured. The engine is set up in Fig. 6-7 with E40 fuel from Tab. 5-4.

6.6.1 PERFORMANCE TEST OF MIXTURE E40

The test results in Fig. 6-10 indicate the torque and power of the engine running on the mixture E40 at different rotational speeds. Maximal values are yet again marked in the figure.

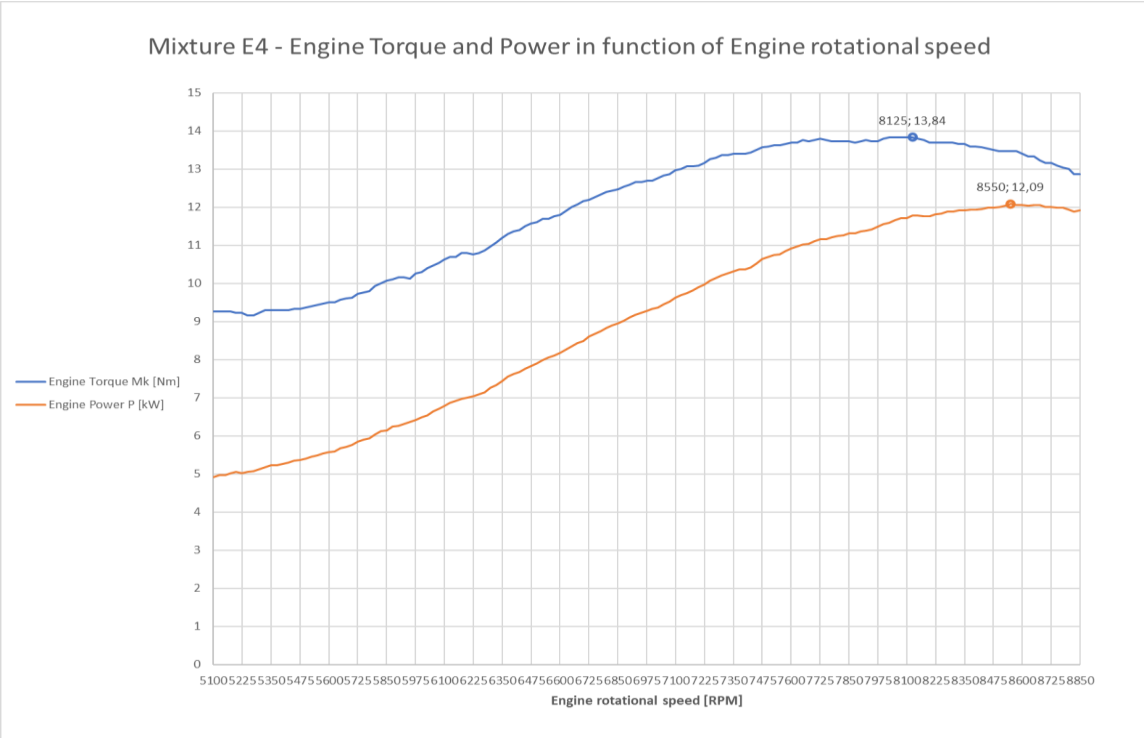


Fig. 6-10 Engine torque and power in function of engine rotational speed for E40 mixture

As the results indicate, maximum torque and maximum power are augmented because of the use of the E40 blend. The maximum torque increased by 0.3 Nm at the higher rotational speed of 8125 RPM. The power therefore rose by 0.4 kW at 8550 RPM. The fact that maximum torque and maximum power are in closer range favors better engine function. Needless to say, only injection settings were modified to achieve the correct AFR. Other engine parameters, like its geometry or ignition settings, were not changed. Partially sustainable fuel E40 seems like a possible way how to increase engine torque with minimal modifications on the SI engine.

6.6.2 EFFICIENCY TEST OF MIXTURE E40

Same as with petrol fuel, E40 is used for a total of three tests at different times. The same values are recorded and noted in Tab. 6-4.

Point	Engine rotational speed [RPM]	Date of measure or statistic value	Mk [Nm]	Power [HP]	Power [kW]	TPS [%]	T air [°C]	T motor [°C]	T INJ akt [ms]	EGT akt [°C]	CO [%vol]
1	5500	21.04.2023 19:44	4.70	3.60	2.69	40.00	28.00	51.00	2.81	510.00	1.83
		22.03.2023 16:08	4.70	3.60	2.69	40.00	24.00	43.00	2.81	501.00	1.88
		23.04.2023 1:21	4.50	3.50	2.61	40.00	28.00	39.00	2.73	500.00	1.15
		Mean value	**4.63**	**3.57**	**2.66**	**40.00**	**26.67**	**44.33**	**2.78**	**503.67**	**1.62**
		Standard deviation	0.12	0.06	0.04	0.00	2.31	6.11	0.04	5.51	0.41
		Standard error	0.07	0.03	0.02	0.00	1.33	3.53	0.03	3.18	0.24
2	6500	21.04.2023 19:44	7.60	7.00	5.22	50.00	28.00	56.00	3.39	518.00	1.91
		22.03.2023 16:08	7.60	7.00	5.22	50.00	26.00	49.00	3.28	513.00	1.82
		23.04.2023 1:21	7.70	7.00	5.22	50.00	30.00	44.00	3.53	510.00	1.89
		Mean value	**7.63**	**7.00**	**5.22**	**50.00**	**28.00**	**49.67**	**3.40**	**513.67**	**1.87**
		Standard deviation	0.06	0.00	0.00	0.00	2.00	6.03	0.12	4.04	0.05
		Standard error	0.03	0.00	0.00	0.00	1.15	3.48	0.07	2.33	0.03
3	7500	21.04.2023 19:44	11.80	12.50	9.33	70.00	29.00	63.00	4.26	573.00	2.44
		22.03.2023 16:08	11.90	12.70	9.47	70.00	31.00	57.00	4.42	577.00	2.46
		23.04.2023 1:21	11.50	12.40	9.25	70.00	32.00	50.00	4.53	571.00	2.63
		Mean value	**11.73**	**12.53**	**9.35**	**70.00**	**30.67**	**56.67**	**4.40**	**573.67**	**2.51**
		Standard deviation	0.21	0.15	0.11	0.00	1.53	6.51	0.13	3.06	0.10
		Standard error	0.12	0.09	0.07	0.00	0.88	3.76	0.08	1.76	0.06
4	8500	21.04.2023 19:44	13.50	16.10	12.01	100.00	30.00	67.00	4.81	600.00	2.94
		22.03.2023 16:08	13.30	16.00	11.94	100.00	33.00	59.00	4.87	601.00	2.99
		23.04.2023 1:21	13.20	15.70	11.71	100.00	35.00	53.00	4.97	604.00	3.07
		Mean value	**13.33**	**15.93**	**11.89**	**100.00**	**32.67**	**59.67**	**4.88**	**601.67**	**3.00**
		Standard deviation	0.15	0.21	0.16	0.00	2.52	7.02	0.08	2.08	0.07
		Standard error	0.09	0.12	0.09	0.00	1.45	4.06	0.05	1.20	0.04

Point	Engine rotational speed [RPM]	Date of measure or statistic value	HC [ppm]	CO2 [%vol]	O2 [%vol]	Lambda [-]	Room temperature sensor [°C]	Air humidity [%]	Air pressure [kPa]	fuel pressure [kPa/100]	BSFC [g/(kW*h)]
1	5500	21.04.2023 19:44	1820.00	9.03	5.73	0.93	21.50	36.00	101.30	4.40	403.21
		22.03.2023 16:08	1772.00	9.25	5.36	0.93	21.10	37.00	101.40	4.35	453.61
		23.04.2023 1:21	2038.00	9.86	5.24	0.95	24.80	40.00	100.70	3.96	466.21
		Mean value	**1876.67**	**9.38**	**5.44**	**0.94**	**22.47**	**37.67**	**101.13**	**4.24**	**441.01**
		Standard deviation	141.77	0.43	0.26	0.01	2.03	2.08	0.38	0.24	33.34
		Standard error	81.85	0.25	0.15	0.01	1.17	1.20	0.22	0.14	19.25
2	6500	21.04.2023 19:44	1855.00	9.50	5.12	0.93	21.40	36.00	102.00	4.40	407.93
		22.03.2023 16:08	1975.00	9.66	4.83	0.93	22.10	37.00	101.40	4.33	336.34
		23.04.2023 1:21	2233.00	9.74	4.80	0.93	25.90	36.00	101.20	3.90	426.25
		Mean value	**2021.00**	**9.63**	**4.92**	**0.93**	**23.13**	**36.33**	**101.53**	**4.21**	**390.17**
		Standard deviation	193.15	0.12	0.18	0.00	2.42	0.58	0.42	0.27	47.51
		Standard error	111.52	0.07	0.10	0.00	1.40	0.33	0.24	0.16	27.43
3	7500	21.04.2023 19:44	1482.00	9.90	4.02	0.93	22.70	37.00	101.60	4.40	370.60
		22.03.2023 16:08	1518.00	9.86	3.86	0.93	25.50	35.00	101.20	4.31	379.02
		23.04.2023 1:21	1768.00	9.97	3.81	0.92	26.80	34.00	101.00	3.93	379.98
		Mean value	**1589.33**	**9.91**	**3.90**	**0.93**	**25.00**	**35.33**	**101.27**	**4.21**	**376.53**
		Standard deviation	155.77	0.06	0.11	0.01	2.10	1.53	0.31	0.25	5.16
		Standard error	89.94	0.03	0.06	0.00	1.21	0.88	0.18	0.14	2.98
4	8500	21.04.2023 19:44	1542.00	9.55	3.98	0.93	23.40	36.00	101.90	4.40	380.06
		22.03.2023 16:08	1515.00	9.53	3.80	0.93	25.40	32.00	101.50	4.30	380.25
		23.04.2023 1:21	1627.00	9.73	3.68	0.93	28.00	34.00	101.20	3.98	384.77
		Mean value	**1561.33**	**9.60**	**3.82**	**0.93**	**25.60**	**34.00**	**101.53**	**4.23**	**381.69**
		Standard deviation	58.45	0.11	0.15	0.00	2.31	2.00	0.35	0.22	2.67
		Standard error	33.75	0.06	0.09	0.00	1.33	1.15	0.20	0.13	1.54

Tab. 6-4 Measured values during efficiency test of E40 mixture

At first sight, it is possible to see minor differences in the emissions. CO emission has decreased with E40 mixture in specific points, while CO_2 emission has increased in ¾ cases. The reason behind this weird behavior might be the wrong settings of the analyzer because it was expected that both GHG emissions would be lower than with conventional petrol. A good result is that the torque and power have increased, while BSFC has almost remained the same. This means that the addition of alcohol to standard petrol improves its performance and does not influence the fuel economy, while GHG emissions should remain the same as with petrol fuel.

6.7 ALTERNATIVE FUEL – ETHANOL

The first fully sustainable fuel subjected to the tests is ethanol from Tab. 5-4. The engine is once again prepared in Fig. 6-7, with a new fuel tank with the ethanol fuel mixture.

6.7.1 PERFORMANCE TEST OF ETHANOL FUEL

Without changing anything apart from the injection timing settings, three performance tests in different times are performed and averaged. The progress of torque and power is shown in Fig. 6-11, with noted maximal values.

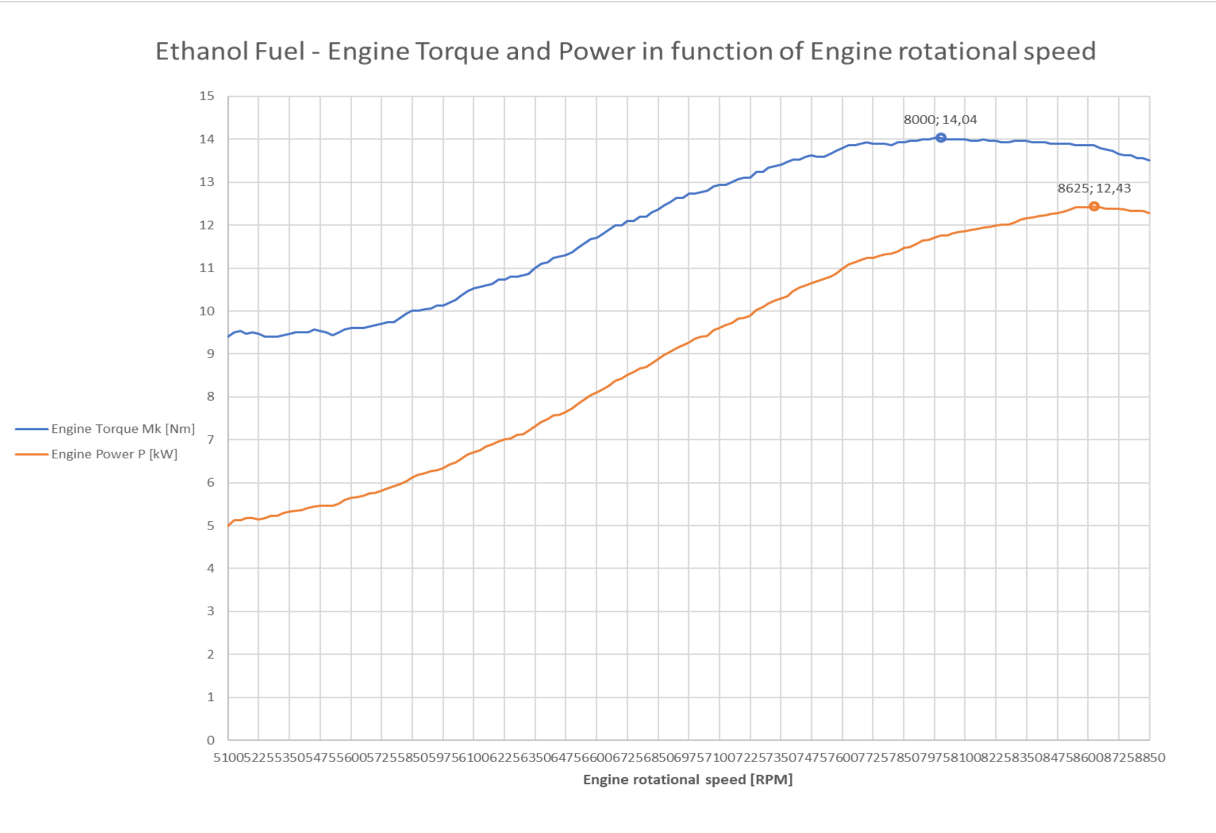


Fig. 6-11 Engine torque and power in function of engine rotational speed for Ethanol fuel

6.7.2 EFFICIENCY TEST OF ETHANOL FUEL

The same analysis, as for petrol and E40 fuel is conducted. All-important values are noted in Tab. 6-5.

Point	Engine rotational speed [RPM]	Date of measure or statistic value	Mk [Nm]	Power [HP]	Power [kW]	TPS [%]	T air [°C]	T motor [°C]	T INJ akt [ms]	EGT akt [°C]	CO [%vol]
1	5500	22,04,2023 10:09:00	4.40	3.40	2.54	40.00	27.00	37.00	3.05	490.00	1.50
		22,04,2023 17:24:00	5.20	4.10	3.06	40.00	25.00	46.00	3.48	482.00	1.56
		23,04,2023 3:22:00	4.80	3.70	2.76	40.00	37.00	41.00	3.20	482.00	1.70
		Mean value	**4.80**	**3.73**	**2.79**	**40.00**	**29.67**	**41.33**	**3.25**	**484.67**	**1.59**
		Standard deviation	0.40	0.35	0.26	0.00	6.43	4.51	0.22	4.62	0.10
		Standard error	0.23	0.20	0.15	0.00	3.71	2.60	0.12	2.67	0.06
2	6500	22,04,2023 10:09:00	7.90	7.30	5.45	50.00	28.00	41.00	3.99	503.00	1.56
		22,04,2023 17:24:00	7.70	7.00	5.22	50.00	27.00	50.00	4.15	490.00	2.83
		23,04,2023 3:22:00	7.90	7.20	5.37	50.00	37.00	46.00	4.41	499.00	1.73
		Mean value	**7.83**	**7.17**	**5.35**	**50.00**	**30.67**	**45.67**	**4.18**	**497.33**	**2.04**
		Standard deviation	0.12	0.15	0.11	0.00	5.51	4.51	0.21	6.66	0.69
		Standard error	0.07	0.09	0.07	0.00	3.18	2.60	0.12	3.84	0.40
3	7500	22,04,2023 10:09:00	12.10	12.80	9.55	70.00	30.00	46.00	5.19	562.00	2.28
		22,04,2023 17:24:00	12.00	12.70	9.47	70.00	31.00	55.00	5.34	560.00	2.21
		23,04,2023 3:22:00	12.00	12.60	9.40	70.00	38.00	52.00	5.39	558.00	2.40
		Mean value	**12.03**	**12.70**	**9.47**	**70.00**	**33.00**	**51.00**	**5.31**	**560.00**	**2.30**
		Standard deviation	0.06	0.10	0.07	0.00	4.36	4.58	0.10	2.00	0.10
		Standard error	0.03	0.06	0.04	0.00	2.52	2.65	0.06	1.15	0.06
4	8500	22,04,2023 10:09:00	13.70	16.40	12.23	100.00	31.00	49.00	5.60	610.00	2.62
		22,04,2023 17:24:00	13.60	16.20	12.09	100.00	32.00	57.00	5.84	604.00	2.88
		23,04,2023 3:22:00	13.40	16.00	11.94	100.00	40.00	54.00	5.52	610.00	2.80
		Mean value	**13.57**	**16.20**	**12.09**	**100.00**	**34.33**	**53.33**	**5.66**	**608.00**	**2.77**
		Standard deviation	0.15	0.20	0.15	0.00	4.93	4.04	0.17	3.46	0.13
		Standard error	0.09	0.12	0.09	0.00	2.85	2.33	0.10	2.00	0.08

Point	Engine rotational speed [RPM]	Date of measure or statistic value	HC [ppm]	CO2 [%vol]	O2 [%vol]	Lambda [-]	Room temperature sensor [°C]	Air humidity [%]	Air pressure [kPa]	fuel pressure [kPa/100]	BSFC [g/(kW*h)]
1	5500	22,04,2023 10:09:00	410.00	9.18	5.82	0.93	23.40	37.00	101.80	4.40	571.66
		22,04,2023 17:24:00	431.00	9.20	5.75	0.93	21.50	37.00	101.40	4.32	554.33
		23,04,2023 3:22:00	1274.00	9.81	4.80	0.92	29.50	30.00	101.60	4.33	592.21
		Mean value	**705.00**	**9.40**	**5.46**	**0.93**	**24.80**	**34.67**	**101.60**	**4.35**	**572.73**
		Standard deviation	492.88	0.36	0.57	0.01	4.18	4.04	0.20	0.04	18.96
		Standard error	284.56	0.21	0.33	0.00	2.41	2.33	0.12	0.03	10.95
2	6500	22,04,2023 10:09:00	631.00	9.89	4.86	0.93	24.00	36.00	101.40	4.40	516.16
		22,04,2023 17:24:00	737.00	9.06	4.80	0.89	23.50	37.00	101.40	4.31	542.80
		23,04,2023 3:22:00	1469.00	10.23	4.19	0.94	29.50	30.00	101.60	4.32	513.15
		Mean value	**945.67**	**9.73**	**4.62**	**0.92**	**25.67**	**34.33**	**101.47**	**4.34**	**524.04**
		Standard deviation	456.31	0.60	0.37	0.03	3.33	3.79	0.12	0.05	16.32
		Standard error	263.45	0.35	0.21	0.02	1.92	2.19	0.07	0.03	9.42
3	7500	22,04,2023 10:09:00	909.00	10.28	3.51	0.93	24.80	34.00	101.30	4.40	468.06
		22,04,2023 17:24:00	1185.00	10.22	3.52	0.94	25.40	34.00	101.20	4.30	478.23
		23,04,2023 3:22:00	1461.00	10.39	3.20	0.93	30.10	27.00	101.50	4.30	478.23
		Mean value	**1185.00**	**10.30**	**3.41**	**0.93**	**26.77**	**31.67**	**101.33**	**4.33**	**474.84**
		Standard deviation	276.00	0.09	0.18	0.01	2.90	4.04	0.15	0.06	5.87
		Standard error	159.35	0.05	0.11	0.00	1.68	2.33	0.09	0.03	3.39
4	8500	22,04,2023 10:09:00	1060.00	10.40	3.03	0.93	25.30	34.00	101.70	4.40	466.21
		22,04,2023 17:24:00	877.00	10.23	3.00	0.93	23.60	34.00	101.80	4.28	467.65
		23,04,2023 3:22:00	1386.00	10.48	2.76	0.93	30.90	27.00	101.50	4.30	471.31
		Mean value	**1107.67**	**10.37**	**2.93**	**0.93**	**26.60**	**31.67**	**101.67**	**4.33**	**468.39**
		Standard deviation	257.83	0.13	0.15	0.00	3.82	4.04	0.15	0.06	2.63
		Standard error	148.86	0.07	0.09	0.00	2.21	2.33	0.09	0.04	1.52

Tab. 6-5 Measured values during efficiency test of ethanol fuel

The most notable change in measured parameters is BSFC, which augmented at all points approximately by 30%. Along with that, the moment only raised by approximately 6% at all measured rotational speeds. The good news is that CO emissions have decreased at all measured points significantly. CO_2 emissions could be considered the same for petrol and Ethanol fuel. However, the measuring device is not well calibrated for alcohol fuels with higher oxygen content, which could have influenced the analysis results. Therefore, the only valuable declaration is the decrease in CO emissions with the ethanol fuel.

