CZECH TECHNICAL UNIVERSITY IN PRAGUE

Faculty of Mechanical Engineering

Department of Automotive, Internal Combustion Engines and Rail Vehicles
Study Program: Master of Automotive Engineering
Field Study: Advanced Powertrains

Prospects of bio-butanol as fuel for small machinery

September 2022
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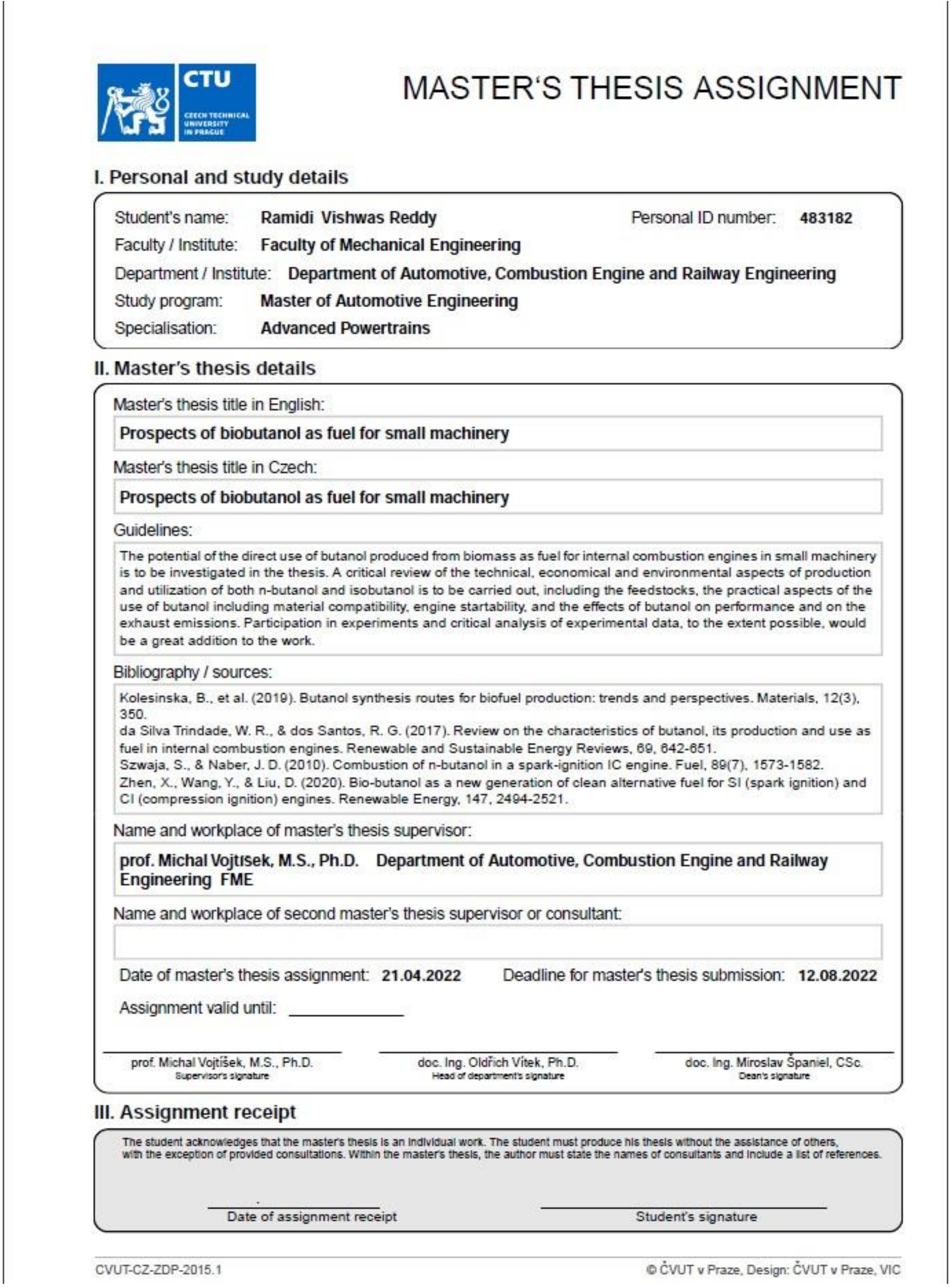

MASTER'S THESIS ASSIGNMENT

I. Personal and study details

Student's name: **Ramidi Vishwas Reddy** Personal ID number: **483182**
Faculty / Institute: **Faculty of Mechanical Engineering**
Department / Institute: **Department of Automotive, Combustion Engine and Railway Engineering**
Study program: **Master of Automotive Engineering**
Specialisation: **Advanced Powertrains**

II. Master's thesis details

Master's thesis title in English:

Prospects of biobutanol as fuel for small machinery

Master's thesis title in Czech:

Prospects of biobutanol as fuel for small machinery

Guidelines:

The potential of the direct use of butanol produced from biomass as fuel for internal combustion engines in small machinery is to be investigated in the thesis. A critical review of the technical, economical and environmental aspects of production and utilization of both n-butanol and isobutanol is to be carried out, including the feedstocks, the practical aspects of the use of butanol including material compatibility, engine startability, and the effects of butanol on performance and on the exhaust emissions. Participation in experiments and critical analysis of experimental data, to the extent possible, would be a great addition to the work.

Bibliography / sources:

Kolesinska, B., et al. (2019). Butanol synthesis routes for biofuel production: trends and perspectives. Materials, 12(3), 350.
da Silva Trindade, W. R., & dos Santos, R. G. (2017). Review on the characteristics of butanol, its production and use as fuel in internal combustion engines. Renewable and Sustainable Energy Reviews, 69, 642-651.
Szwaja, S., & Naber, J. D. (2010). Combustion of n-butanol in a spark-ignition IC engine. Fuel, 89(7), 1573-1582.
Zhen, X., Wang, Y., & Liu, D. (2020). Bio-butanol as a new generation of clean alternative fuel for SI (spark ignition) and CI (compression ignition) engines. Renewable Energy, 147, 2494-2521.

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Name and workplace of second master's thesis supervisor or consultant:

Date of master's thesis assignment: **21.04.2022** Deadline for master's thesis submission: **12.08.2022**

Assignment valid until: ____________

prof. Michal Vojtíšek, M.S., Ph.D. Supervisor's signature	doc. Ing. Oldřich Vítek, Ph.D. Head of department's signature	doc. Ing. Miroslav Španiel, CSc. Dean's signature

III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt Student's signature

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Declaration of Authorship

I hereby declare that the following thesis is my independent work and to the best of my knowledge. All information has been acknowledged in the text with list of reference.

In Prague: 12-08-2022

Ramidi Vishwas Reddy

Abstract:

This diploma thesis deals with the utilization of butanol blends of alcohol fuels produced from biomass (bio-butanol) and their application in small spark ignition engines. The goals of thesis were **1)** To conduct a critical review on the technical, economical, and environmental aspects of production of butanol from biomass, **2)** To evaluate the practical aspects of use of butanol isomers including material compatibility and engine startability and **3)** To compare and evaluate the performance and emission characteristics of butanol isomer gasoline blends and pure gasoline on small spark-ignition engine generator. The study done in this thesis covers different aspects of butanol, from production of bio-butanol from biomass, its life cycle assessment and carbon foot print from bio-butanol production. Studies on material compatibility and engine startability of butanol are presented in this thesis, along with performance and experimental analysis of emission characteristics of different blends of butanol gasoline fuel on an air-cooled single-cylinder four-stroke gasoline engine used to power the generator, with some modifications to the carburetor nozzle diameter, were evaluated and results were analyzed to study the effect of butanol alcohol as fuel along with effect of air/fuel ratio on the specific emissions of different percentage of alcohol content in fuel blends.

Keywords: alcohol fuels, bio-butanol, n-butanol, iso-butanol, small spark ignition engine, exhaust emissions, air/fuel ratio.

Acknowledgement

First, I would like to thank God Almighty for his blessing and strength granted upon me and my family. Also, I would like to give my respect and love to my parents for all their supports and prayers during my entire life. I would like to express my sincere gratitude to my supervisor Prof. Michal Vojtisek, M.S, Ph.D., Faculty of Mechanical Engineering, Czech Technical University, Prague for his guidance, opportunities and patience provided in completion of the thesis work. Besides my supervisor, I would also like to extend my gratitude to doc. Martin Pechout, M.S., Ph.D., Faculty of Technology, Czech University of Life Sciences, Prague for his consultations and for all the help that was needed to understand this study. And finally, I would like to thank my beloved friends for their supports and prayers throughout my studies.

Ramidi Vishwas Reddy

Table of Contents

1. Introduction

The EU's revised Renewable Energy Directive (2018/2001/EU) (RED II) [1] entered into force in December 2018, creating a binding renewable energy consumption target for the EU of at least 32% of total energy consumption by 2030. Increased use of renewable fuels and energy sources in the transportation sector is seen as an effective strategy to meet this objective, with renewable energy accounting for at least 14% of total transportation energy consumption by 2030. A biofuel is a hydro-carbon based fuel derived from biological material (once living or nonliving) in a brief time frame. The various types of biofuels and the corresponding fuel they substitute are ethanol (gasoline/ethanol), methanol, bio-butanol (gasoline/ butanol).

Generally, fuels which are less viscous and have lower cetane number as compared to standard diesel are regarded as Low viscous low cetane fuels. Such fuels are likely to have less viscosity and low cetane number due to relatively shorter carbon chain length and absence of fatty acids. These fuels can also be considered as light biofuels. Unlike vegetable oils which are extracted from seeds these fuels originate from different plants or biomass. Some of the fuels with such traits are alcohol fuels such as methanol, ethanol, butanol and other higher alcohols [2].