6.8 ALTERNATIVE FUEL – METHANOL

At last, methanol fuel is analyzed. Methanol is the trickiest fuel to measure because of its low AFR. Engine running on methanol fuel must have a large flow of fuel in the injection; therefore, the injector type BOSCH 0 280 158 038 is used because of its higher flow rate. The new flow rate is equal to 244.8 g/min – as mentioned in chapter 6.3.3. Methanol has got higher RON number than gasoline, and given the facts from chapter 6.3.3, a new type of sparkplug NGK BP6HS is used.

After these modifications, injection timing is modified. This time, also ignition timing is changed based on the information from chapter 5.2.4.

6.8.1 PERFORMANCE TEST OF METHANOL FUEL

During the experiment, methanol fuel posed a lot of troubles to be precisely measured. It was not possible to set the engine correctly to reach desired torque and power output. Thus, all values from performance and efficiency tests can be only indicative but should not be directly compared with other alternative fuels. To measure this fuel correctly, more adjustments should be made, given the reasons described later in this chapter.

Test results average values are pasted to Fig. 6-12, with polynomials of 6^{th} degree to approximate the progress of the torque and power[2].

[2] different sampling rate and different test is used for methanol fuel. The load increase happens quicker, and a single test is not averaged from multiple increases

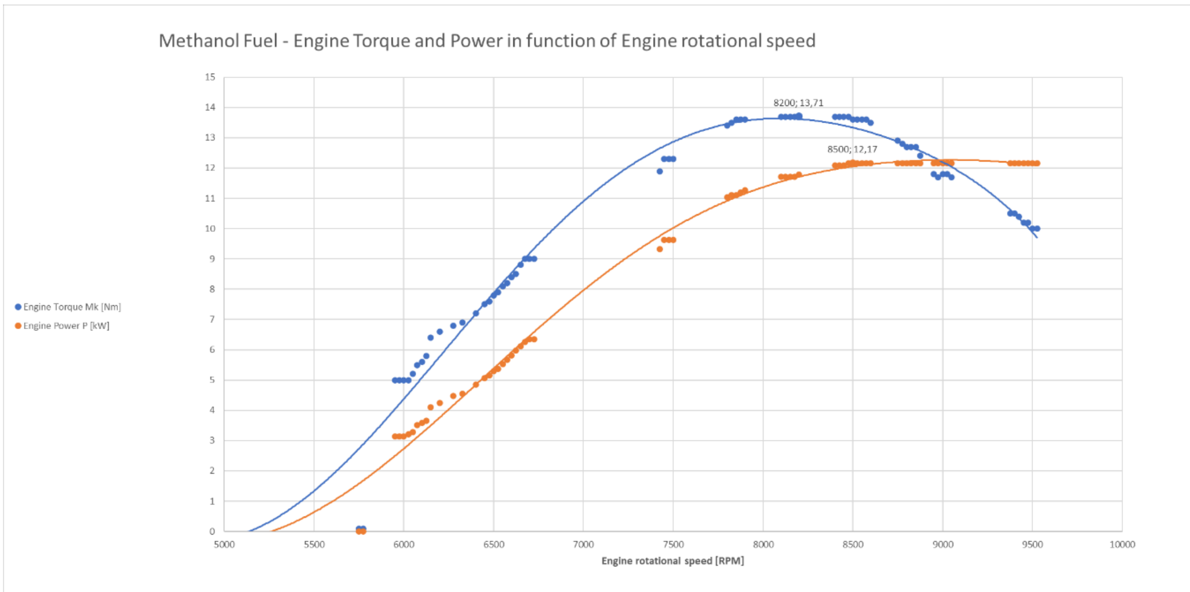


Fig. 6-12 Engine torque and power in function of engine rotational speed for Methanol fuel

6.8.2 EFFICIENCY TEST OF METHANOL FUEL

As it was mentioned, methanol is not easy to analyze because of its low AFR. Therefore, only two efficiency tests were conducted. Also, because of its high fuel consumption, only one measure of BSFC could have been made. This reduced data is shown in Tab. 6-6.

Point	Engine rotational speed [RPM]	Date of measure or statistic value	Mk [Nm]	Power [HP]	Power [kW]	TPS [%]	T air [°C]	T motor [°C]	T INJ akt [ms]	EGT akt [°C]	CO [%vol]
1	5500	21.04.2023 19:44	5.7	4.40	3.28	40	29	43	2.549	433	0.37
		22.03.2023 16:08	5.9	4.60	3.43	40	23	39	2.582	428	0.22
		Mean value	**5.80**	**4.50**	**3.36**	**40.00**	**26.00**	**41.00**	**2.57**	**430.50**	**0.30**
		Standard deviation	0.14	0.14	0.11	0.00	4.24	2.83	0.02	3.54	0.11
		Standard error	0.10	0.10	0.07	0.00	3.00	2.00	0.02	2.50	0.08
2	6500	21.04.2023 19:44	8.2	7.50	5.60	50	29	47	3.201	471	1.24
		22.03.2023 16:08	8.3	7.50	5.60	50	26	44	3.234	470	1.02
		Mean value	**8.25**	**7.50**	**5.60**	**50.00**	**27.50**	**45.50**	**3.22**	**470.50**	**1.13**
		Standard deviation	0.07	0.00	0.00	0.00	2.12	2.12	0.02	0.71	0.16
		Standard error	0.05	0.00	0.00	0.00	1.50	1.50	0.02	0.50	0.11
3	7500	21.04.2023 19:44	12.7	13.50	10.07	70	29	45	6.172	434	9.48
		22.03.2023 16:08	12.9	13.70	10.22	70	28	40	6.229	435	9.71
		Mean value	**12.80**	**13.60**	**10.15**	**70.00**	**28.50**	**42.50**	**6.20**	**434.50**	**9.60**
		Standard deviation	0.14	0.14	0.11	0.00	0.71	3.54	0.04	0.71	0.16
		Standard error	0.10	0.10	0.07	0.00	0.50	2.50	0.03	0.50	0.12
4	8500	21.04.2023 19:44	12.9	15.30	11.41	100	29	43	6.349	504	9.62
		22.03.2023 16:08	12.7	15.00	11.19	100	29	39	6.394	505	10.13
		Mean value	**12.8**	**15.15**	**11.3019**	**100**	**29**	**41**	**6.3715**	**504.5**	**9.875**
		Standard deviation	0.141421	0.212132	0.15825	0	0	2.828427	0.03182	0.707107	0.36062446
		Standard error	0.1	0.15	0.1119	0	0	2	0.0225	0.5	0.255

Point	Engine rotational speed [RPM]	Date of measure or statistic value	HC [ppm]	CO2 [%vol]	O2 [%vol]	Lambda [-]	Room temperature sensor [°C]	Air humidity [%]	Air pressure [kPa]	fuel pressure [kPa/100]	BSFC [g/(kW*h)]
1	5500	21.04.2023 19:44	1595	8.67	7.25	0.98	23.1	39	101.3	3.85	687.391304
		22.03.2023 16:08	862	9.09	7.09	0.99	20.7	40	100.8	3.84	
		Mean value	**1228.50**	**8.88**	**7.17**	**0.99**	**21.90**	**39.50**	**101.05**	**3.85**	**687.39**
		Standard deviation	518.31	0.30	0.11	0.01	1.70	0.71	0.35	0.01	
		Standard error	366.50	0.21	0.08	0.01	1.20	0.50	0.25	0.01	
2	6500	21.04.2023 19:44	1683	9.42	5.61	0.95	23.1	37	101.2	3.77	665.684211
		22.03.2023 16:08	828	9.65	5.68	0.96	22.5	41	100.8	3.79	
		Mean value	**1255.50**	**9.54**	**5.65**	**0.96**	**22.80**	**39.00**	**101.00**	**3.78**	**665.68**
		Standard deviation	604.58	0.16	0.05	0.01	0.42	2.83	0.28	0.01	
		Standard error	427.50	0.12	0.03	0.01	0.30	2.00	0.20	0.01	
3	7500	21.04.2023 19:44	1692	6.07	3.84	0.72	23.1	39	101.1	3.7	929.167883
		22.03.2023 16:08	888	6.16	3.63	0.72	24	41	100.8	3.69	
		Mean value	**1290.00**	**6.12**	**3.74**	**0.72**	**23.55**	**40.00**	**100.95**	**3.70**	**929.17**
		Standard deviation	568.51	0.06	0.15	0.00	0.64	1.41	0.21	0.01	
		Standard error	402.00	0.04	0.11	0.00	0.45	1.00	0.15	0.01	
4	8500	21.04.2023 19:44	1717	6.22	3.5	0.72	23.1	43	101.1	3.66	928.88
		22.03.2023 16:08	1747	6.22	3.15	0.71	24.7	42	100.3	3.7	
		Mean value	**1732**	**6.22**	**3.325**	**0.715**	**23.9**	**42.5**	**100.7**	**3.68**	**928.88**
		Standard deviation	21.2132	0	0.247487	0.007071068	1.13137085	0.707107	0.56569	0.028284	
		Standard error	15	0	0.175	0.005	0.8	0.5	0.4	0.02	

Tab. 6-6 Measured values during efficiency test of methanol fuel

Huge augmentation in BSFC is obvious. This is caused by the low value of AFR for methanol fuel and the inefficiency of the fuel with current engine settings. At 7500 RPM, an engine with methanol fuel generates the highest torque and power, but this information is not confirmed at 8500 RPM. In addition, CO emission is significantly lower at low rotational speeds (5500 RPM and 6500 RPM), but they are higher at higher rotational speeds. It is not possible to conclude whether this proclamation is true because of inappropriate settings of the emission analyzer and inconvenient measurement methods of the engine performance on the test bench. Therefore, CO_2 emission – which is lower during all rotational speeds – cannot be counted as truthful either.

Based on the results, it is supposed that methanol fuels generally have better CO and CO_2 emissions than conventional fuel, but it cannot be fully confirmed.

Another noticeable change is the significantly lower temperature of exhaust gases (EGT). This is caused by the fact described in chapter 6.3.3.

7 DIRECT COMPARISON OF RESULTS OF FUELS ON ENGINE TEST BENCH

Every important parameter (torque, power, etc.) from individual analyzes is fused together in one large comparative analysis. This allows us to see the differences between different fuels.

7.1 PERFORMANCE ANALYSIS

First, the general performance of the engine is analyzed. It is not required that alternative fuels generate more torque with the same engine at the same physical setup. Nevertheless, especially alternative alcohol fuels may make the engine more powerful because of their higher RON number (see chapter 5.1), which would be – of course – beneficial for engine operation.

Solely engine's maximum torque at a certain rotational speed and the engine's maximum power in relative rotational speed is considered during the performance test. Tab. 7-1 indicates the comparison of all tested fuels on their performance level.

Fuel	Rotational speed [RPM]	Max Mk [Nm]	rotational speed [RPM]	Max P [kW]
Petrol	7775	13.54	8525	11.69
E40 Mixture	8125	13.84	8550	12.09
Ethanol	8000	14.04	8625	12.43
Methanol	8200	13.71	8500	12.17

Tab. 7-1 Comparison of different fuels maximum torque (Mk) and power (P)

The data in the Tab. 7-1 comply with individual analysis for each fuel and its torque and power characteristics (see Fig. 6-9, Fig. 6-10, Fig. 6-11, and Fig. 6-12). To better see the difference in the results, a bar chart in Fig. 7-1 is generated along with Fig. 7-2, which presents the progress of torque and power in function of rotational speed for different fuels. Data in Fig. 7-21 corresponds with individual tests of different fuels.

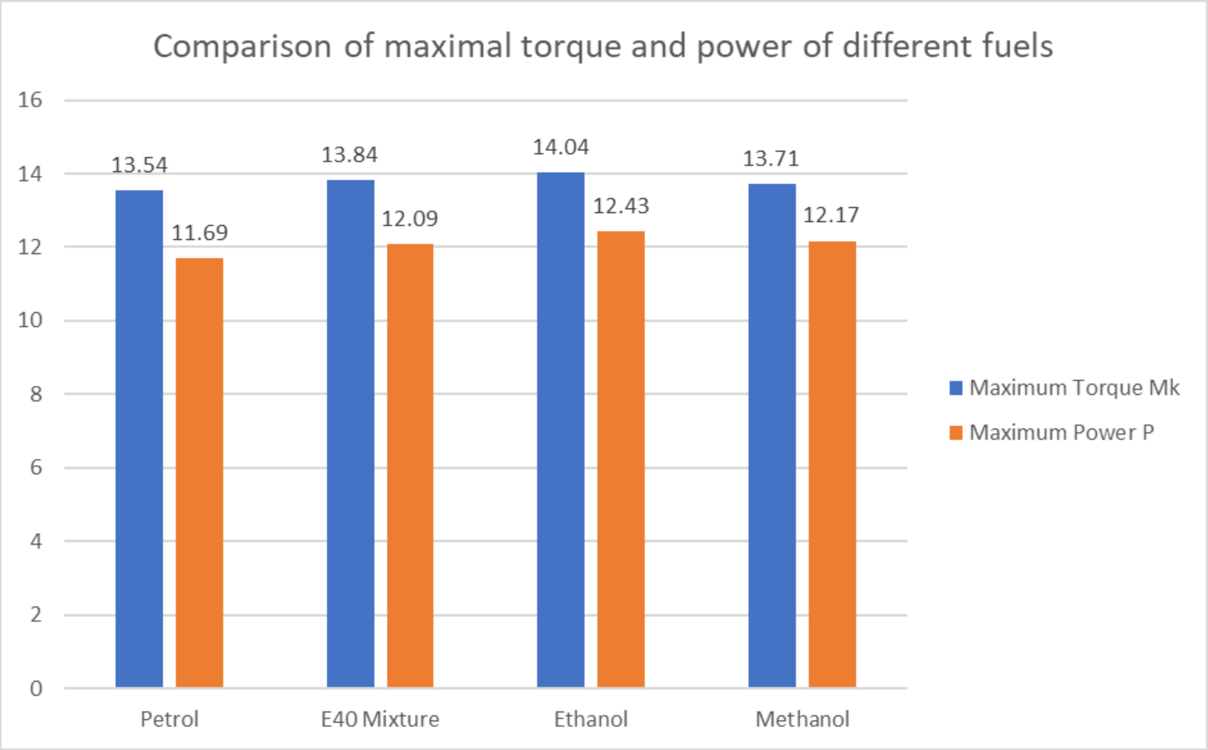


Fig. 7-1 Comparison of different fuels maximum torque (Mk) and power (P) in bar chart

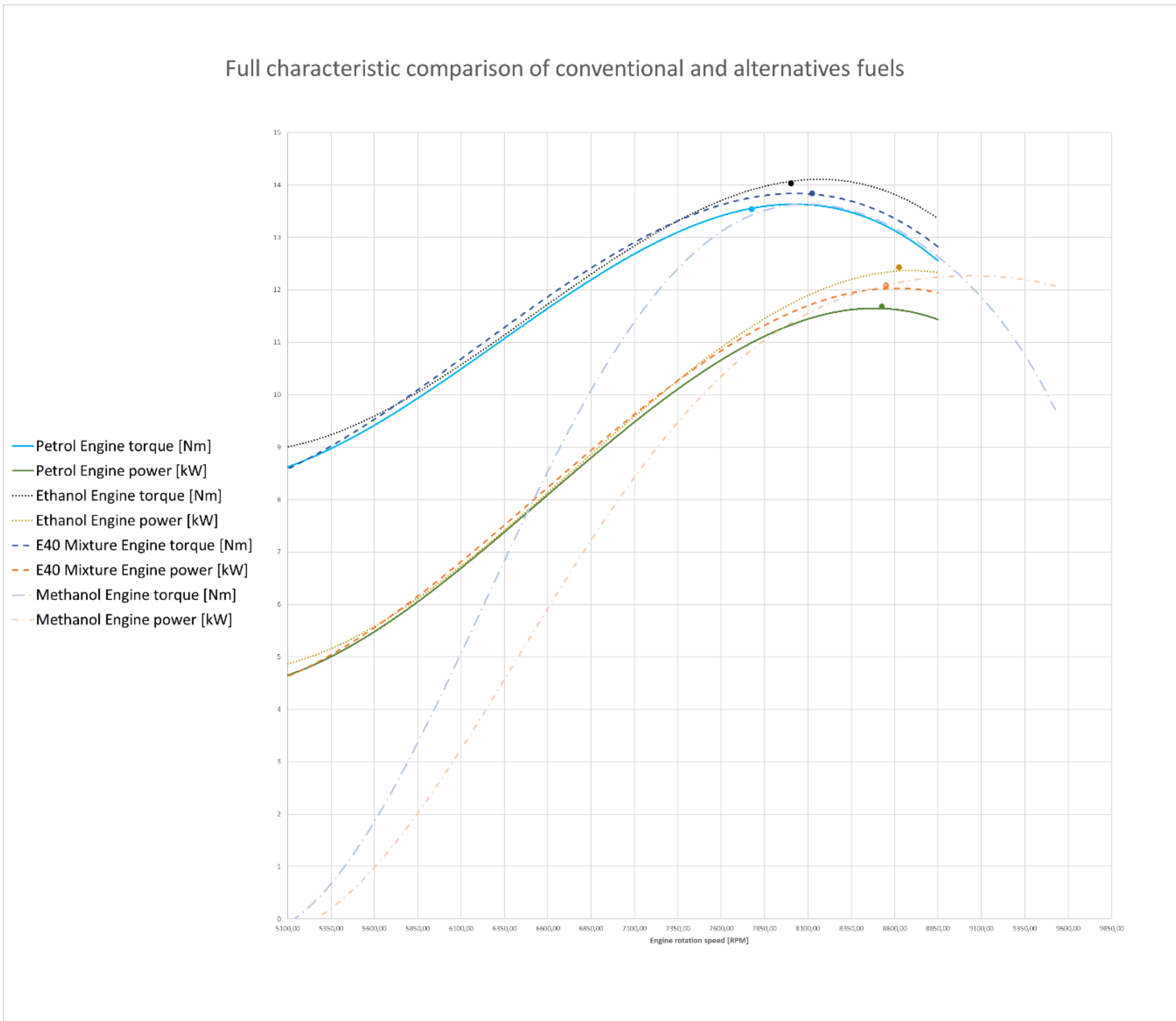


Fig. 7-2 Comparison of different fuels torque (Mk) and power (P) in different engine speeds

At first sight, with the addition of ethanol to conventional petrol, both torque and power are increasing. When the fuel mixture consists of 100% ethanol with oil, the torque output is the highest – approximately 104% of the maximum torque of petrol fuel. Surprisingly, methanol fuel does not generate more power than ethanol fuel. As it was mentioned earlier in chapter 6.8, methanol fuel could not be tested correctly because of the very difficult setting of the engine on the engine test bench. Therefore, it is possible that the maximum torque has not been reached with methanol fuel. Note that adequate rotational speed for maximal torque also changes (Tab. 6-7). From the look of the engine user, it is better if the rotational speed for maximum torque is closer to the one of maximum power. This would allow better control of the engine at this specific rotational speed, which should be, therefore, the optimal operating speed. This relation sits to the mixture E40 the best.

To conclude, alternative alcohol fuels can generate slightly more torque and thus more power without changing anything than the injection timing on the engine.

7.2 EFFICIENCY ANALYSIS

For the efficiency comparative analysis, only BSFC, CO, and CO_2 emissions are considered because other parameters could not be measured precisely or are not relevant to the experiment. Tab. 7-2 presents the comparison of all fuels at specific rotational speeds.

rotational speed [RPM]	Fuel	Mk [Nm]	P [kW]	BSFC [g/(kW*h)]	BSFC [g/(kWh*100)]	CO [% vol]	CO2 [% vol]
5500	Petrol	4.33	2.51	412.82	4.13	2.51	8.48
	Blend	4.63	2.66	441.01	4.41	1.62	9.38
	Ethanol	4.80	2.79	572.73	5.73	1.59	9.40
	Methanol	5.80	3.36	687.39	6.87	0.30	8.88
6500	Petrol	7.37	5.10	345.12	3.45	1.76	9.64
	Blend	7.63	5.22	390.17	3.90	1.87	9.63
	Ethanol	7.83	5.35	524.04	5.24	2.04	9.73
	Methanol	8.25	5.60	665.68	6.66	1.13	9.54
7500	Petrol	11.50	9.05	325.01	3.25	2.36	9.84
	Blend	11.73	9.35	376.53	3.77	2.51	9.91
	Ethanol	12.03	9.47	474.84	4.75	2.30	10.30
	Methanol	12.80	10.15	929.17	9.29	9.60	6.12
8500	Petrol	12.77	11.46	345.37	3.45	3.52	8.85
	Blend	13.33	11.89	381.69	3.82	3.00	9.60
	Ethanol	13.57	12.09	468.39	4.68	2.77	10.37
	Methanol	12.80	11.30	928.88	9.29	10.13	6.22

Tab. 7-2 Comparison of different fuels torque (Mk), power (P), BSFC, CO, and CO_2 emissions in specific rotational speeds

Based on this data, four bar charts for each rotational speed are generated. These bar charts (Fig. 7-3a, Fig. 7-3b, Fig. 7-3c, Fig. 7-1d) show explicitly the main differences between fuels.