Major criteria for fuel to be considered as an alternative fuel are

1. Affordability.
2. Availability.
3. Safety.
4. Potential Carbon Footprint Reduction

1.1 Goal of thesis

The primary goal of this thesis is to evaluate the potential use of isomers of butanol (n-butanol and iso-butanol) produced from biomass as fuels on small SI Engine.

1. Critical review on the technical, economical, and environmental aspects of production of butanol from biomass.

2. To evaluate practical aspects of use of butanol isomers including material compatibility and engine startability.

3. To compare and evaluate the performance and emission characteristics of butanol isomer gasoline blends and pure gasoline on small SI engine generator.

1.2 Alcohols as fuels

Alcohols have a strong potential to be used as transportation fuels, particularly those having a carbon chain length of one to four atoms. They can be used directly in internal combustion engines with minimal or moderate modifications and are characterized by appropriate burning behaviors, such as offering a high-octane rating and reduced pollutants. Furthermore, from methanol to butanol alcohol fuels can be made from biomass and waste materials in a variety of ways allowing for the efficient use of available resources [3]. They offer a potential and essential way to fulfill legal requirements in the transportation sector for renewable and advanced renewable energy carriers.

Alcohol blends with gasoline can contribute in significant reduction of gasoline exhaust emissions and the reliability on oil. Alcohols are appropriate gasoline additives because they are rich in oxygen content and are found in liquid nature . Low carbon alcohols (chains having three or fewer carbon), such as methanol and ethanol, as a blend with gasoline fuel gained attention due to their sophisticated production technologies and rich oxygen content, which can significantly improve combustion characteristics as well as reduce the exhaust emissions. Ethanol produces 25% more energy than the energy supplied into its creation from biomass, compared to the conventional fuels they decrease greenhouse gas emissions by 12% by the production and combustion of ethanol from biomass [4]. Furthermore, it was observed that combining alcohols such methanol, ethanol, and butanol had a substantial impact on the fuel characteristics, combustion, and emissions of petroleum fuels. When blended into gasoline fuel, these mixes significantly reduce exhaust emissions and increase octane number. This type of improvement is especially important in unleaded fuels. As a result, methanol, ethanol, and butanol–gasoline fuel blends are potential alternative fuels. There are significant benefits to developing alcohol-based fuels, for instance, among so many other renewable alternative resources. First, it can improve the emission environment, particularly for vehicle exhaust; second, it can assist in ensuring a country's energy balance and reduce reliance on conventional fossil fuels; third, it can ensure national energy security and long-term development; and fourth, it can ensure national energy security and long-term development. Fourth, developing renewable resources can help the country establish more job prospects.

2 Butanol

Butanol is a four-carbon alcohol that exists in four separate isomers: Normal-butanol(1-butanol) (CH3-CH2CH2CH2OH), secondary-butanol(2-butanol) (CH3CH2CHOHCH3), iso-butanol(2-methyl propanol) (CH3)2CH2CHOH), and tertiary-butanol(3-butanol) (CH3)3COH).

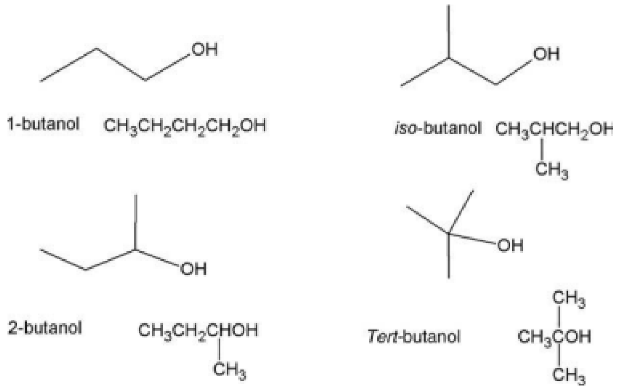
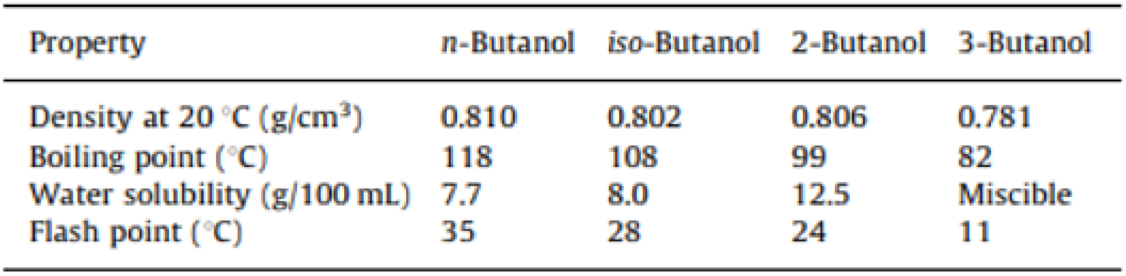