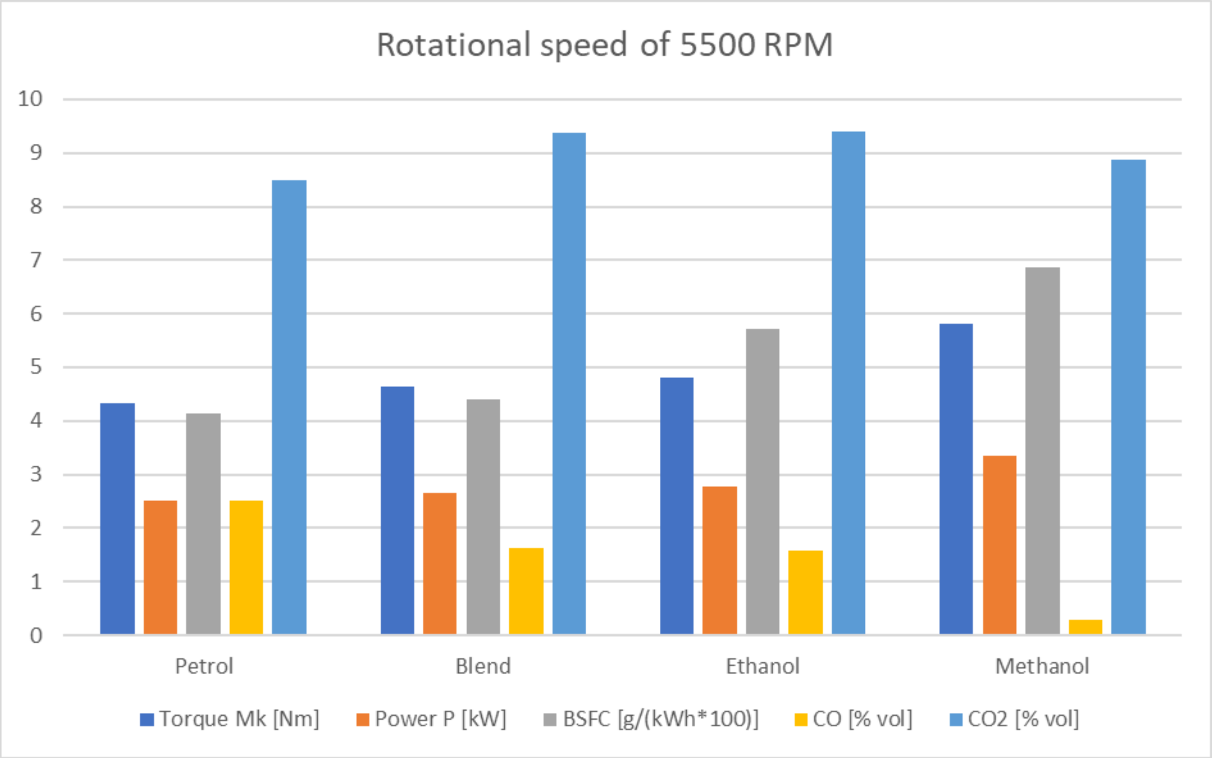


Fig. 7-3a Comparison of different fuels torque (Mk), power (P), BSFC, CO, and CO_2 emissions in a bar chart for rotational speed 5500 RPM

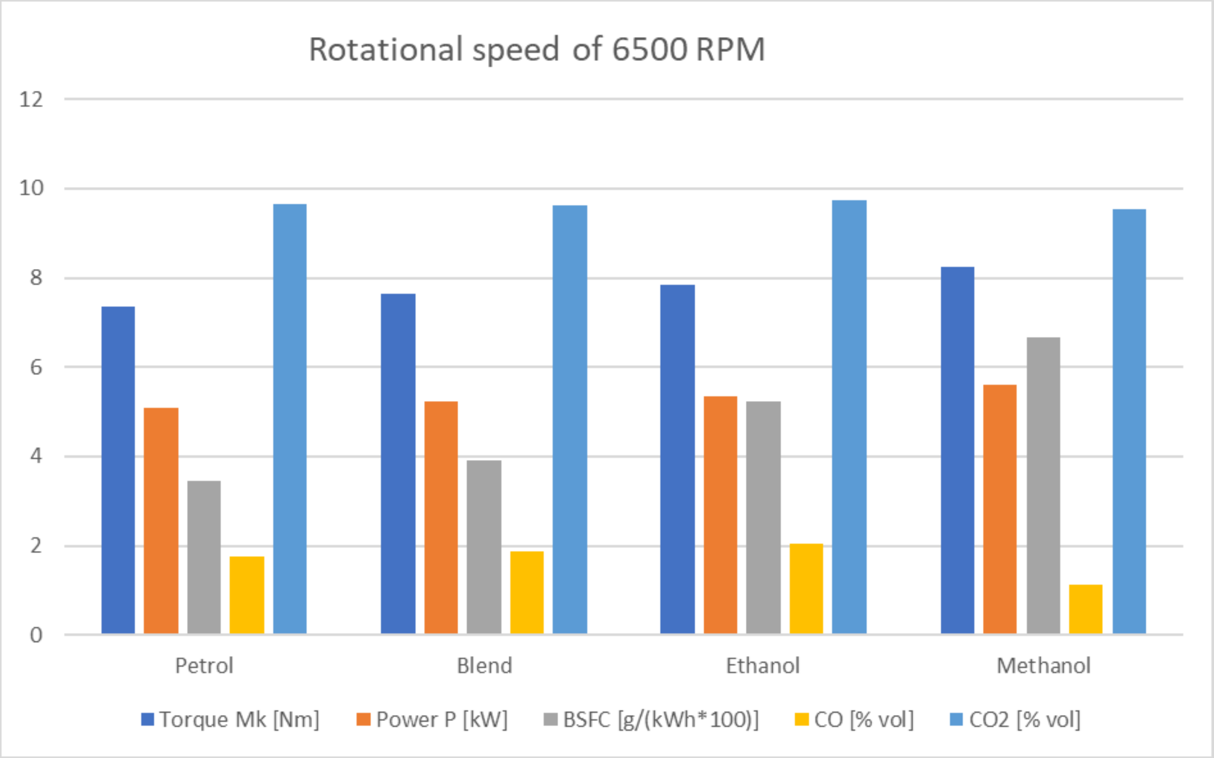


Fig. 7-3b Comparison of different fuels torque (Mk), power (P), BSFC, CO, and CO_2 emissions in a bar chart for rotational speed 6500 RPM

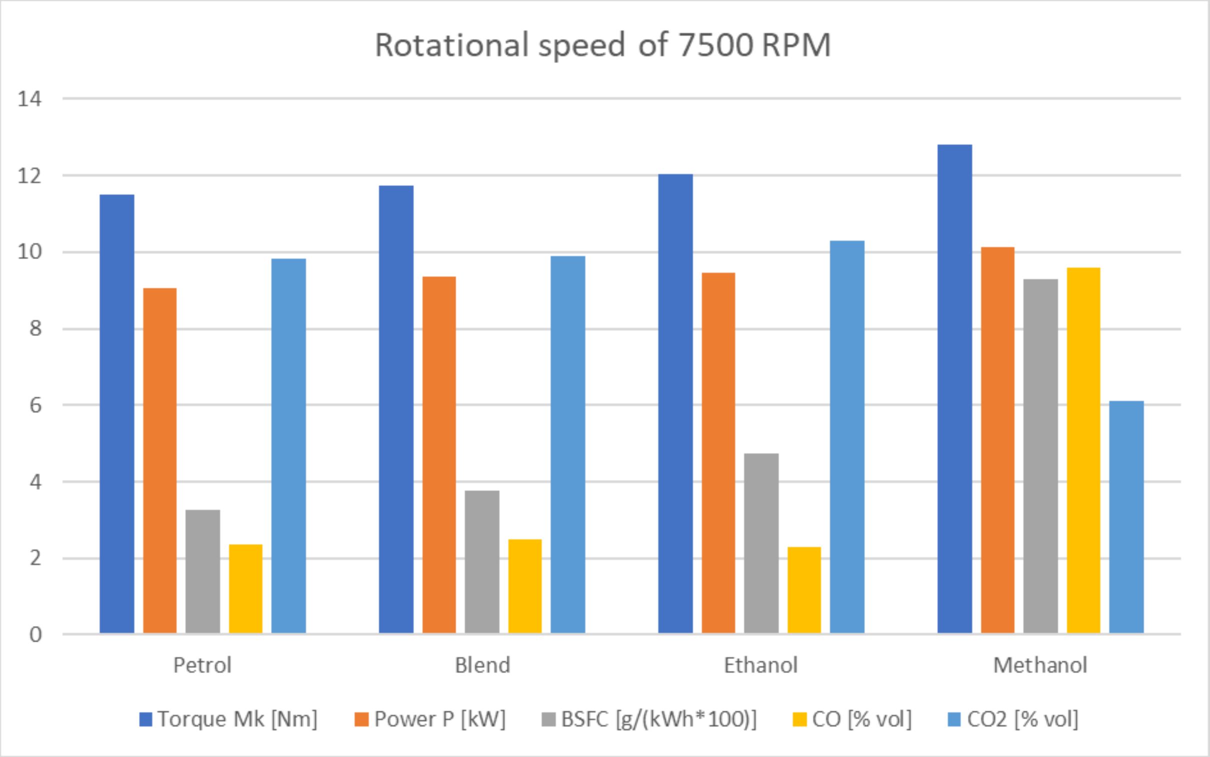


Fig. 7-3c Comparison of different fuels torque (Mk), power (P), BSFC, CO, and CO_2 emissions in a bar chart for rotational speed 7500 RPM

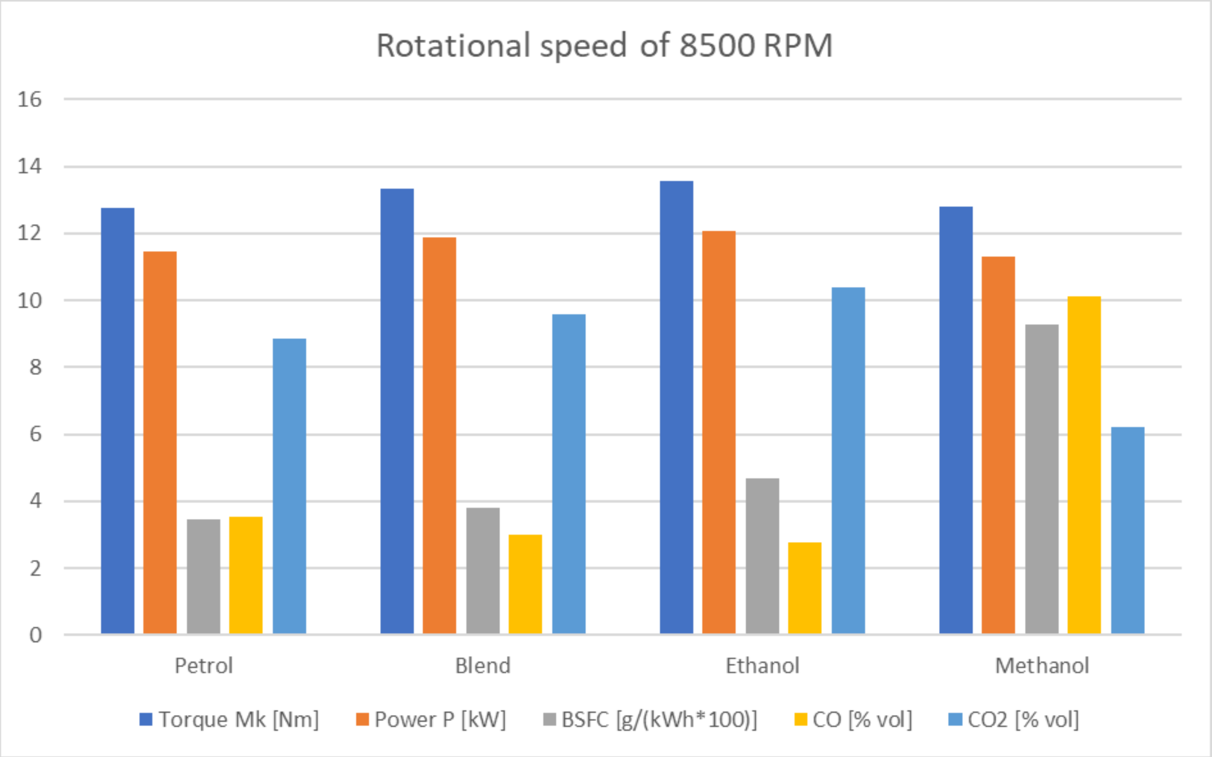


Fig. 7-3d Comparison of different fuels torque (Mk), power (P), BSFC, CO, and CO_2 emissions in a bar chart for rotational speed 8500 RPM

The phenomenon of increased torque and power with the addition of ethanol to the fuel is confirmed even during this test series. Bar charts in Fig. 7-3 prove this effect.

BSFC changes as well with the addition of ethanol fuel, again increasing its value. This is considered a negative effect because more fuel mass is needed for ethanol-based fuels to deliver the same power. Methanol fuel BSFC is undoubtedly the highest, almost 285% of petrol fuel BSFC at the rotational speed of 7500 RPM. This is mainly due to the low AFR of methanol fuel and low value of lambda (approx. 0.75) in Tab. 6-6. As it was mentioned earlier in chapter 5.2.3, methanol fuel-based engines need significantly more fuel to operate than petrol-based engines. Because of this problem, methanol cannot be considered as an alternative fuel for MSR NG 100 engine without any further modifications. It is possible that with more non-returnable changes on the engine (an increase in compression ratio, different exhaust pipe length, etc.), better results could be achieved with methanol fuel.

The emission of CO gas has been very similar for the first three tested fuels. Only slight differences in the emission can be caused by measurement error of the measuring device or wrong setup of the device for alcohol-based fuels. It can be only proclaimed that the emissions of CO gas do not change drastically with alternative fuels.[3]

During all measures, CO_2 emissions also seem to remain stable. Based on the information from Fig. 7-3a and Fig. 7-3d, CO_2 emission increases slightly with ethanol-based alternative fuels. In Fig. 7-3b and Fig. 7-3c, CO_2 emission does not change significantly with ethanol fuels. If the engine's optimal operation rotational speed were 7500 RPM, it would be true that CO_2 emission does not change with different alternative fuels. Methanol fuel has got significantly lower CO_2 emission during higher rotational speeds, which could be caused by lower carbon content in the molecule of methanol (only one carbon atom). Once more, it is not possible to state whether this information is true.

7.3 ENGINE TEST BENCH ANALYSIS CLOSURE

To conclude, even though alcohol-based fuels have usually got higher BSFC, the GHG emissions on MSR NG 100 two-stroke engines do not increase considerably, while the torque output grows by a few percent indeed. The use of alcohol-based sustainable alternative fuels seems possible in small two-stroke combustion engines.

[3] methanol fuel is not considered in this affirmation, because of anomalous behavior of the measure of CO emission at 7500 RPM and 8500 RPM

8 SIMULATION OF ENGINE HEAT CYCLE WITH DIFFERENT FUELS

The simulation of alternative fuels using the software GT Suite is conducted to prove and confirm the results from engine test bench. This simulation presents another point of view on alternative fuels and their application to the MSR NG 100 engine. All three selected alternatives (methanol, ethanol, and E40 mixture), along with conventional petrol, are simulated in the software on the model engine, which must be created in advance. A complete model of the MSR NG 100 engine is generated and adjusted in the software. After correctly setting up the model and fuels in the software, two types of simulation are performed – firstly, the engine performance test and later, the engine economy test. The results from both analyses of all four tested fuels are compared, and in the end, conclusions are made.

8.1 SETTING UP THE MODEL OF THE ENGINE MSR NG 100

To achieve the most precise results, the complete geometry and thermal properties of the engine must be imported into the simulation software. Fig. 8-1 represents the virtual configuration (model map) of the engine imported in the simulation software.

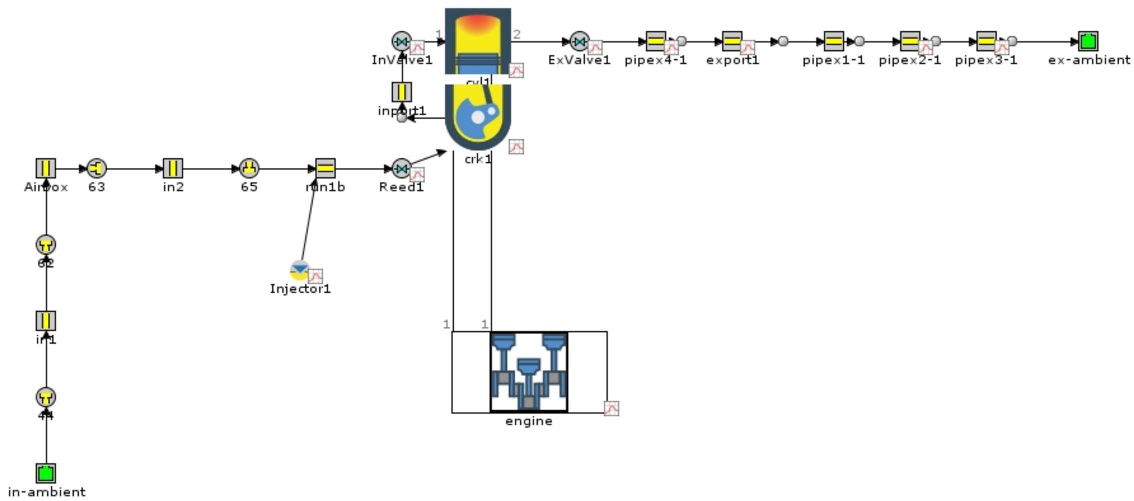


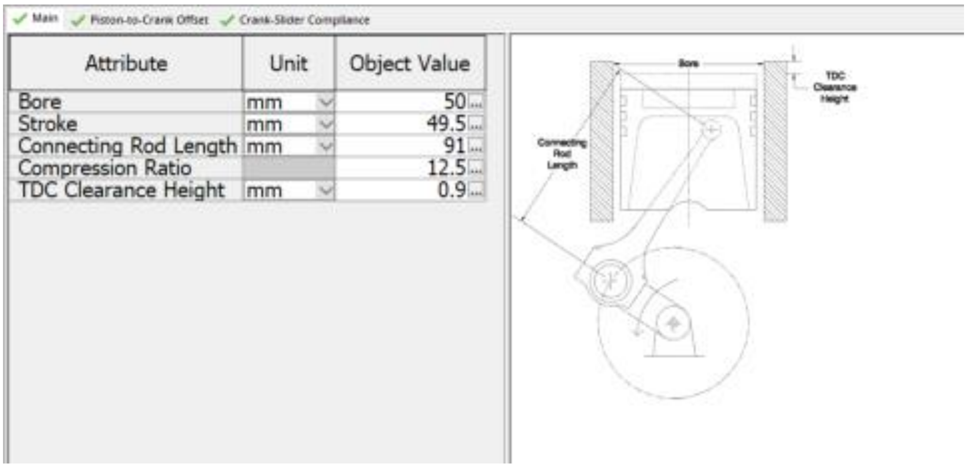
Fig. 8-1 Model map of the MSR NG 100 engine in the simulation software

In Fig. 8-1, `engine` represents the engine model, `crk1` is the crankcase, and `cyl1` is the cylinder of the engine. The left part of the image (from `in-ambient` to `Reed1`) presents the air intake – inlet port. The right side of the image (from `ExValve1` to `ex-ambient`) is the engine exhaust part – outlet port. Between the crankcase and cylinder is the transfer port (`inport1` and `InValve1`) of the two-stroke engine. Indirect fuel injection (`Injector1`) is situated in front of the reed valve (`Reed1`) as it is in the real engine.

As a next step, boundary conditions and precise engine parameters must be defined to make the simulation most like the real engine run. In the next chapters, figures from GT Suite software are used to describe the user-defined conditions.

8.1.1 ENGINE PARAMETERS

In the engine part, engine main parameters are set up. The type of engine is selected as two-stroke with speed specification (engine rotational speed is defined separate case of the engine cycle). The start of the cycle is at -92°. Cylinder geometrical properties are the same as mentioned in the chapter 1.3.4 and described in Fig. 8-2.



Attribute	Unit	Object Value
Bore	mm	50
Stroke	mm	49.5
Connecting Rod Length	mm	91
Compression Ratio		12.5
TDC Clearance Height	mm	0.9

Fig. 8-2 Engine geometry in the simulation software

8.1.2 CRANKCASE SETUP

After correctly setting up the engine, crankcase parameters are imported based on the information from the GT Suite. All necessary information from the crankcase setup is in Fig. 8-3, Fig 8-4a, and Fig 8-4b.

Attribute	Unit	Object Value
Bore	mm	50
Compression Ratio		1.23
Exposed Liner Length at BDC	mm	1
Initial State Name		intake
Heat Transfer Object		htr-crankcase
Wall Temperature Object		twall-crank...
Initial State Scaling		on

Fig. 8-3 Crankcase main setup

Inside Fig. 8-3, the Heat transfer object must be defined as it is in Fig. 8-4a. Moreover, Wall Temperature object settings must be made, as Fig. 8-4b shows.

Attribute	Object Value
Heat Transfer Model	WoschniGT
Overall Convection Multiplier	0.5
Individual Convection Multipliers	
Head/Bore Area Ratio	2.05
Piston/Bore Area Ratio	1.016
Radiation Multiplier	ign
Convection Temperature Evaluation	hybrid
Low Speed Heat Transfer Enhancement for Woschni* Mo...	✓

Fig. 8-4a Heat transfer model

For the heat transfer model, based on the recommendation from the GT Suite, the Woschni heat transfer model is selected, and geometry information is imported.

Attribute	Unit	Object Value
Head Temperature	K	453
Piston Temperature	K	473.15
Cylinder Temperature	K	338

Fig. 8-4b Wall temperature settings

Wall temperatures are set up on the estimation from the experiment on the engine test bench from chapter 6.5.

8.1.3 CYLINDER SETUP

In the next part, crucial information about the engine combustion process in the cylinder is set up. Data from the software is displayed below in Fig. 8-5.

Attribute	Object Value
Initial State Object	intake
Wall Temperature defined by Reference Object	cyltwall
Wall Temperature defined by FE Structure part ('EngCy...	
Heat Transfer Object	htr
Flow Object	ign
Combustion Object	comb
Measured Cylinder Pressure Analysis Object	ign
Cylinder Pressure Analysis Mode	off

Fig. 8-5 Cylinder main setup

A precise specification of Wall temperature, Heat transfer object, and Combustion model is needed. The first one is adjusted in a similar way (Fig. 8-6a) as in Fig. 8-4b for crankcase setup. Woschni model from the GT Suite library is selected as Heat transfer object– Fig. 8-6b.

Attribute	Unit	Object Value
Head Temperature	K	453
Piston Temperature	K	473
Cylinder Temperature	K	338

Fig. 8-6a Wall temperature settings for cylinder

Attribute	Object Value
Heat Transfer Model	WoschniGT
Overall Convection Multiplier	1.15
Individual Convection Multipliers	
Head/Bore Area Ratio	2.05
Piston/Bore Area Ratio	1.016
Radiation Multiplier	ign
Convection Temperature Evaluation	hybrid
Low Speed Heat Transfer Enhancement for Woschni* Mo...	✓

Fig. 8-6b Heat transfer object settings

Wiebe combustion model in the cylinder is one of the crucial parameters of the two-stroke engine. This model precisely describes the combustion process, and therefore, the values of the model change massively engine behavior and properties. Therefore, Optimization by GT Optimization software must be made. The unknown parameters Anchor angle [AA], Duration of 50% of combustion [Dur], and Wiebe exponent [Wiebe], with their predefined range of values, are described in chapter 8.3.2.

Attribute	Object Value
Anchor Angle (def = 50% burn)	[AA]
Duration (def = 10% to 90%)	[Dur]
Wiebe Exponent	[Wiebe]

Fig. 8-6c Wiebe combustion model parameters

Later, several other parameters must be determined, but considering the reach and simplicity of this analysis, most of the parameters in Fig 8-7 are ignored (`ign`). However, the scavenging object must be defined precisely. As mentioned in chapter 1.3.4, scavenging presents the biggest challenge when improving the two-stroke engine. Because the scavenging process with MSR NG 100 engine is not known or measured, this study uses a basic scavenging model of the two-stroke engine from GT Suite sources.

Attribute	Unit	Object Value
Scavenging Object		scav-curve
Evaporation Object		ign
Film Evaporation Object		ign
Emissions Map Object		ign
Blowby Object		ign
External Cylinder Model Object		ign
Exhaust Energy Fraction Object		ign
Maximum Cylinder Substep During Combustion	deg	ign
Cylinder Copying Option		off
Initial State Scaling		on
Crank Angle at EVO (when valves are not present)	deg	def

Fig. 8-7 Advanced parameters in cylinder settings

The scavenging curve, which is the value of the Exhaust residual ratio in function of the Cylinder residual ratio, is shown in Fig. 8-8. The function represents the filling of the cylinder after opening the exhaust and intake port and its proportion. The correct scavenging process is the key to achieving high engine torque, where the result depends solely on the intake and exhaust port geometry. This software works only in one dimension. Thus, instead of 3D geometry, the scavenging process is described with the curve in Fig. 8-8.

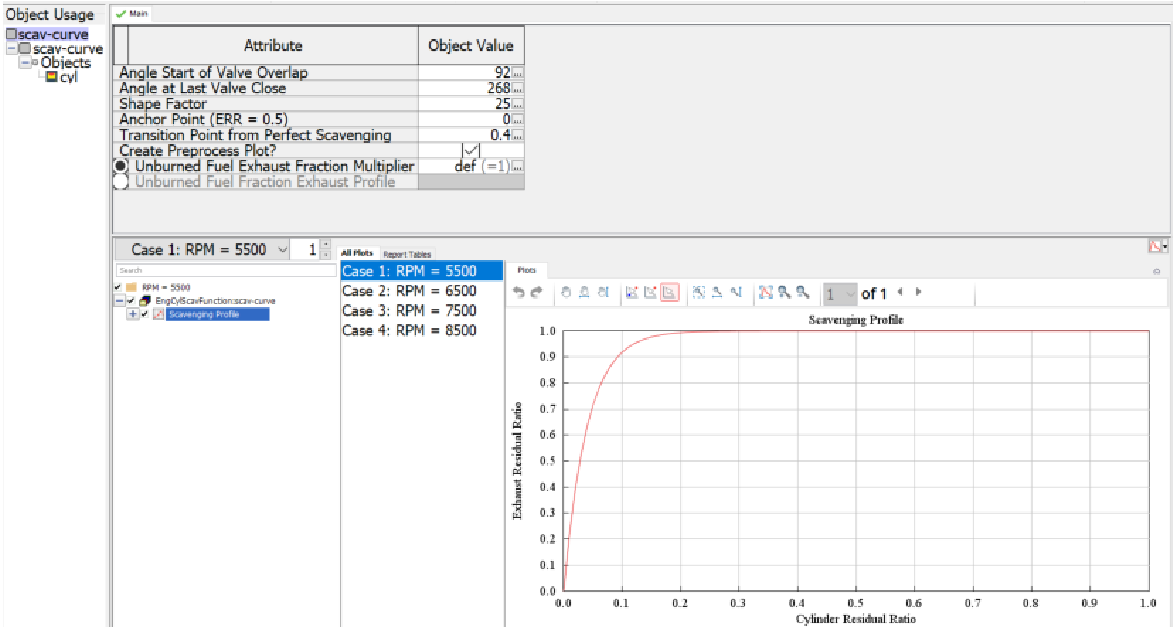


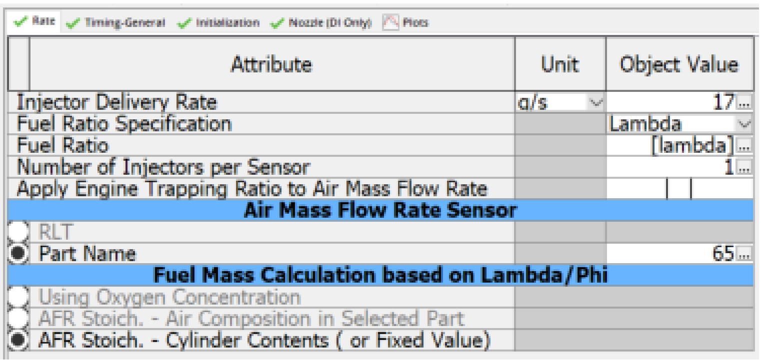
Fig. 8-8 Scavenging process description and scavenging curve

8.1.4 INJECTION SETTINGS

MSR NG 100 engine has got an indirect injection of fuel in front of the reed valve, typical for two-stroke engines. This type of injection is modeled in Fig. 8-1.

The injector controls how much fuel enters the mixture flow. Precise control in the simulation is assured by the value of lambda [lambda] (described in chapter 6.3.1) and injection duration [inj], which are optimized during the simulation optimization process. The injector delivery rate is determined based on the information from the producer BOSCH.

It is this component in which the type of fuel is defined. The fuel type is naturally adjusted for each fuel simulation. Other parameters are set up like on the real engine. Fig. 8-9a, 8-9b, and 8-9c show how these parameters are entered into the software.



Attribute	Unit	Object Value
Injector Delivery Rate	g/s	17
Fuel Ratio Specification		Lambda
Fuel Ratio		[lambda]
Number of Injectors per Sensor		1
Apply Engine Trapping Ratio to Air Mass Flow Rate		
Air Mass Flow Rate Sensor		
RLT		
Part Name		65
Fuel Mass Calculation based on Lambda/Phi		
Using Oxygen Concentration		
AFR Stoich. - Air Composition in Selected Part		
AFR Stoich. - Cylinder Contents (or Fixed Value)		

Fig. 8-9a Rate parameters of the injection settings

Rate | Timing-General | Initialization | Nozzle (DI Only) | Plots

Attribute	Unit	Object Value
Source of Angle		
Attached Cylinder		
Part on Map		cyl1
Driver Reference Object		
Injection Timing Angle	See ...	[inj]
Injection Timing Flag		injection-st...
Injector Location (Pipes only)		0.5
Injected Fluid Temperature	K	300
Fluid Object		indolene-co...
Vaporized Fluid Fraction		0.2

Fig. 8-9b Settings of the timing of the injection

Rate | Timing-General | Initialization | Nozzle (DI Only) | Plots

Attribute	Unit	Object Value
Initialization for Air Mass Flow Rate Sensor		
Volumetric Efficiency	fracti...	0.65
Number of Injectors per EngineCrankTrain		1
Air Mass Flow Rate	g/s	0

Fig. 8-9c Initialization conditions

8.1.5 Reed valve settings

The engine has got a reed valve made from carbon fiber plates. This special type of valve is unique to MSR NG 100 Engine. Its area is measured with the modeling software DS Solidworks, and the stiffness is experimentally determined. A series of measures conducted within this study has proven that the spring stiffness is equal to 147 N/m. In addition, maximum lift and valve mass are measured. This information is entered into the software and shown in Fig. 8-10a and 8-10c.

Flow properties have a large impact on the engine performance. Because it is not possible and not in reach of this study to measure correct flow characteristics, the values in the flow array (Fig. 8-10c) are chosen based on personal estimation. This action may negatively influence the results of the simulation.

Main | Options | Flow Arrays | Dynamics Basic | Dynamics Detail | Plots

Attribute	Unit	Object Value
Valve Reference Diameter	mm	24
Discharge Coefficient Reference Area Definition		constant
Upstream Pressure Area	mm^2	600
Downstream Pressure Area	mm^2	600

Fig. 8-10a Main reed valve characteristics

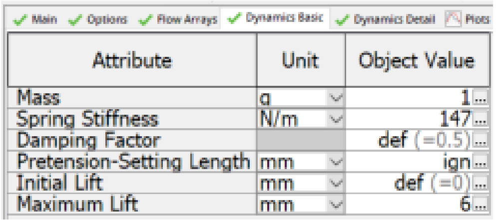


Fig. 8-10b Dynamics reed valve characteristics

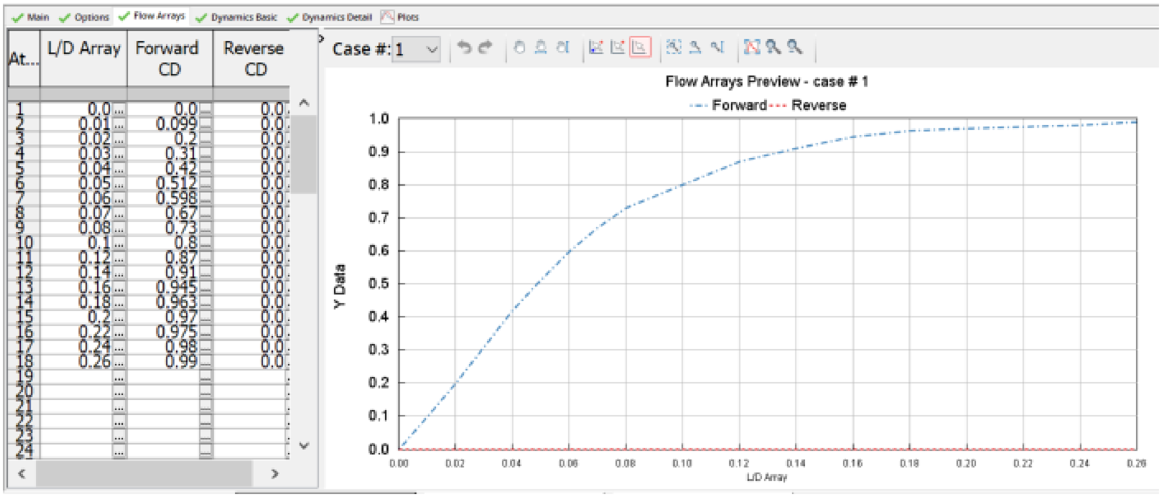


Fig. 8-10c Flow characteristics of the reed valve

8.1.6 INTAKE PORT SETTINGS

The geometry of the intake ports is another important characteristic of every two-stroke engine. In this study, the exact 3D geometry is transferred to the opened surface area in the function of the piston position. This transfer is manually calculated in this study using the information from the modeling software DS Solidworks, where the precise geometry of the cylinder is described. The result is shown in Fig. 8-11.

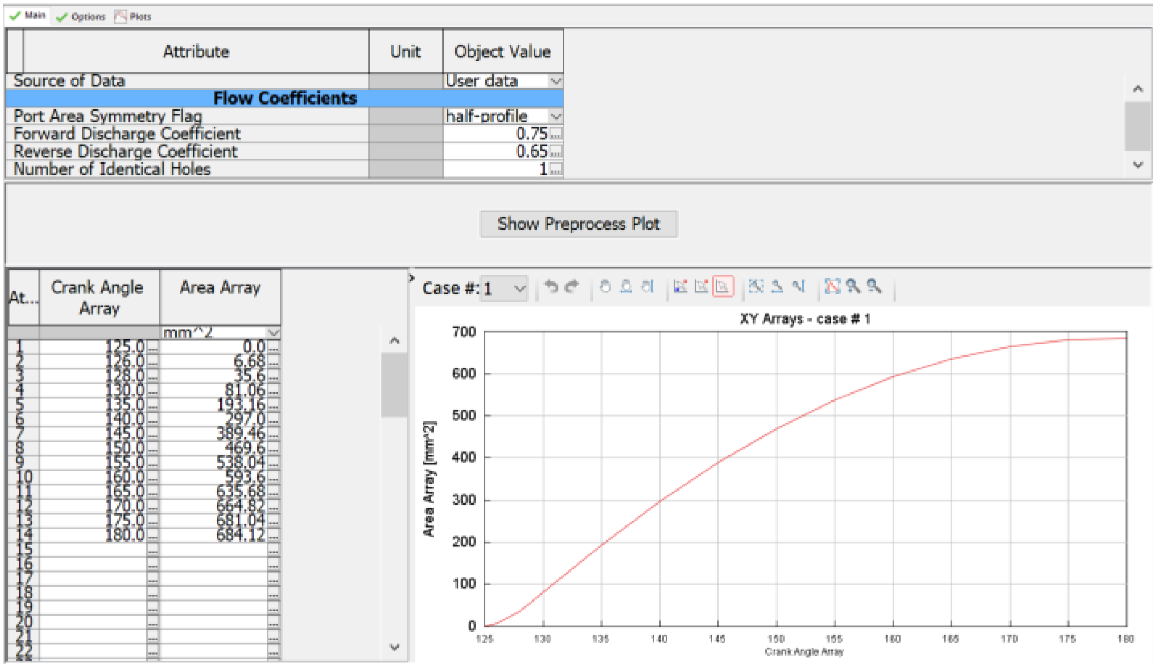


Fig. 8-11 Intake port characteristic curve

8.1.7 Exhaust port settings

Like intake ports, exhaust ports geometry is also transferred to the ratio of opened canal area in the function of piston position. The result from the manual transfer is shown in Fig. 8-12.

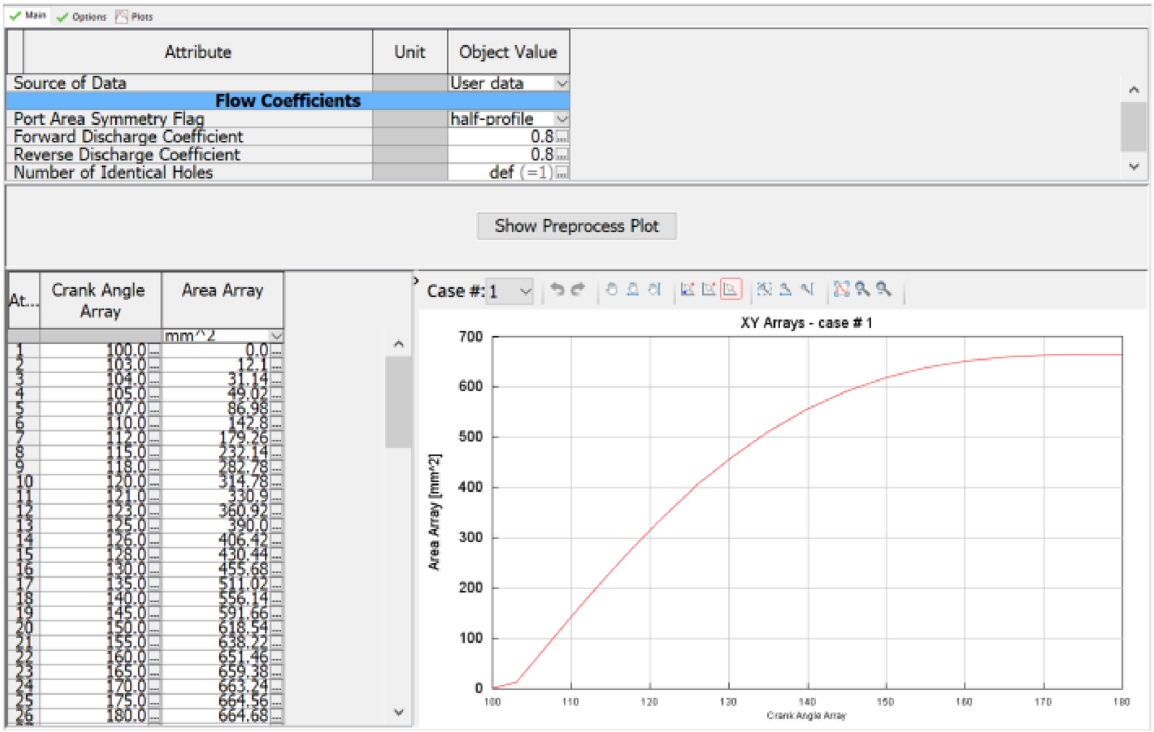


Fig. 8-12 Exhaust port characteristic curve

8.1.8 AIRBOX SETTINGS

MSR NG 100 engine is usually produced for small engine-powered surfboards. The engine is placed inside the surfboard hull, and the air intake to the engine happens through the airbox. Precise airbox dimensions are approximated by a system of pipes within the simulation model.

8.1.9 EXHAUST SETTINGS

The most important part of the two-stroke engine is undoubtedly the exhaust system. MSR NG 100 engine has got double layer reverse cone exhaust (Fig. 8-13) because of limited space inside the surfboard hull.

Fig. 8-13 Exhaust of MSR NG 100

Because this shape modeling is beyond the reach of this study, simplification of the exhaust in the shape of one expanding cone with connecting cylinder and connecting narrowing cone must be made. This exhaust, geometrically different, should be thermodynamically the same.

Because of the unknown scavenging process and approximated filling of the cylinder, the exhaust parameters cannot be fixed on real production values, and its dimension must be optimized. The dimensions – inlet diameter, cone lengths and angles, middle diameter, and outlet diameter – are optimized on slightly different values to achieve the correct behavior of the engine in the simulation.

It is necessary to mention that all simplifications and approximations in this study are used to reduce computing time and to achieve the simulation results comparable with the real engine test from chapter 6.

8.2 CASES SETUP

Two tests are conducted during the simulation. The first one is the engine performance test, and the second is the engine efficiency/economy test. Both tests are speed-based, which means that the engine rotational speed is controlled by the simulation and torque output calculated. During the performance test, an optimization is made with a torque goal. The goal is set up in ten different engine rotational speeds (5000, 5500, 6000, 6500, 7000, 7500, 8000, 8250, 8500, and 8800 RPM) based on the results from the engine test bench (see chapter 6.4.1). In other words, the optimization tries to reach the torque value measured on the engine test bench during a real performance test. During the economy test, only 4 different engine rotational speeds (5500, 6500, 7500, and 8500 RPM) are analyzed. The speeds match the ones from the efficiency test from chapter 6.4.2. Once again, the analysis is made with an optimization. The software tries to match engine torque output and similar BSFC as during the efficiency test on the engine test bench.

8.3 OPTIMIZATION OF THE SIMULATION

Because of the simplicity of this study, a few optimizations of the model must be made. Firstly, it is necessary to determine the correct exhaust dimensions. Later parameters mentioned in 8.1, such as lambda value, injection timing, anchor angle, combustion duration, and Wiebe coefficient, are optimized with defined exhaust dimensions from previous optimization. The goal of all optimizations is to reach demanded torque output in the performance test or demanded torque and BSFC in the fuel economy test.

All optimizations use Accelerated GA algorithm and default settings, as the study recommends.

8.3.1 EXHAUST DIMENSIONS OPTIMIZATION

Standard exhaust from the engine set (double layer reverse cone type) is replaced by thermodynamically same exhaust with a different shape in Fig. 8-15. This exhaust is defined by diameters and lengths. To properly optimize the exhaust dimensions, diameters values are fixed, and only lengths are optimized. The results of the optimization, where all lengths are recalculated, are shown in Fig. 8-16. Note that during this optimization (Fig. 8-14), several parameters are calculated independently while exhaust dimensions are calculated in the `sweep` mode – globally. The targeted torque values are taken from the test in chapter 6.5.1 for petrol fuel.

New calculated dimensions of the exhaust are noted and, from now on, used during all simulations and optimizations as defined parameters.