Figure 1. Molecular structures of butanol isomers [6]

The above Figure 1, describes the different Molecular structure of butanol isomers, in Table 1 below the chemical properties of different butanol isomers are given. While there are four isomers of butanol, only iso-butanol and n-butanol blend efficiently up to 15% on volumetric basis with gasoline which replaces ethanol that blends only 10% with petrol, iso-butanol, n-butanol for gasoline blending is the most actively commercialized. In US Two parts of the Clean Air Act allow up to 12.5 percent bio-butanol by volume to be blended with gasoline. A 16 percent bio-butanol blend is also a permitted fuel equivalent to E10 under a waiver issued by the US Environmental Protection Agency (EPA) (10 percent ethanol, 90 percent gasoline). The ASTM D7862 fuel quality standard applies to butanol mixes of up to 12.5 percent with gasoline [5].

Table 1. Chemical Properties of Butanol Isomers



Property	*n*-Butanol	*iso*-Butanol	2-Butanol	3-Butanol
Density at 20 °C (g/cm^3)	0.810	0.802	0.806	0.781
Boiling point (°C)	118	108	99	82
Water solubility (g/100 mL)	7.7	8.0	12.5	Miscible
Flash point (°C)	35	28	24	11

Butanol is getting more attention due to the drawbacks of ethanol as a universal fuel and component in gasoline mixes. To begin with, butanol has a larger calorific value than ethanol (its energy content is 29.2 MJ/L versus 19.6 MJ/L for ethanol). It also has greater gasoline and diesel miscibility, lower water miscibility, a high-octane rating ([n-butanol- 96], [iso-butanol- 113]), and is less volatile. Butanol can be stored in humid circumstances due to its higher hydrophobicity compared to ethanol. Furthermore, it is noncorrosive and can be utilized in existing combustion engines in up to 30%(v/v) gasoline blends. Butanol's characteristics are very similar to those of current gasoline, historically, corn-based ethanol has been the major biofuel for the gasoline industry. however, there are several disadvantages to using ethanol: it has a smaller energy content than gasoline, it cannot be distributed by pipelines, and the amount that can be blended into gasoline for use in conventional vehicles is restricted by environmental regulations and engine compatibility. Ethanol (CH3-CH2-OH) is 35-percent-oxygen-by-weight oxygenated molecule. As a result, compared to gasoline, more ethanol (both by weight and volume) is required to make a stoichiometric mixture with a given amount of air. Compared to 48% for ethanol an increase about only 18% of butanol fuel volume is needed for maintaining the stoichiometric air fuel mixture. As a result, when running on ethanol, any engine geared to run on gasoline must increase the amount of ethanol fuel provided to the engine, another concern that has arisen as a result of the usage of ethanol in fuel cars is its hygroscopic behavior and aggressivity towards epoxy resins and other materials used in the fuel flow systems. Higher molecular weight alcohols, such as n-butanol and iso-butanol, have more energy content and higher heating value compared to lower carbon number alcohols, it means that an engine running on n-butanol is expected to present a lower fuel consumption and a better mileage when compared with ethanol [6].

2.1 Types of ways to produce butanol

Butanol can be produced in two ways: from biomass (as "bio-butanol") or from fossil fuels (as "petro-butanol"), but the chemical characteristics of both biobutanol and Petro-butanol are the same. Today, the majority of butanol generated is synthetic and comes from a petrochemical reaction (petro-butanol). However, the earliest report of butanol production in microbial fermentation was published in 1861[7]. Butanol is generally synthesized from petroleum sources nowadays, but it was produced primarily from biological sources in earlier days. Commercial butanol production dates back to World Wars I and II, when corn and molasses were used in ABE (acetone–butanol–ethanol) fermentation [6]. Butanol output declined in the 1950s due to rising molasses prices and process reliability issues, However, in the 1980s, chemical synthesis replaced biological butanol production due to the rise of the petroleum industry and rising corn and molasses prices. Commercial production of butanol from biomass was common in the first part of the twentieth century, and today's butanol users expect it to happen again. Because most of the fuel qualities of two of the isomers (n-butanol and iso-butanol) are more similar petroleum fuel, it has benefits over methanol and ethanol for usage as an alternative fuel in internal combustion engines [6].

2.1.1 Butanol production using oxo process

The hydroformylation of propene is used in oxo synthesis, propene produced from fossil gas and CO $+H_2$ are employed as feed streams, with a catalyst. Following that, the resulting aldehydes are catalytically hydrogenated. The reaction parameters (pressure, temperature) and catalyst employed in the hydroformylation process might vary. Traditional high-pressure techniques produce about 75% 1-butanol and 25% 2-methyl-1-propanol (iso-butanol), but modern low-pressure processes using modified Rh-catalysts can produce 95 percent n-butanol and 5% 2-methyl-1-propanol(iso-butanol). Fig 2 shows the major characteristics of the oxo process [7].