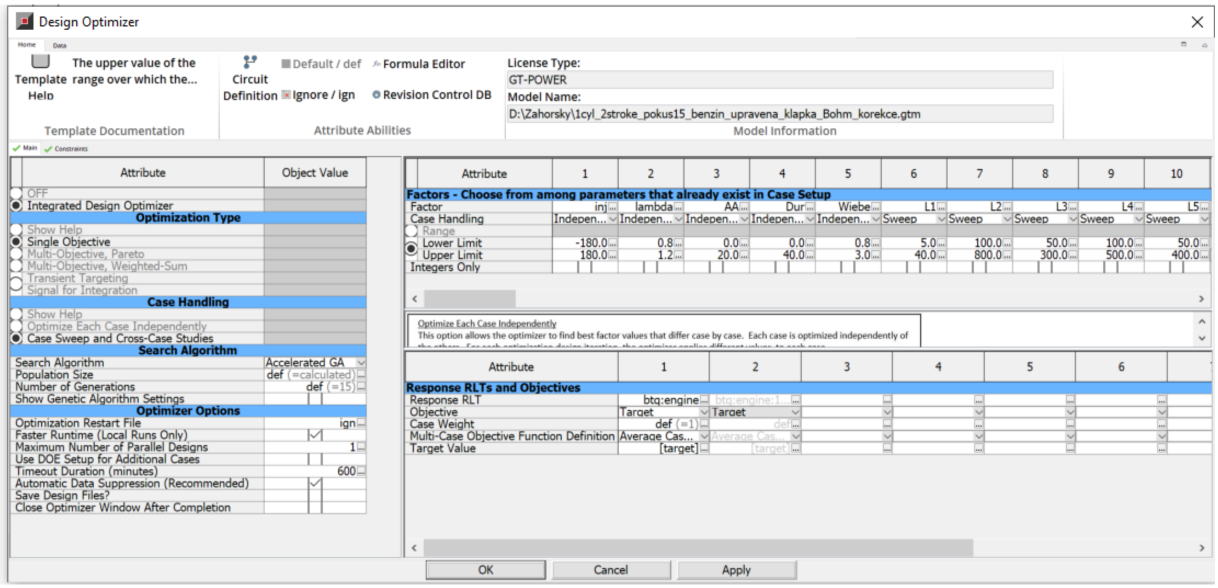


Fig. 8-14 Exhaust Optimization setup

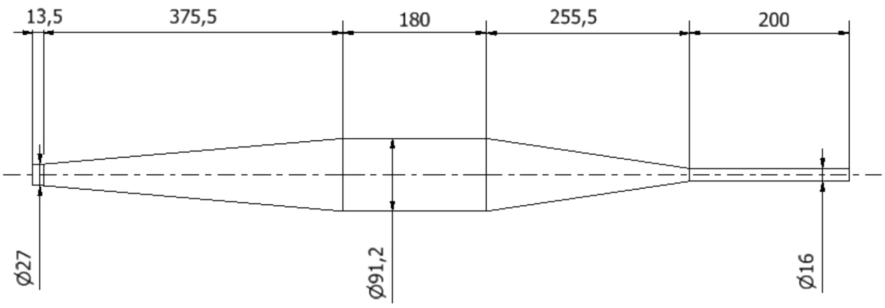


Fig. 8-15 Standard exhaust dimensions [mm]

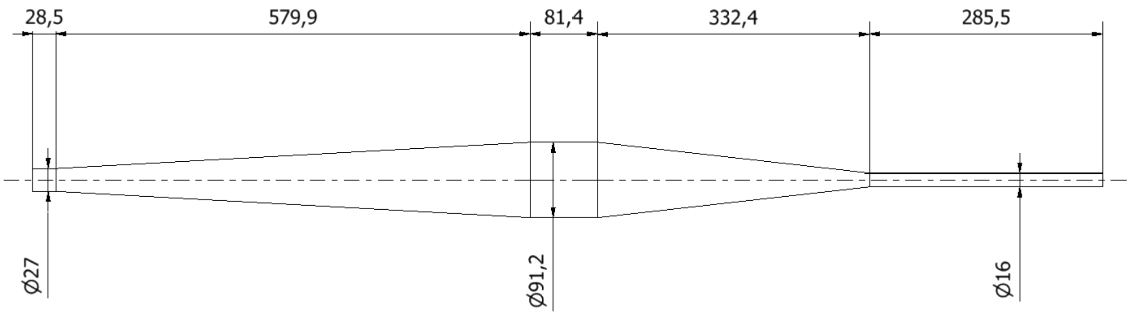


Fig. 8-16 Optimized exhaust dimensions [mm]

8.3.2 INDEPENDENT PERFORMANCE TEST OPTIMIZATION

The first test – the engine performance test – must be optimized. The reason is that during the simulation, correct values of lambda, injection duration, and combustion model depend on the engine rotational speed and are not known. A specific range of estimated values of the unknown factors is defined for the optimization along with the objective[4]. The range and the objective depend on different fuels.

This optimization is a single objective, with all cases (different rotational speeds) considered independent, as Fig. 8-17 shows.

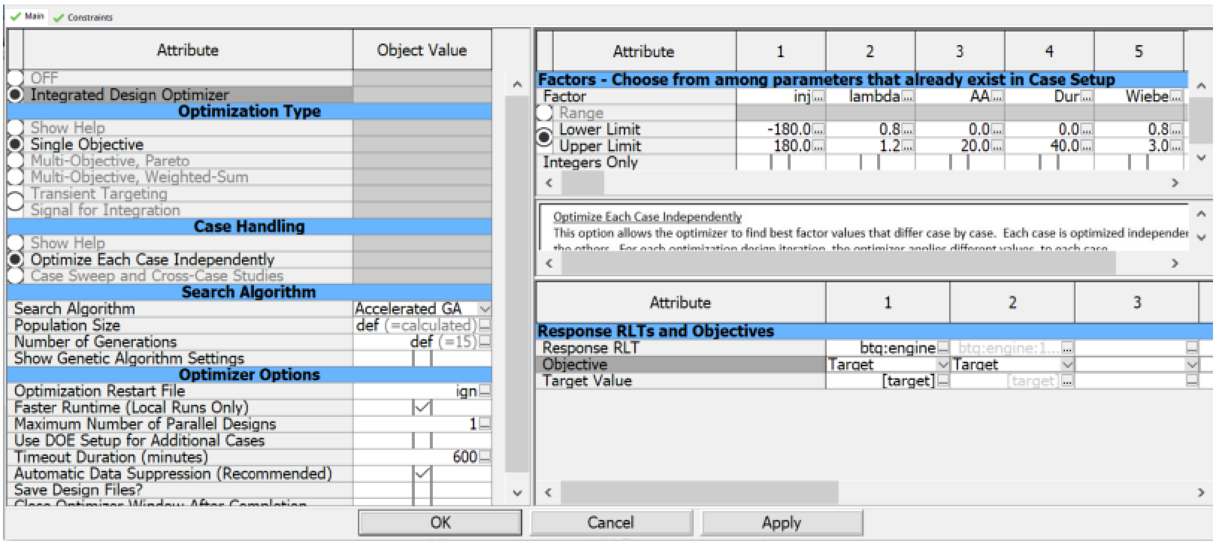


Fig. 8-17 Performance test optimization setup

8.3.3 INDEPENDENT EFFICIENCY TEST OPTIMIZATION

Another test of alternative fuels is the same as in chapter 6.4.2. For specific rotational speeds, BSFC and torque present the objectives[5]. The unknown factors remain within the same reach as in the performance test from chapter 8.3.2. However, the range can again change with different fuels.

This optimization is Multi-objective, Weighted-sum type. Torque target values have a response weight equal to 150% of the response weight of BSFC target values, as shown in Fig. 8-18.

The software measures emissions of gases in [ppm] – parts per million, which are manually recalculated to [% vol] – volumetric percentages, using Eq. 8-1

$$[\%\ vol] = \frac{[ppm]}{10000} \qquad \text{Eq. 8-1}$$

[4] torque values are known from previous performance test on the engine test bench
[5] both BSFC and related torque values are known from the efficiency test on the engine test bench

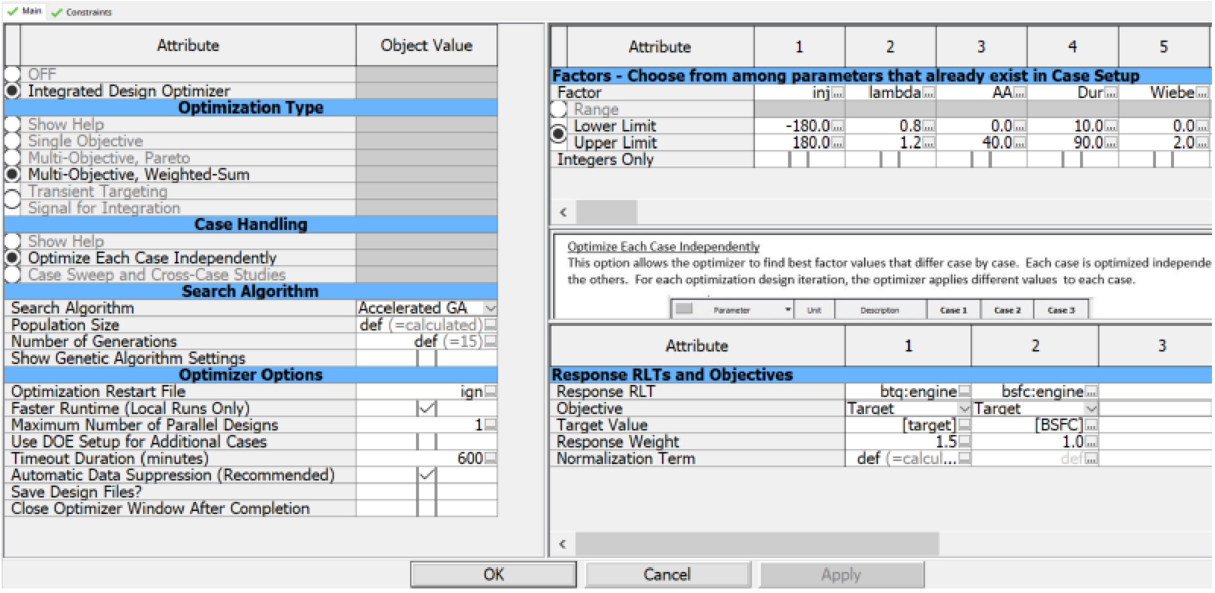


Fig. 8-18 Efficiency test optimization setup

8.4 CONVENTIONAL FUEL – PETROL

At first, standard conventional petrol fuel is used in the engine heat cycle model. This type of fuel is predefined in the GT Suite library as indolene-combust fuel.

8.4.1 PERFORMANCE SIMULATION – PETROL

Optimization parameters are set up as in chapter 8.3.2; targeted torque value is set up by the results achieved in chapter 6.5.1. Optimized values of output torque and power are plotted in a graph in the function of engine rotational speed (Fig. 8-19), with maximum achieved values marked. In addition, polynomials of 3rd degree are used to approximate engine characteristics.

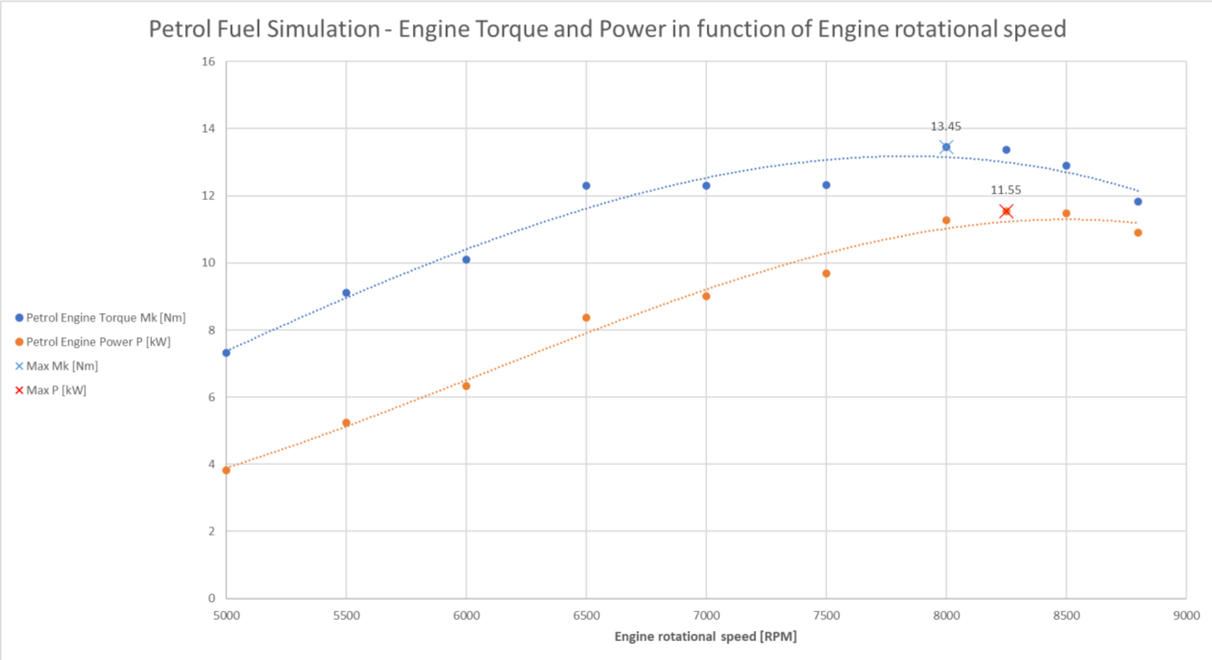


Fig. 8-19 Engine torque and power in function of engine rotational speed for petrol fuel simulation

As it is visible in Fig. 8-19, torque progress is continuous through all points of optimization. Only deviation happens at the rotational speed of 7500 RPM, where the torque and power, respectively decrease. This effect is probably due to optimized exhaust geometry. In two-stroke engines, exhaust lengths play a crucial role when setting up the correct speed range of the engine. It can occur that during certain speeds, the geometry does not work very well, and therefore decrease in torque can be observed.

8.4.2 Efficiency simulation - petrol

Optimization parameters are set up as mentioned in chapter 8.3.3. Target values of torque and BSFC are used from chapter 6.5.2. The results from optimization are shown in Tab. 8-1.

Point	Rotational speed [RPM]	Torque Mk [Nm]	Power P [kW]	CO [% vol]	CO2 [% vol]	BSFC [g/kWh]
1	5500	9.09	5.24	0.0007	10.9709	305.37
2	6500	11.25	7.65	0.0041	10.5674	352.52
3	7500	12.34	9.69	1.8482	11.9394	302.32
4	8500	12.89	11.47	4.4450	9.2079	374.61

Tab. 8-1 Achieved values during efficiency optimization of petrol fuel

The torque values and power values are pretty similar to the ones achieved in the performance test from chapter 8.4.1. As it was mentioned in chapter 6.5.2, the steady state in the engine speed has a negative influence on torque during the real efficiency test. This problem, caused by real measure conditions, does not occur during precise computer simulations.

8.5 ALTERNATIVE FUEL – MIXTURE E40

After calibrating the model with conventional fuel, alternative fuels are simulated. The ethanol fuel is defined in the GT Suite library, and therefore user-defined fuel (mixture E40) can be created very easily. No parameters during both optimizations are changed compared to the information in chapters 8.3.2 and 8.3.3.

8.5.1 PERFORMANCE SIMULATION – MIXTURE E40

Target values of torque from chapter 6.6.1 are used. Optimization results are once more shown in the graph as a function of rotational speed (Fig. 8-20). Maximum values are marked, and polynomials of 3rd degree are imported.

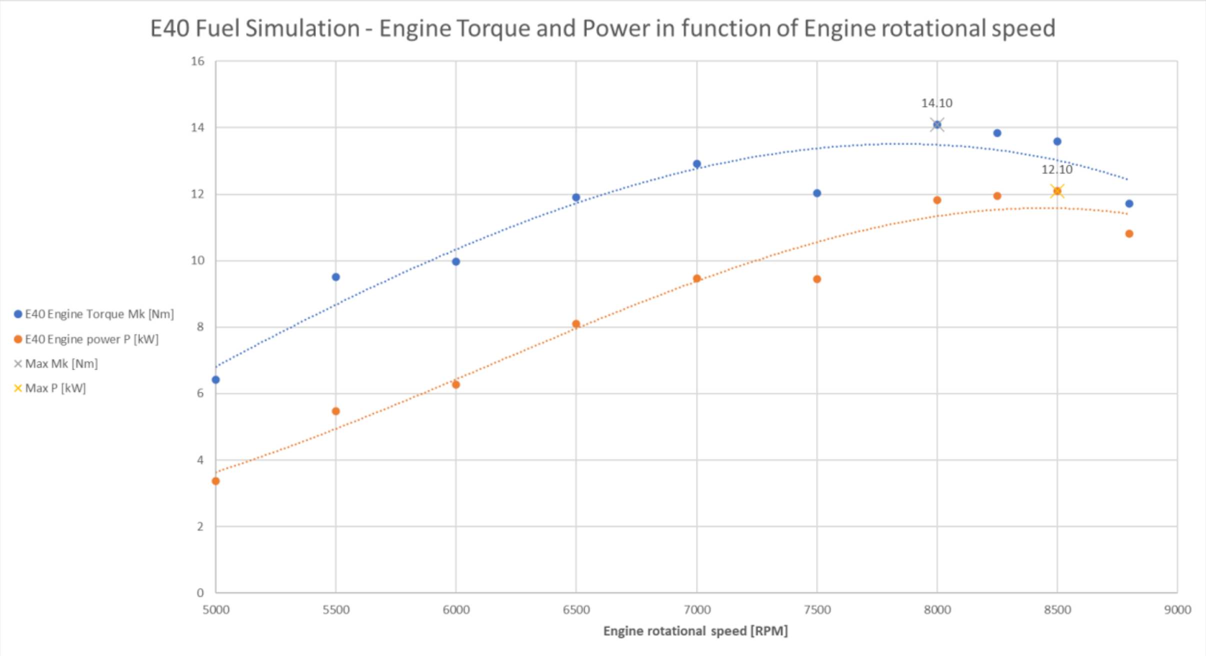


Fig. 8-20 Engine torque and power in function of engine rotational speed for E40 fuel simulation

At first sight, the decrease in torque at a speed of 7500 RPM has enlarged (against the decrease in Fig. 8-19), which has negatively influenced the polynomial's progress. Nevertheless, the characteristics still have continuous development.

8.5.2 EFFICIENCY SIMULATION – MIXTURE E40

Goal values are taken from chapter 6.6.2. The result from optimization is shown in Tab. 8-2.

Point	Rotational speed [RPM]	Torque Mk [Nm]	Power P [kW]	CO [% vol]	CO2 [% vol]	BSFC [g/kWh]
1	5500	9.50	5.47	4.2658	9.1649	455.06
2	6500	11.91	8.11	0.0004	9.8507	360.39
3	7500	11.85	9.31	2.6165	11.0892	368.80
4	8500	13.22	11.77	3.1908	9.5548	401.93

Tab. 8-2 Achieved values during efficiency optimization of E40 fuel

At all points, an increase in torque and power is visible. Emissions of CO_2 gas remain stable, while CO emissions result during the second point of simulation is out of reach. This error has an unknown cause.

8.6 Alternative fuel – ethanol

After testing the E40 fuel, full alcohol fuel with ethanol is tested. The ethanol fuel necessary for the simulation is available in the GT Suite library.

8.6.1 Performance simulation – ethanol

Without changing the parameters defined in chapter 8.3.2, target values from chapter 6.7.1 are inserted into the model. Results from the optimization are shown in Fig. 8-21 as a function of engine rotational speed, with maximum values marked. Once more, polynomials of 3rd degree are used for approximation of the development.

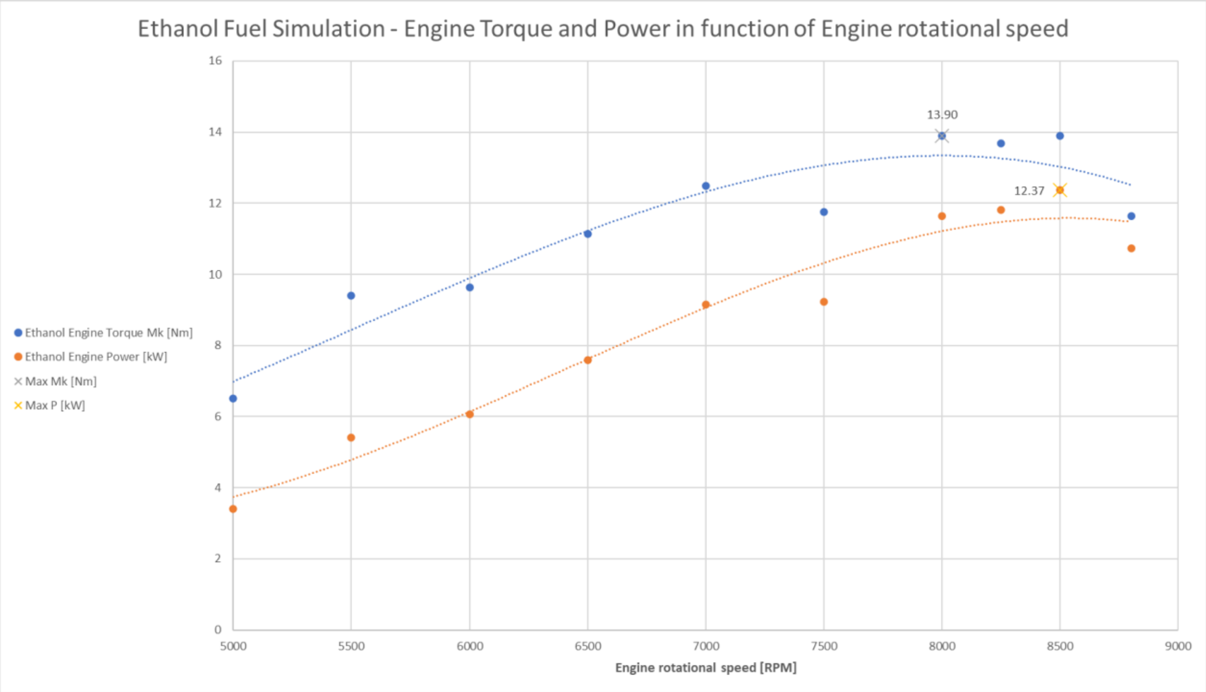


Fig. 8-21 Engine torque and power in function of engine rotational speed for ethanol fuel simulation

8.6.2 EFFICIENCY SIMULATION – ETHANOL

Goal values are taken from chapter 6.7.2. The result from optimization is shown in Tab. 8-3.

oint	Rotational speed [RPM]	Torque Mk [Nm]	Power P [kW]	CO [% vol]	CO2 [% vol]	BSFC [g/kWh]
1	5500	9.42	5.43	1.3973	10.1054	554.68
2	6500	11.11	7.56	0.0013	9.5644	542.51
3	7500	11.65	9.15	1.3925	11.1126	477.55
4	8500	13.66	12.16	4.2670	8.4038	575.90

Tab. 8-3 Achieved values during efficiency optimization of ethanol fuel

The same error with CO emissions in point 2 can be observed. A small increase in torque and power is possible due to a higher RON number of ethanol. A dramatic increase in BSFC values for all points is caused by the low AFR of alcohol fuel, as mentioned in chapter 5.2.4.

8.7 ALTERNATIVE FUEL – METHANOL

Finally, methanol fuel is tested in the simulation software. Methanol is also available as fuel in the software library. Simulation parameters from chapter 8.3.2 are the same as with previous cases, but the range of lambda values must be adjusted. As it was observed during the test on the engine test bench (chapter 6.8.2), the value of lambda for methanol fuel was below 0,8. Therefore, the range is adjusted to values of lambda from 0.6 to 1.1.

8.7.1 PERFORMANCE SIMULATION – METHANOL

Target values from chapter 6.8.1 are used. Even though the test on the engine test bench is not truly accurate, the simulation results comply with the real test. The progress of torque and power for methanol fuel is shown in Fig. 8-22, with maximum values marked and polynomials of 3rd degree like in previous cases.

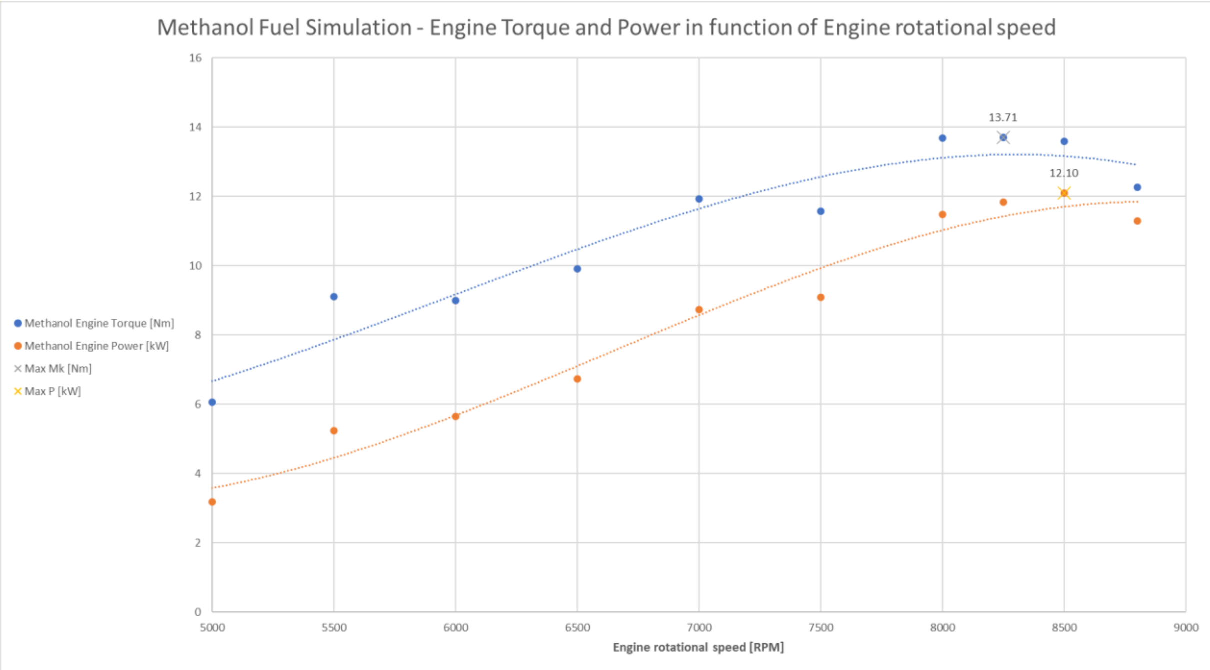


Fig. 8-22 Engine torque and power in function of engine rotational speed for methanol fuel simulation

With the use of methanol fuel, maximum torque or power did not increase, which was not supposed. In addition, the whole progress is worse than for ethanol fuel in Fig. 8-21.

8.7.2 EFFICIENCY SIMULATION – METHANOL

Goal values are taken from chapter 6.8.2, and results are shown in Tab. 8-4.

oint	Rotational speed [RPM]	Torque Mk [Nm]	Power P [kW]	CO [% vol]	CO2 [% vol]	BSFC [g/kWh]
1	5500	9.11	5.24	0.9523	10.1469	684.29
2	6500	10.44	7.10	0.0014	8.8892	753.92
3	7500	11.31	8.88	4.6936	8.5875	761.09
4	8500	13.59	12.10	6.9164	6.9647	932.76

Tab. 8-4 Achieved values during efficiency optimization of methanol fuel

The biggest change in the values is undoubtedly the BSFC increase. Methanol has got very low AFR, and with a very low value of lambda, the engine must consume a high amount of fuel. CO_2 emissions decreased by a small measure, while CO emissions stayed almost the same (or increased) as with the use of ethanol fuel in Tab. 8-3.

9 COMPARISON OF RESULTS OF DIFFERENT FUELS FROM SIMULATION

Every important parameter (torque, power, etc.) from each simulation is fused together in one large comparative analysis. This allows us to see the differences between different fuels after the simulation. The comparison uses the same methods as in chapter 7 with the engine test bench analysis.

9.1 PERFORMANCE ANALYSIS

At first, the performance of the engine is considered. During all simulations, torque and power are observed, and it is the goal of the setup of the simulation model to reach similar values to the ones from the engine test bench analysis.

In the same way, as in chapter 7.1, only maximal torque and maximal power during certain rotational speeds are considered. Tab. 9-1 shows these values, and to image better the differences between each fuel, a bar chart in Fig. 9-1 is generated.

Because each fuel is simulated during a range of rotational speeds, the complete characteristics of engine torque and power can be compared in Fig. 9-2. All the data used during these comparisons is available in chapters 8.4.1, 8.5.1, 8.6.1, and 8.7.1.

Fuel	Rotational speed [RPM]	Max Mk [Nm]	Rotational speed [RPM]	Max P [kW]
Petrol	8000	13.45	8500	11.55
E40 mixture	8000	14.1	8500	12.1
Ethanol	8000	13.9	8500	12.37
Methanol	8250	13.7	8500	12.1

Tab. 9-1 Comparison of different fuels maximum torque (Mk) and power (P) from simulations

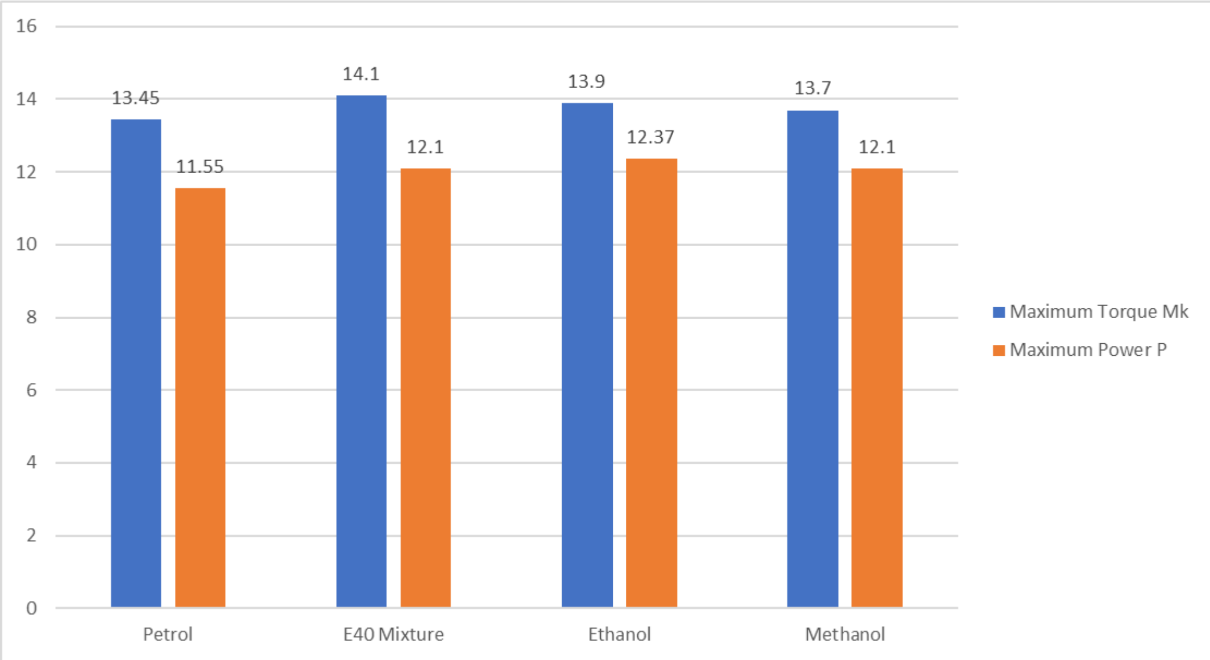


Fig. 9-1 Comparison of different fuel's maximum torque (Mk) and power (P) from simulations in bar chart

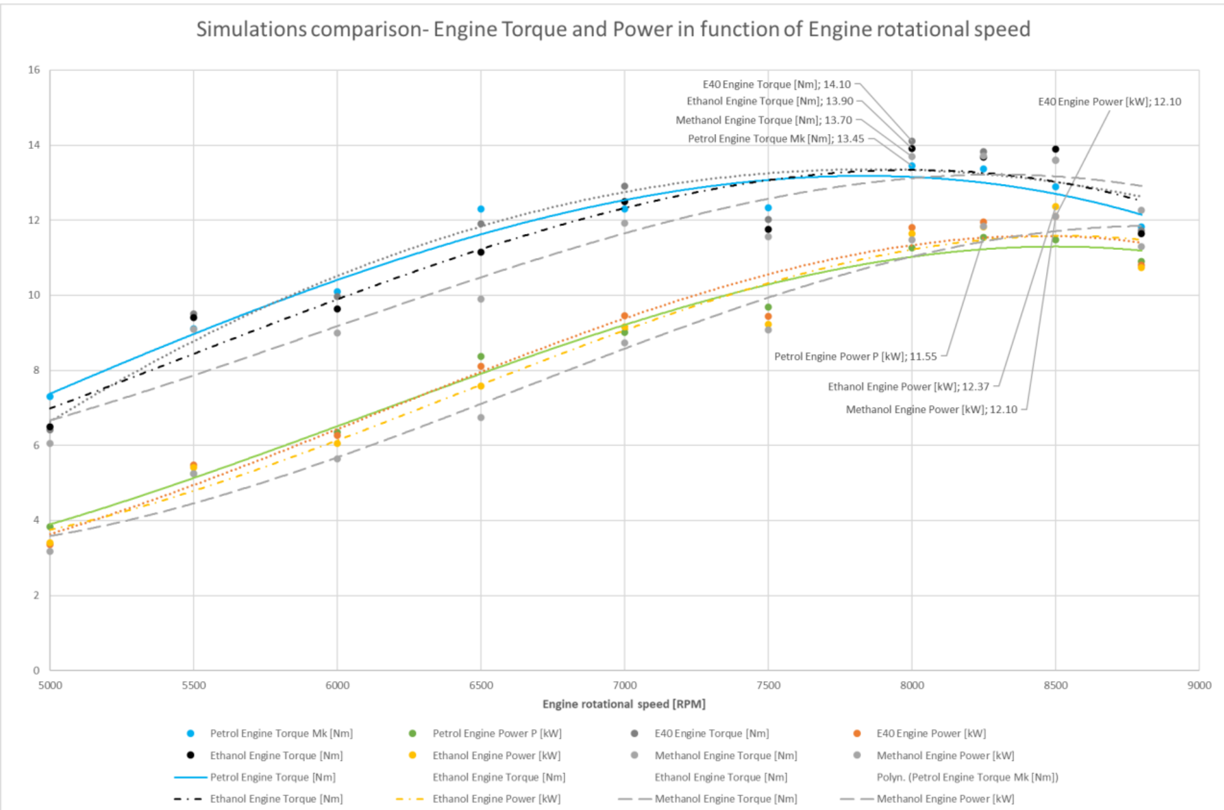


Fig. 9-2 Comparison of different fuel's maximum torque (Mk) and power (P) from simulations in different engine speeds, with maximal values marked

During this type of analysis of the fuels, there were some surprising results. Even though methanol has got higher RON number than petrol fuel, the torque progress and power progress are not better at lower speeds. In the middle speeds (6000 RPM to 7500 RPM), the E40 mixture seems as the most performing fuel, while in the highest speeds, ethanol and methanol fuels have the biggest torque and power output. Surprisingly, petrol fuel (with a significantly lower RON number) performs the best at low speeds.

To conclude, change in the fuels does not significantly affect the engine performance. It must be noted that methanol fuel shows some anomaly in the torque output, although its RON number is very high – which should improve the performance. Needless to say that many parameters (such as ignition timing and combustion model – see chapters 8.2 and 8.3) are variable during the optimization, and their values can have a very wide range, incomparable with the real experiment from chapter 6.

9.2 Efficiency analysis

This analysis is analogical to the study in chapter 7.2. The software basic simulation model used for this study can only compare simple emission values (CO_2, CO, HC gases) and fuel economy based on BSFC. In addition, during this type of simulation, torque and power are naturally calculated. Tab. 9-2 shows all calculated data.

rotational speed [RPM]	Fuel	Mk [Nm]	P [kW]	BSFC [g/(kW*h)]	BSFC [g/(kWh*100)]	CO [% vol]	CO2 [% vol]
5500	Petrol	9.09	5.24	305.37	3.05	0.0007	10.9709
	Blend	9.50	5.47	455.06	4.55	4.2658	9.1649
	Ethanol	9.42	5.43	554.68	5.55	1.3973	10.1054
	Methanol	9.11	5.24	684.29	6.84	0.9523	10.1469
6500	Petrol	11.25	7.65	352.52	3.53	0.0041	10.5674
	Blend	11.91	8.11	360.39	3.60	0.0004	9.8507
	Ethanol	11.11	7.56	542.51	5.43	0.0013	9.5644
	Methanol	10.44	7.10	753.92	7.54	0.0014	8.8892
7500	Petrol	12.34	9.69	302.32	3.02	1.8482	11.9394
	Blend	11.85	9.31	368.80	3.69	2.6165	11.0892
	Ethanol	11.65	9.15	477.55	4.78	1.3925	11.1126
	Methanol	11.31	8.88	761.09	7.61	4.6936	8.5875
8500	Petrol	12.89	11.47	374.61	3.75	4.4450	9.2079
	Blend	13.22	11.77	401.93	4.02	3.1908	9.5548
	Ethanol	13.66	12.16	575.90	5.76	4.2670	8.4038
	Methanol	13.59	12.10	932.76	9.33	6.9164	6.9647

Tab. 9-2 Comparison of different fuels torque (Mk), power (P), BSFC, CO, and CO_2 emissions in specific rotational speeds during the simulation

To better see the differences in the results, bar charts are generated for each rotational speed. Fig. 9-3a, 9-3b, 9-3c, and 9-3d show the values from Tab. 9-2.

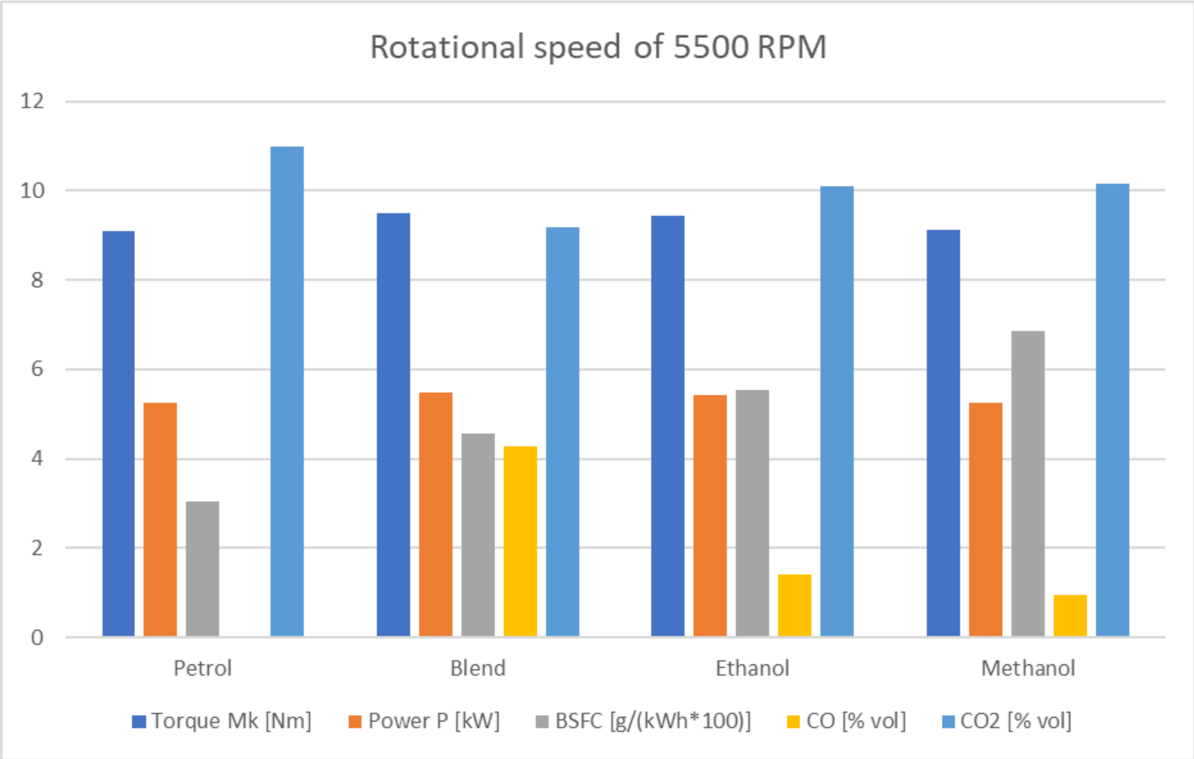


Fig. 9-3a Comparison of different fuels torque (Mk), power (P), BSFC, CO, and CO_2 emissions in a bar chart for rotational speed 5500 RPM using simulation

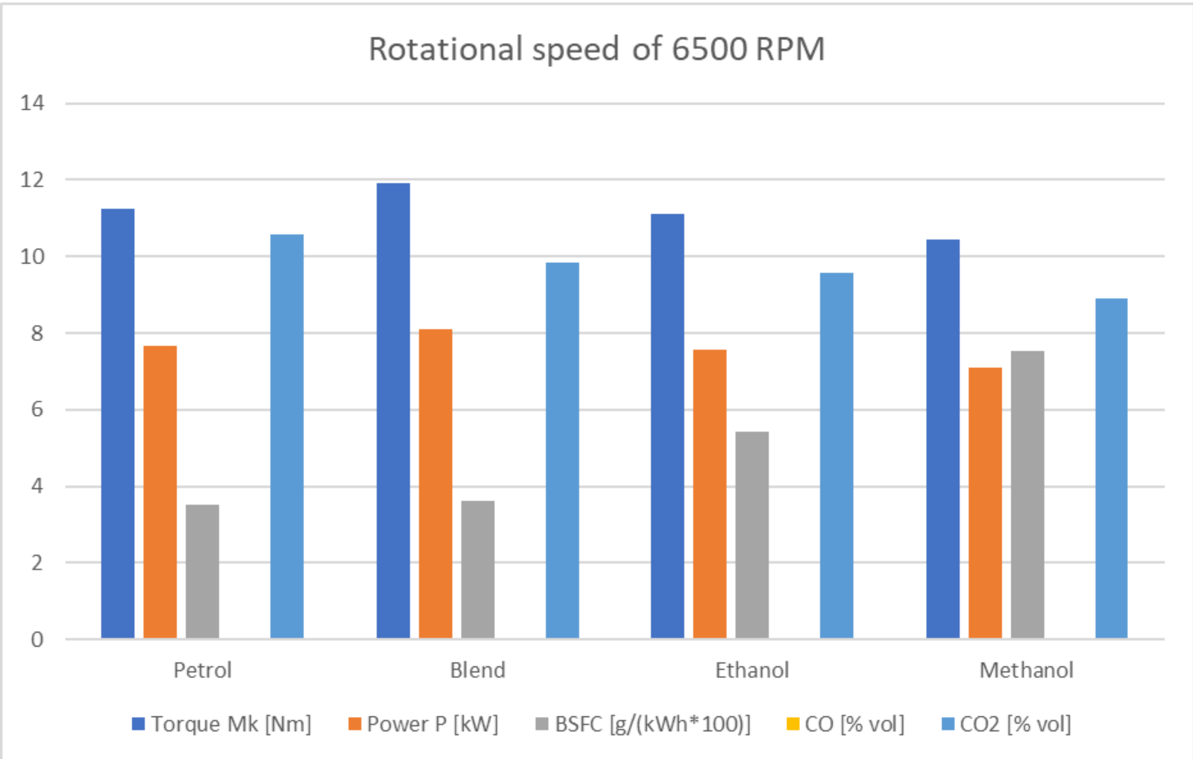


Fig. 9-3b Comparison of different fuels torque (Mk), power (P), BSFC, CO, and CO_2 emissions in a bar chart for rotational speed 6500 RPM using simulation