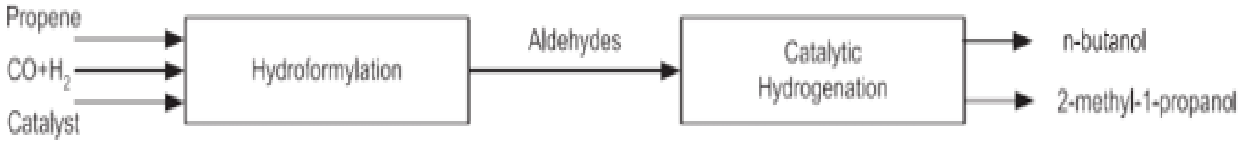


Figure 2. Main features of oxo process [7]

2.1.2 Butanol production using ABE process in batch reactor

Renewable butanol can be produced from the fermentation of carbohydrates in a process better known as ABE fermentation since its major chemical products are acetone, butanol and ethanol. In a 3:6:1 mass ratio, the final product is distilled to recover acetone, butanol, and ethanol, which is 3 parts acetone, 6 parts butanol, and 1 part ethanol. Interest in using clostridial species for acetone–butanol–ethanol fermentation due cheap price of feedstock and micro-organisms required for fermentation revived ABE fermentation process in the 1980s, due to the rising price of petroleum. Due to the current concern about renewable energy sources, pollution and emissions regulations, new opportunities have emerged for the traditional ABE fermentation industry since it could again be potentially competitive with chemical synthesis process. Figure 3 below shows the production process of butanol through ABE process Figure 4, shows the schematics of butanol production plant [7,8].

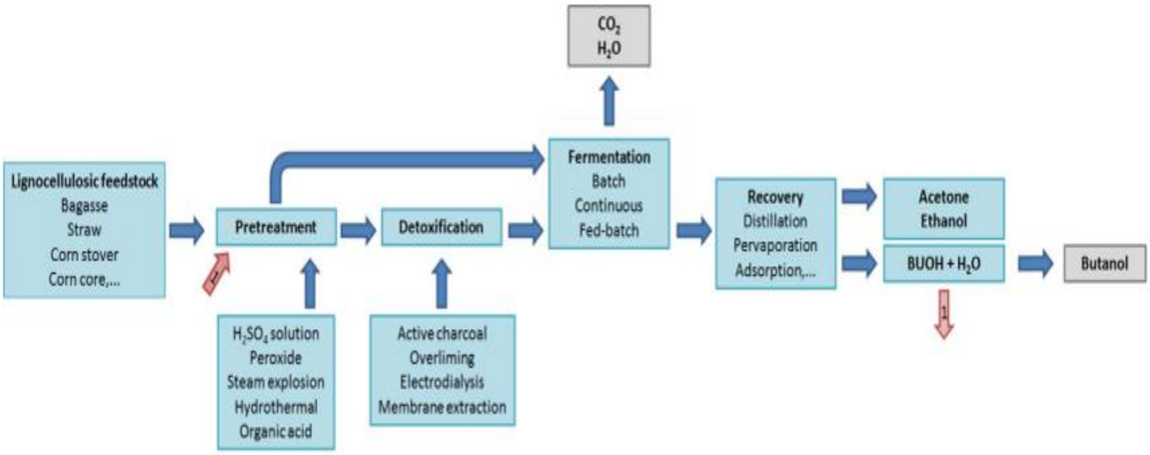


Figure 3. Production of Butanol through ABE fermentation process [8]

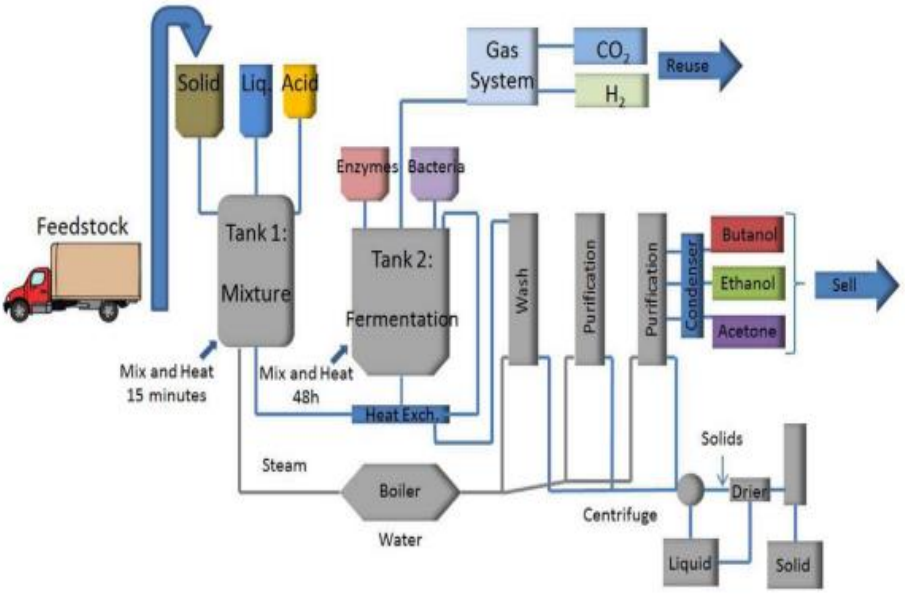


Figure 4. Schematics of butanol production plant [8]

In the ABE production process the following parameters should be considered:

2.1.2.1 Type of feedstock

Agricultural wastes can be used to make biofuels that are both cost-effective and environmentally friendly. More than 40 million tons of inedible plant material are produced each around the world, with the majority of it being thrown. Agricultural wastes can be used to make biofuels that are both cost-effective and environmentally friendly. Wheat straw, maize stover, switchgrass, salix, spruce, flax shives, hemp hurds, poplar, alfalfa stems and corn cobs, organic waste materials from inedible sections of plants, and food processing waste are all abundant and potential sources of biomass. It should now be a top priority to figure out how to turn this woody biomass into biofuel. Because materials that do not compete with food supply are more sustainable, the choice of substrate entails technological, economic, and even social considerations. Other raw sources being investigated include glycerol (a by-product of biodiesel production) and algae [9,10]. First-generation bio-butanol is essentially derived from conventional food crops, whereas the second-generation bio-butanol are based upon the byproducts of forestry and lignocellulosic biomass, while third-generation bio-butanol is produced from algae biomass, Figure 5, shows the process of biobutanol production with different feedstocks. This Figure 5, basically shows the steps followed during the process [9,10].

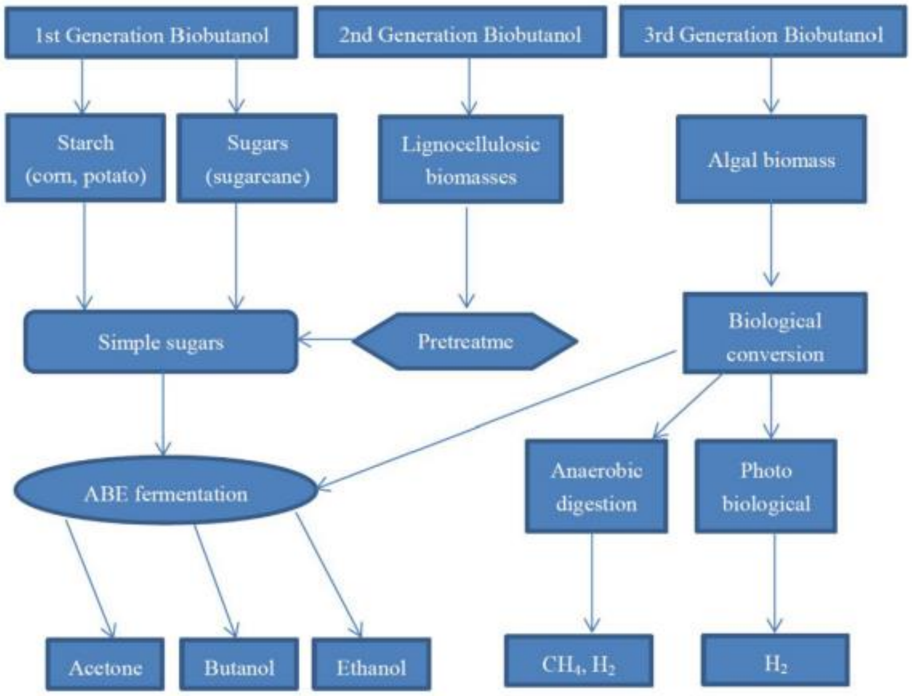


Figure 5. Bio-butanol generation process [7]

2.1.2.2 Type of microorganisms:

Clostridium acetobutylicum, Clostridium aurantibutyricum, Clostridium beijerinckii, Clostridium butyricum, and a variety of other microbes can be employed in this method. Clostridium acetobutylicum and Clostridium beijerinckii, however, are the most important in butanol production utilizing ABE fermentation because they produce a large amount of butanol. Clostridia bacteria secretes a large number of extracellular enzymes, including amylase, saccharase, glucosidase, glucoamylase, pullulanase, and amylopullulanase, to break down polysaccharides into simple monosaccharides (glucose, xylose, and arabinose). Other carbon substrates, such as corn, sugar beets, sugar cane, potatoes, tapioca, or millet, can be converted to butanol with the help of these enzymes [9,10,11].