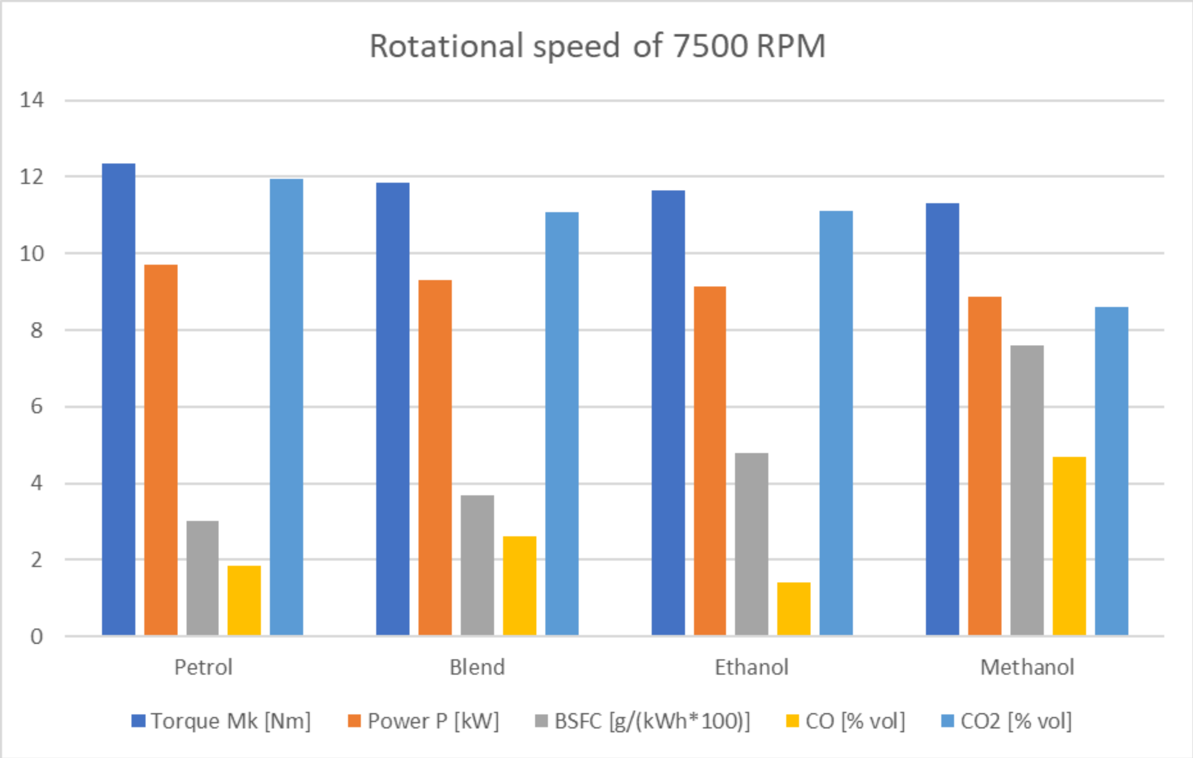


Fig. 9-3c Comparison of different fuels torque (Mk), power (P), BSFC, CO, and CO_2 emissions in a bar chart for rotational speed 7500 RPM using simulation

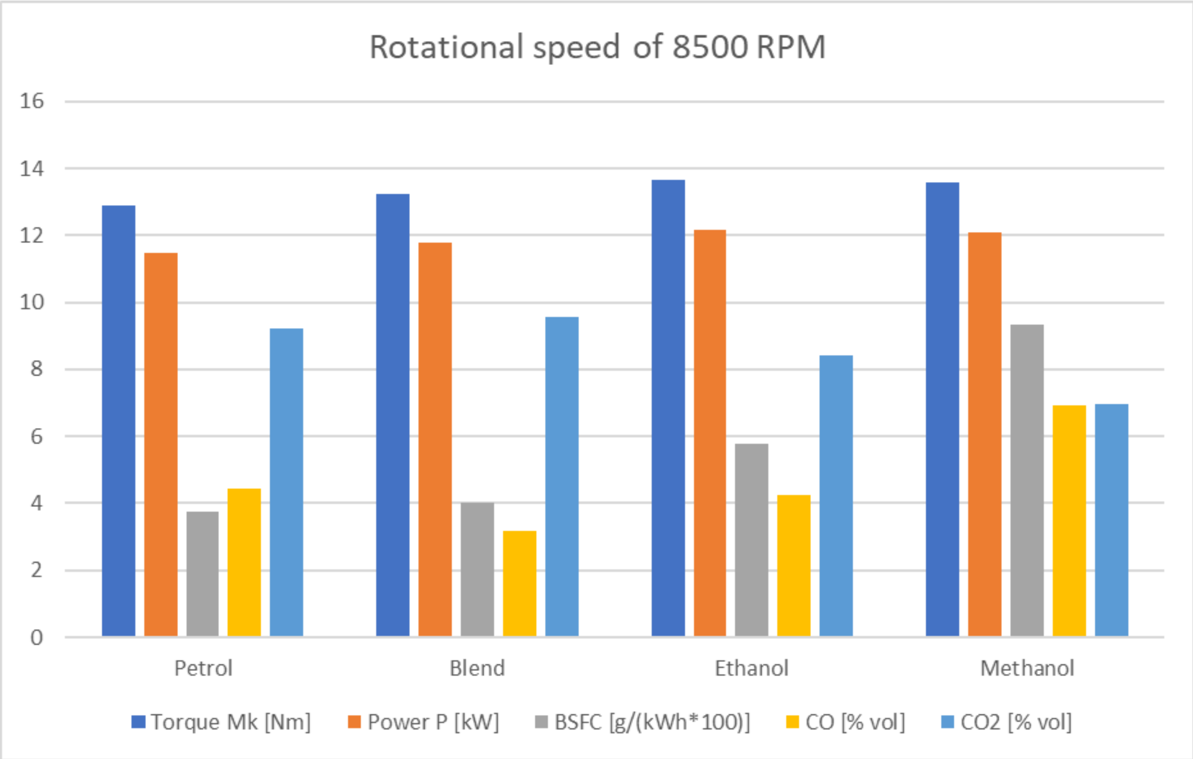


Fig. 9-3b Comparison of different fuels torque (Mk), power (P), BSFC, CO, and CO_2 emissions in a bar chart for rotational speed 8500 RPM using simulation

During this analysis, no radical increase in torque or power with the use of different fuels is visible. In the highest speed in Fig. 9-3d, power and torque increase slightly with the use of alternative fuels, at the speed of 7500 RPM, both values decrease. Generally, mixture E40 may be considered the best-performing fuel because it seems to perform the best at all speeds (Fig. 9-3a, Fig. 9-3b, Fig. 9-3d) except 7500 RPM (Fig. 9-3c).

Change in the BSFC is the same during all speeds. With the use of fuels with lower AFR (see chapter 5.2.3), engine consumption rises. Independently on the engine speed, methanol consumption is certainly the largest, while standard petrol fuel seems as the most economical. At the speed of 8500 RPM (Fig. 9-3d), blended fuel E40 has a very similar BSFC as standard petrol fuel.

Calculation of the emissions of CO gas does not seem accurate in all cases. At a speed of 6500 RPM (Fig. 9-3b), CO emissions are close to zero, which could be considered an anomaly behavior of the simulation. The results seem inaccurate also at speeds of 7500 RPM and 8500 RPM (Fig. 9-3c and Fig. 9-3d, respectively) because methanol fuel should have the lowest emissions of CO due to its low carbon content.

On the other hand, CO_2 emissions results look very promising. In all cases, there is a visible decrease in emissions with the use of alternative alcohol fuels. The best fuel, in this case, is the methanol fuel, the second-best pure ethanol fuel. However, the E40 mixture does not perform significantly worse than ethanol fuel (at a speed of 5500 RPM, it performs even better) and could also be considered in second place. The worse emission of CO_2 has the standard petrol fuel based on the information from the simulations.

9.3 GENERAL CLOSURE OF THE SIMULATION ANALYSIS

In the end, although the consumption (BSFC) may be higher for alternative fuels, its use reduces CO_2 emissions and does not influence CO emissions. Torque and power also remain stable for all kinds of fuels. The simulation of the heat cycle of the MSR NG 100 engine has confirmed that the use of alcohol-based alternative fuels is possible for small combustion engines. In addition, better efficiency can be achieved with zero impact on the performance of the engine.

10 FUTURE FUEL SELECTION BASED ON BOTH ANALYSIS

Two analyses – measured on the engine test bench (chapter 6) and calculation of the heat cycle of the engine (chapter 8) – were made during this study. Both achieved reasonable results, which mostly comply with the theoretical information given in chapter 5.

10.1 SELECTION BASED SOLELY ON THE PERFORMANCE OF THE FUEL

The output torque and power of the engine are selected as the first criteria of the study. In this study, two methods of analyzing new fuels are realized. The final comparison of results from the experimental test on the engine test bench and from simulation software is noted in Tab. 10-1.

	Torque				Power			
	Experiment		Simulation		Experiment		Simulation	
	rotational speed [RPM]	*Max Mk [Nm]*	*rotational speed [RPM]*	*Max Mk [Nm]*	*rotational speed [RPM]*	*Max P [kW]*	*rotational speed [RPM]*	*Max P [kW]*
Petrol	7775	13.54	8000	13.45	8525	11.69	8500	11.55
E40 Mixture	8125	13.84	8000	14.1	8550	12.09	8500	12.1
Ethanol	8000	14.04	8000	13.9	8625	12.43	8500	12.37
Methanol	8200	13.71	8250	13.7	8500	12.17	8500	12.1

Tab. 10-1 Comparison of two methods for the performance test

To better visualize the differences between both analyses, a bar chart on Fig. 10-1 is generated based on the data from Tab. 10-1.

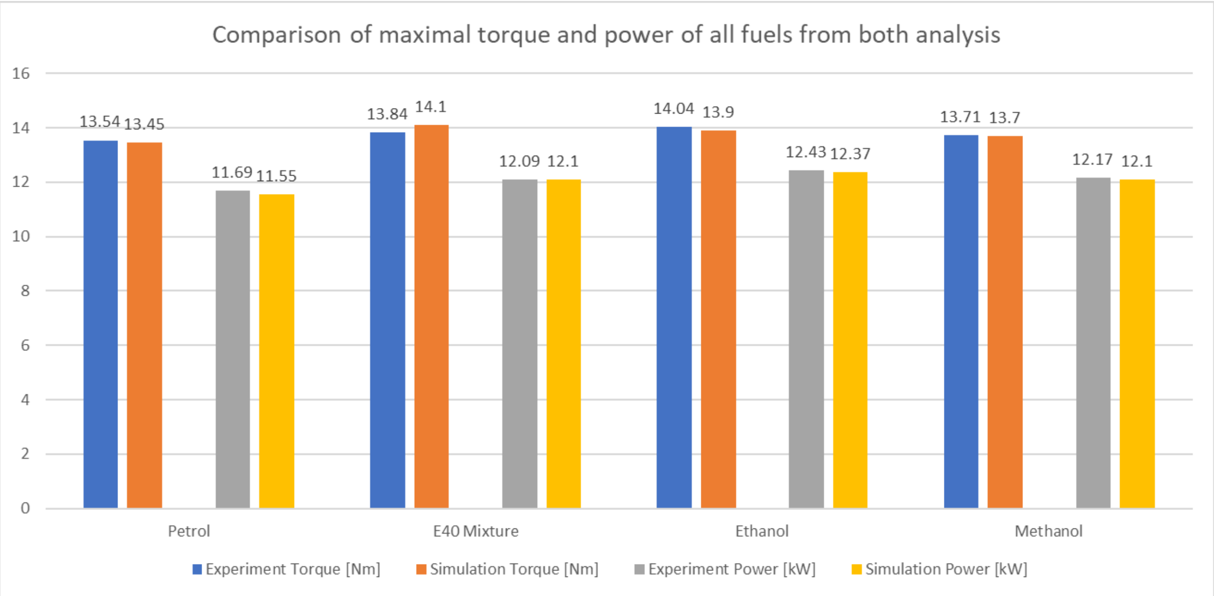


Fig. 10-1 Bar charts with comparison of two methods for the performance test

At first sight, both methods have achieved very similar values of maximal torque and power of the engine, running on different fuels. Therefore, the results of maximal values from performance tests from chapters 6 and 7 can be proclaimed valid.

To confirm this statement, the complete progress of torque and power of each fuel from experimental and simulation methods are shown in Fig. 10-2a, 10-2b, 10-2c, and 10-2c for petrol, E40, ethanol, and methanol fuel, respectively.

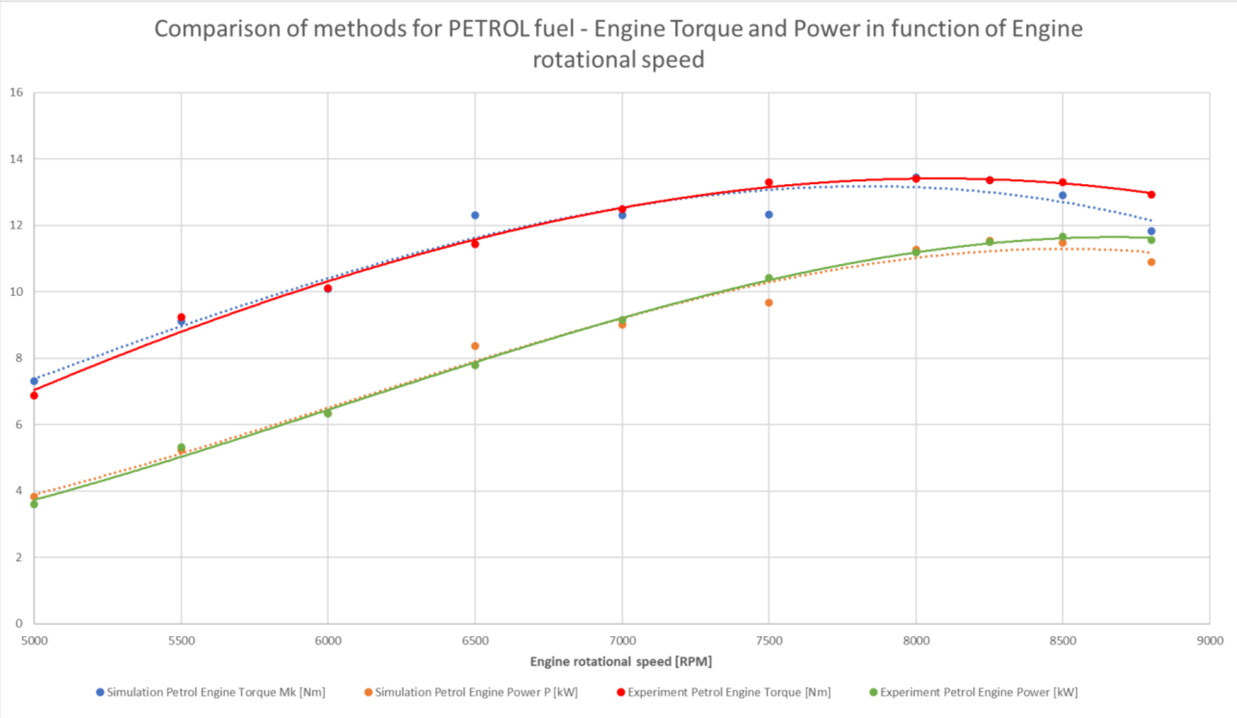


Fig. 10-2a Comparison of the progress of torque (Mk) and power (P) of petrol fuel using experimental and simulation method

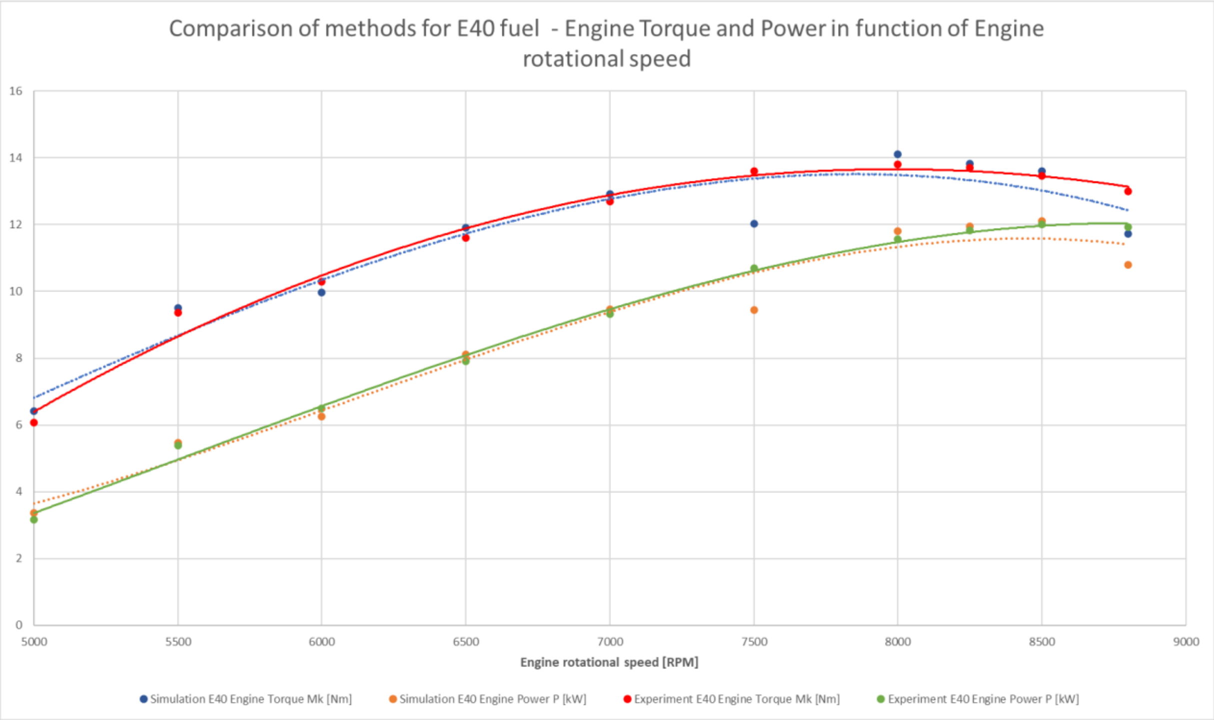


Fig. 10-2b Comparison of the progress of torque (Mk) and power (P) of E40 fuel using experimental and simulation method

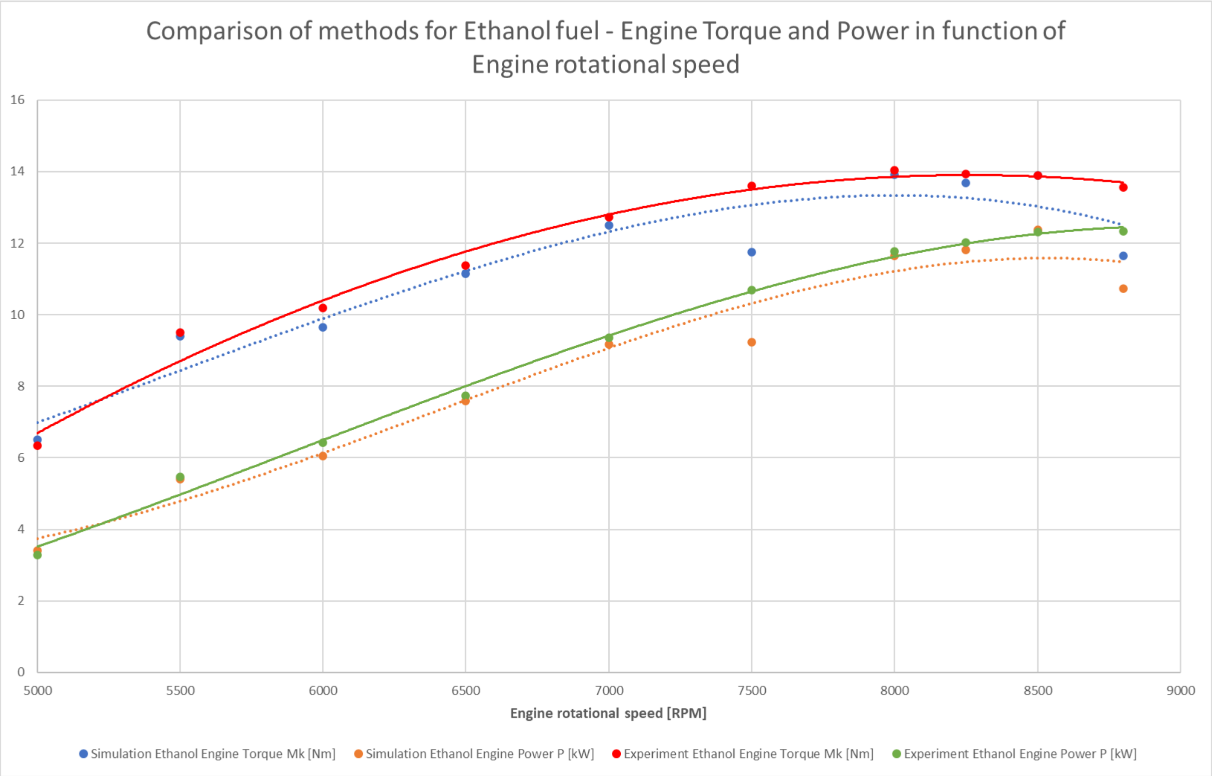


Fig. 10-2c Comparison of the progress of torque (Mk) and power (P) of ethanol fuel using experimental and simulation method