2.1.2.2 Fermentation processes

Fermentation can be done in one of three ways: fed-batch, batch, or continuous. The substrate and nutrients are introduced in the reactor before the enzyme is added in batch fermentation. Fermentation takes place at 35–37°C, and once the process is complete, the solids are removed and the liquid is ready for distillation. The productivity of this method is low. When the substrates are harmful to microorganisms, fed-batch fermentation is used. A tiny amount of substrate is first fed into the reactor, and more substrate is added as the process progresses, always keeping the substrate concentration below the hazardous limit. Because butanol is harmful to microorganisms, the solvent (acetone-butanol-ethanol) is usually removed by subsequent recovery processes. New recovery algorithms are applied in this procedure, allowing for the simultaneous recovery of all products. Continuous fermentation allows for production optimization. A single stage or numerous stages can be used in the system. The variability in output levels is one of the major challenges [10,11].

2.1.2.3 Recovery processes

Liquid-liquid extraction, perstraction, pervaporation, and gas stripping are the key downstream fermentation processes. In the first step, a solvent is applied, and butanol is extracted since it is more soluble in the extractant. Back extraction or distillation can then be used to recover it. Perstraction similarly employs an extractant, but because to the presence of a membrane that facilitates ABE diffusion, there is no direct contact between the extractant and the fermentation broth. A selective membrane is used in pervaporation, and the volatiles are removed into a gaseous phase on the other side. After that, the volatiles are condensed and recovered. Nitrogen or fermentation gases are continually sparged into the reactor and sent to a condenser in gas stripping. The volatile solvents are then recovered by cooling [9,10].

2.1.2.4 Inhibitory processes

One of the most significant disadvantages of ABE fermentation is inhibitory processes, which contribute to low productivities. Microorganisms can be poisoned by the substrate, and most clostridial cultures are poisoned by the fermentation products (acetone, butanol, and ethanol). On the other hand, the maximum concentration is roughly 20 g/L, imposing substrate-level limits. The constant elimination of solvents is a popular remedy for this problem. The introduction of new strains with better resistance is another option. Pretreatment and hydrolysis are required when using lignocelluosic materials, although this can result in the formation of other inhibitory components such as formic acid, acetic acid, levulinic acid, furfural, and hydroxymethyl furfural [10,11]. Butanol manufacturing is gaining popularity again, thanks to the promotion of renewable energy sources and the fact that it may be used as a fuel. With the advancement of bio-butanol production technology, it has been discovered that there is good potential for its utilization in cars.

2.2 Life Cycle Assessment (LCA) of Bio-Butanol Production

Life Cycle Assessment is technically the assessment of environmental implications of a product or service throughout its life cycle, from raw material extraction to waste disposal. It examines the material flow and energy throughout the life cycle, including production, use, and disposal.

The Life Cycle Assessment of butanol was done by Brito and Martins [12], on three different butanol production namely oxo synthesis and two ABE fermentation processes (wheat straw and Corn). This study gives us good understanding of LCA of different butanol productions. the study was based on collected data from bibliography and Ecoinvent database. In this study the methodology used for impact assessment was ‘IMPACT 2002+’. In a combined approach to damage, this method suggests a viable implementation of a midpoint. It takes into account four types of damage: human health, environmental quality, climate change, and resource depletion. The authors described their methodologies in the paper and they also supplied detailed information describing the construction of the LCA models as well as key parameters for each life cycle stage in the Supporting Information section of the paper [12]. Impacts were allocated first and foremost based on the mass ratio of the products obtained, i.e; the ratio of mass of butanol obtained from the total mass of all the products obtained from the process, and then on the economic value of the products obtained at the end of production. By examining the data in Table 2, obtained from the study it is clear that when the allocation technique is based on economic value, the weight of n-butanol increases dramatically due to the low economic value of gases. The comparable percentage for the wheat straw process is more than double the economic value obtained for mass allocation. The weight of n-butanol grows greatly in the corn procedure, but only by around 1.5 times [12].

Table 2.Mass and Economic Ratio Allocation for different ABE process feedstock [12]

Products	ABE process with wheat straw (%)		ABE process with corn (%)	
	Mass Ratio	Economic Ratio	Mass Ratio	Economic Ratio
n-butanol	19.82	44.34	31.02	49.31
Acetone	10.48	19.95	7.06	9.54
Ethanol	3.83	3.65	0.19	0.13
Methane	9.58	9.17	15.33	10.43
Gases	56.29	22.89	41.33	11.94
Oil	-	-	5.07	18.65

When Environmental impact assessment was done for 1 kg butanol production from three different butanol production process, the following impacts points was obtained.

Figure 6, represents the impact of oxo process for all damage categories:

1.Climate change

2.Ecosytem quality

3.Human health

4.Resources

In the Figure 6, the points on the y-axis indicate the impact points for all damage categories calculated or based on impact assessment using ‘IMPACT 2002+’ by the author. From Figure 6, we can observe that oxo process has adverse implications in the damage categories of climate change and resources.