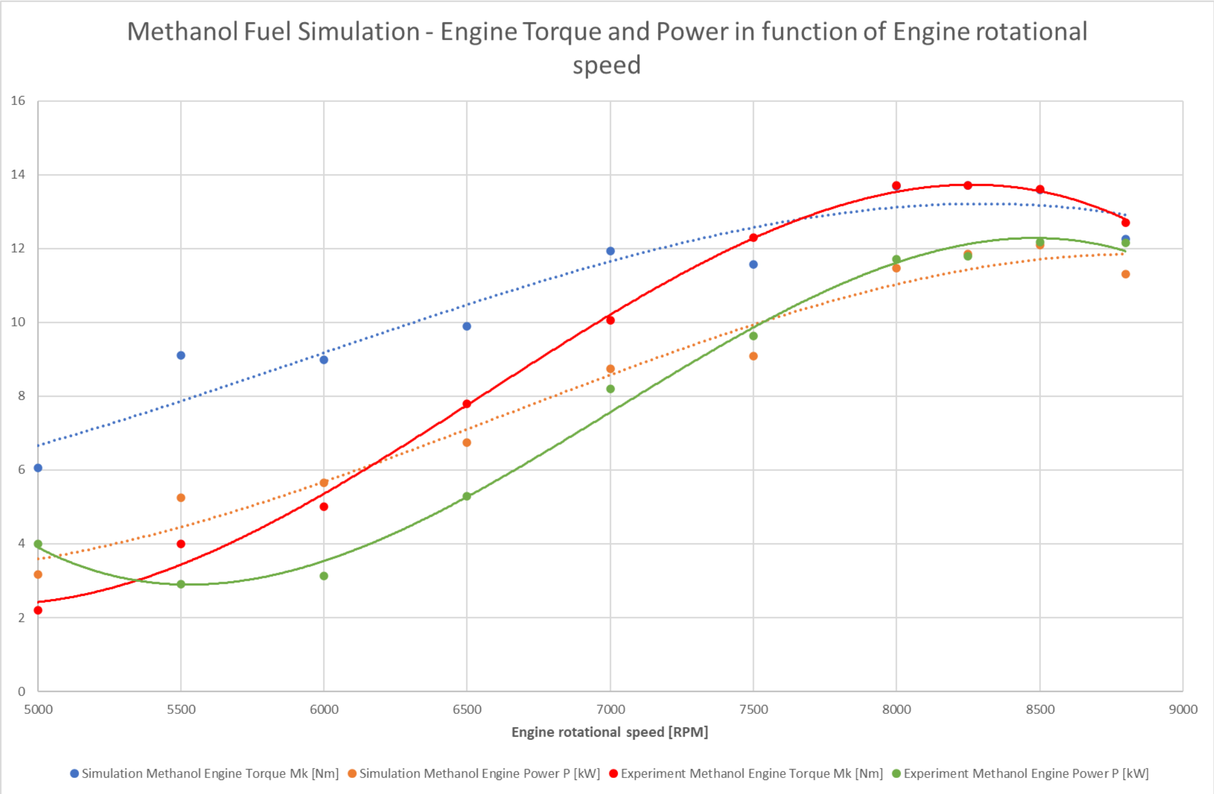


Fig. 10-2d Comparison of the progress of torque (Mk) and power (P) of methanol fuel using experimental and simulation method

Progress of the torque and power of petrol, E40, and ethanol fuel from Fig. 10-2a, 10-2b, and 10-2c are very close regardless of the method of the analysis. Progress from the experimental measure of methanol fuel in Fig. 10-2d does not resemble the one from the simulation. The reason is the anomalous behavior of the methanol fuel on the engine test bench, as mentioned in chapter 6.8.1. Thus, methanol fuel can only be analyzed with the data from the simulation.

Maximal torque and power are reached with the use of 100% alternative fuel – ethanol. Thus, it is recommended to use clear ethanol as an alternative fuel for small combustion engines while focusing only on the improvement in torque and power. Needless to say, E40 fuel allows the engine to reach over 98% of the torque of the ethanol fuel, which should also be considered in the choice of the new alternative fuel. The increase of the maximal torque has been over 3,5% with the use of ethanol fuel instead of petrol.

10.2 Selection based on the performance and efficiency of the fuel

Both methods from chapters 6 and 8 compare the efficiency of different fuels should be compared. Results from the two methods (experimental on the engine test bench and simulation in the simulation software) are written in Tab. 10-2, based on the known data from Tab. 7-1 and Tab. 9-1.

rotational speed [RPM]	Fuel	Mk [Nm] Experiment	Mk [Nm] Simulation	P [kW] Experiment	P [kW] Simulation	BSFC [g/(kW*h)] Experiment	BSFC [g/(kW*h)] Simulation
5500	Petrol	4.33	9.09	2.51	5.24	412.82	305.37
	Blend	4.63	9.50	2.66	5.47	441.01	455.06
	Ethanol	4.80	9.42	2.79	5.43	572.73	554.68
	Methanol	5.80	9.11	3.36	5.24	687.39	684.29
6500	Petrol	7.37	11.25	5.10	7.65	345.12	352.52
	Blend	7.63	11.91	5.22	8.11	390.17	360.39
	Ethanol	7.83	11.11	5.35	7.56	524.04	542.51
	Methanol	8.25	10.44	5.60	7.10	665.68	753.92
7500	Petrol	11.50	12.34	9.05	9.69	325.01	302.32
	Blend	11.73	11.85	9.35	9.31	376.53	368.80
	Ethanol	12.03	11.65	9.47	9.15	474.84	477.55
	Methanol	12.80	11.31	10.15	8.88	929.17	761.09
8500	Petrol	12.77	12.89	11.46	11.47	345.37	374.61
	Blend	13.33	13.22	11.89	11.77	381.69	401.93
	Ethanol	13.57	13.66	12.09	12.16	468.39	575.90
	Methanol	12.80	13.59	11.30	12.10	928.88	932.76

rotational speed [RPM]	Fuel	BSFC [g/(kWh*100)] Experiment	BSFC [g/(kWh*100)] Simulation	CO [% vol] Experiment	CO [% vol] Simulation	CO2 [% vol] Experiment	CO2 [% vol] Simulation
5500	Petrol	4.13	3.05	2.51	0.00	8.48	10.97
	Blend	4.41	4.55	1.62	4.27	9.38	9.16
	Ethanol	5.73	5.55	1.59	1.40	9.40	10.11
	Methanol	6.87	6.84	0.30	0.95	8.88	10.15
6500	Petrol	3.45	3.53	1.76	0.00	9.64	10.57
	Blend	3.90	3.60	1.87	0.00	9.63	9.85
	Ethanol	5.24	5.43	2.04	0.00	9.73	9.56
	Methanol	6.66	7.54	1.13	0.00	9.54	8.89
7500	Petrol	3.25	3.02	2.36	1.85	9.84	11.94
	Blend	3.77	3.69	2.51	2.62	9.91	11.09
	Ethanol	4.75	4.78	2.30	1.39	10.30	11.11
	Methanol	9.29	7.61	9.60	4.69	6.12	8.59
8500	Petrol	3.45	3.75	3.52	4.44	8.85	9.21
	Blend	3.82	4.02	3.00	3.19	9.60	9.55
	Ethanol	4.68	5.76	2.77	4.27	10.37	8.40
	Methanol	9.29	9.33	10.13	6.92	6.22	6.96

Tab. 10-2 Comparison of two methods for the efficiency test

To better understand the differences in both methods, bar charts on Fig. 10-3a and 10-3b are created from data in Tab. 10-2.

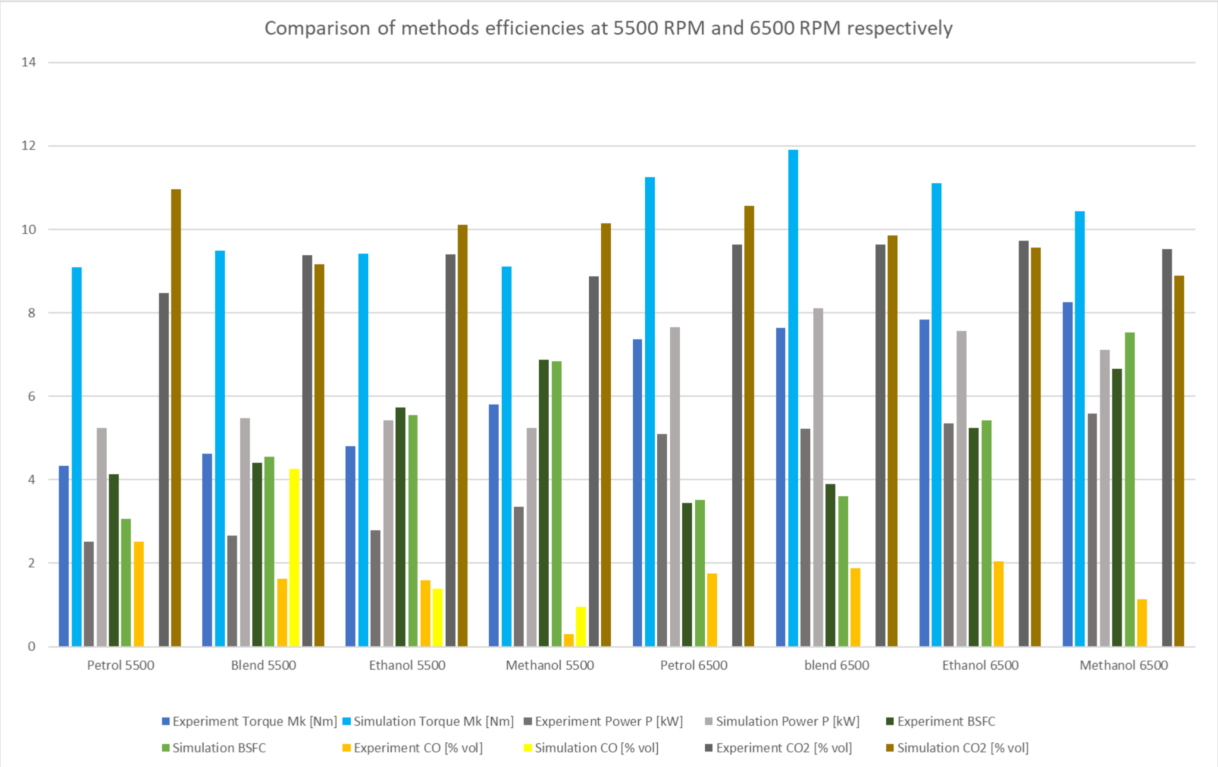


Fig. 10-3a Comparison of the values of torque (Mk), power (P), BSFC, CO, and CO_2 emissions of different fuels from both analyses at speeds of 5500 RPM and 6500 RPM (low speeds)

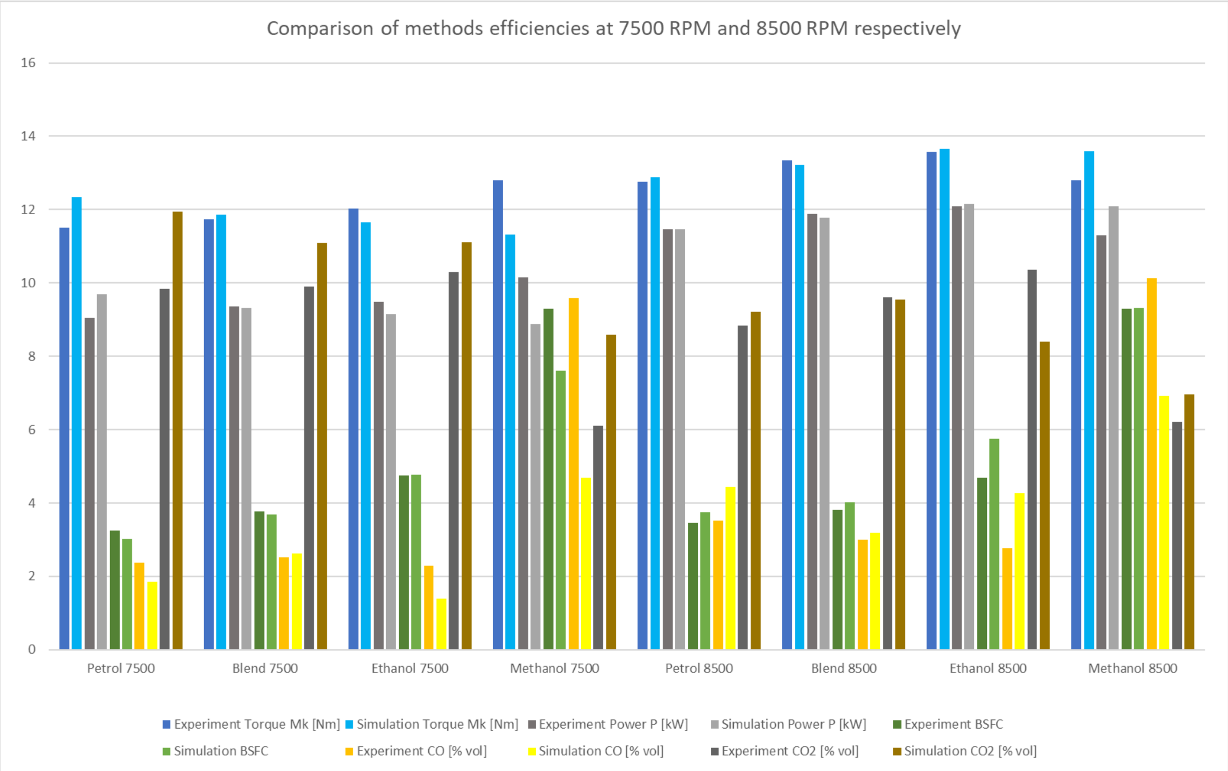


Fig. 10-3b Comparison of the values of torque (Mk), power (P), BSFC, CO, and CO_2 emissions of different fuels from both analyses at speeds of 7500 RPM and 8500 RPM (high speeds)

Thanks to good visibility of data in Fig. 10-3a and Fig. 10-3b, it is possible to see key differences from both analyses. The torque and power output of the engine is not the same at low speeds – simulation has achieved higher torque and power values. This effect is due to the nature of the measuring device on the engine test bench – the water brake. The water brake does not work with 100% accuracy at low speeds, and the results are, therefore, not very accurate. This issue could be solved by using an electrical brake instead. At high speeds, both torque and power values are almost the same regardless of the analysis method. The most powerful fuel is, once again, ethanol fuel, which reaches the highest value of torque and power at 8500 RPM.

If there is some data, which has got the same value regardless of the measurement method, it is the BSFC. Almost the same values of the BSFC are reached during both analyses at all speeds. BSFC rises slightly with the addition of ethanol to petrol at low speeds, but at high speeds, BSFC of clear petrol and E40 mixture are getting closer. BSFC of ethanol is at almost 140% of the value of petrol fuel at 5500 RPM, and BSFC of methanol is at 280% of the value of petrol fuel at 7500 RPM. This dramatic increase is caused by low AFR and low lambda values during both analyses. Therefore, methanol fuel should not be used in small combustion engines as alternative fuel due to its lack of economic function. The standard volume of the fuel tank of a Jetsurf Titanium DFI engine-powered surfboard is 2.5 liters [46]. With given methanol consumption, a full fuel tank would have lasted only approximately 10 minutes, which is not usable for production.

CO emissions are difficult to analyze because of the low accuracy of measuring devices on the engine test bench with alcohol fuels. It can only be evaluated during high speeds when the values of CO emissions seem stable. Nevertheless, there is no evident pattern in the changes in CO emissions for different fuels. At 7500 RPM, ethanol fuel has got the lowest emissions, but at 8500 RPM, it is the E40 mixture that leads the chart. In this case, it could have been proclaimed that the addition of ethanol could have had a positive impact on CO emissions, but this phenomenon cannot be confirmed.

Carbon dioxide emissions present another important criterion in the selection of a new alternative fuel. The difference in the values between the two methods is not large, and the results can be considered valid. In all cases, methanol proved to be the most ecological fuel from the study. However, due to its high BSFC, it cannot be considered in the choice of new alternative fuel. Therefore, ethanol and E40 mixture can be considered the most ecological fuels. During all speeds, a slight decrease in the CO_2 emissions of E40 and ethanol fuel is visible against conventional petrol. The highest difference can be seen at 6500 RPM. Results from the simulation method favor alternative fuels (E40 and ethanol) and make them more eco-friendly, while the real-life test cannot confirm this statement. Based solely on the simulation, alternative fuels seem to have slightly lower emissions of CO_2.

To conclude, E40 and ethanol fuel are selected as new alternative fuels by the efficiency test. E40 fuel is only partially sustainable (because of the conventional petrol content) but achieves better BSFC values than ethanol fuel while having similar CO_2 emissions. Ethanol fuel can be nowadays 100% sustainable, but its economy is yet to be improved by modifications to the engine. Both drawbacks should be considered in the choice of the new alternative fuel.

CONCLUSION

Two methods of analysis of different fuels were used during this study. Firstly, the experimental method on the engine test bench set the benchmark values of torque, power, BSFC, and emissions of conventional and alternative fuels. Later the simulation in the GT Suite software confirmed these values using optimization programs. Both methods have achieved very similar results, which can be considered valid and objective.

Based on the extensive analyses, new alternative fuel has been selected for the MSR NG 100 small combustion engine. If only performance characteristics (torque and power) should be considered, clear sustainable ethanol fuel seems like the best choice (as Fig. 10-1 indicates). However, after analyzing the efficiency of all fuels, it has been discovered that E40 mixed fuel [6] would be the best option for the engine considering the performance and efficiency, even though this fuel is not 100% sustainable. Both factors should be considered when choosing the new alternative fuel for small combustion engines. In addition, methanol fuel achieved the lowest emissions of GHG during all measures, but because of its high BSFC values, which make the fuel strongly uneconomic, it cannot be used as a replacement for conventional petrol.

The new model of the heat cycle of the MSR NG 100 engine has been made in the simulation software. It has been optimized to comply with the real engine behavior, which may be used in future analyses of alternative fuels. Nevertheless, it is recommended to adjust the model parameters more precisely (combustion model and injection settings) to create a complete copy of the real engine. Moreover, instead of using the exhaust optimization method, the complete 3D geometry of the exhaust could be imported into the model with the use of GEM software. If a complete virtual copy of the real engine were created, it would have been possible to improve the engine performance and efficiency using only the simulation software without costly experiments on the engine test bench.

The future of alternative fuels in small combustion engines seems bright. During this study, only one biofuel of second generation (ethanol) is used, while other fuels have a fossil character. Nevertheless, it should be theoretically possible to run the engine also with synthetic alcohol fuels, as the chemical composition remains the same regardless of the method of production. As it was mentioned in chapter 2, synthetic fuels do not produce GHG emissions during the production process. Small combustion engines are currently used in sports equipment (motorized surfboard Jetsurf) or hobby products, where the immediate application of alternative fuels does not require a large production volume. Thus, ecologically friendly synthetic fuels could present the future in this sector of industry. In addition, biological oil – for two-stroke engines – with CO_2 neutral production process must be used. It would not be convenient to use conventional oil with sustainable synthetic fuel.

To conclude, essential measures should be put in place to improve the world´s ecological situation. Green alternative fuels for small combustion engines are a working concept that should be transferred to public use. Naturally, more research in this field needs to be conducted in terms of production process, distribution, and long-term use in ICE. In the end, the application of alternative sustainable green fuels to combustion engines can be considered as a certain way how to reduce GHG emissions and improve Earth´s environment.

[6] consists of 40% clear ethanol and 60% of conventional petrol

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LIST OF ABBREVIATIONS AND SYMBOLS

% vol		Volumetric percentages
AC		Alternative current
AFR		Air-to-fuel ratio
CAN		Controller area network
CH_4		Methane
CO		Carbon monoxide
CO_2		Carbon dioxide
DC		Direct current
E40		Fuel mixture of 40% ethanol and 60% petrol
EGT		Exhaust gas temperature
GHG		Greenhouse gases
HFCs		Hydrofluorocarbons
ICE		Internal combustion engine
O_2		Oxygen
ppm		Parts per million
RON		Research octane number
TPS		Throttle position sensor
BSFC	[g/kWh]	Brake-specific fuel consumption
F	[N]	Force
kW	[kW]	Kilowatts
Mk	[Nm]	Torque
n	[s^{-1}]	Number of revolutions
n_{RPM}	[min^{-1}]	Number of revolutions in RPM
P	[W]	Power
P_1	[kPa]	Pressure
P_2	[kPa]	Pressure
Q_1	[g/min]	Flow
Q_2	[g/min]	Flow
r	[m]	Distance
RPM	[RPM]	Revolutions per minute
ω	[rad/s]	Rotational speed