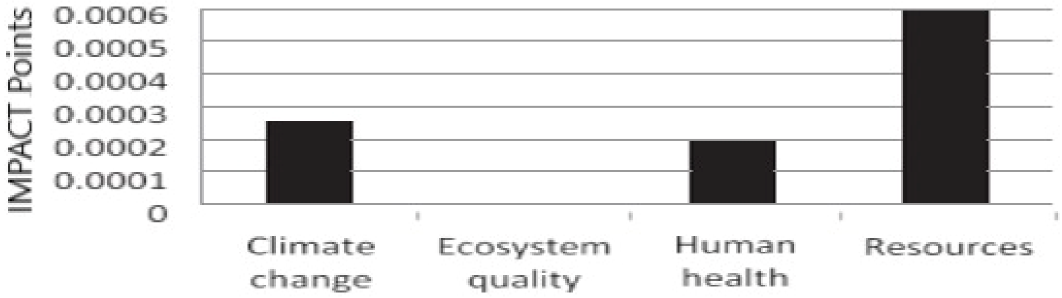


Figure 6. Impact Assessment for 1kg Butanol production through oxo process [12]

Figure 7, presents the impacts points for 1 kg of butanol for two ABE process on similar damage categories, and Figure 8, presents the overall environmental impact points of both ABE processes and allocations is shown.

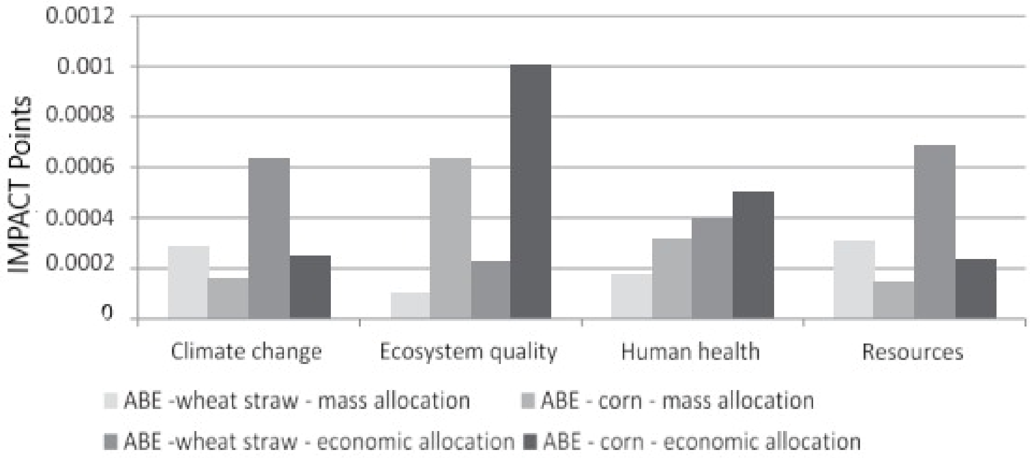


Figure 7. Impact Assessment for 1kg Butanol - ABE process [12]

According to Figure 8, ABE production using wheat straw employing mass allocation has the least environmental impact points of all methods, followed by the oxo process. When economic allocation is taken into account however, the total environmental impact of ABE processes is substantially larger than that of the oxo process, and the values obtained for both ABE processes are extremely close. The low economic worth of gases released during fermentation explains this.

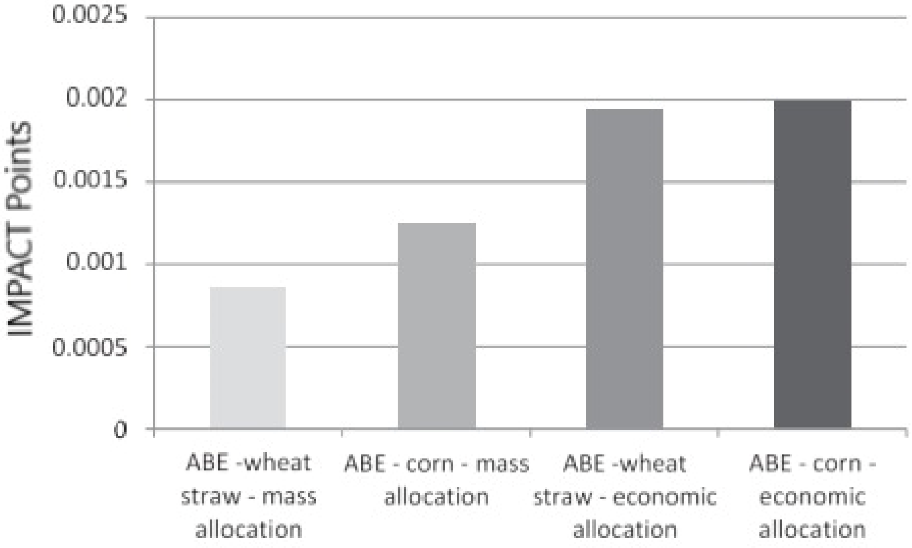


Figure 8. Total Environmental Impact Assessment for 1kg Butanol - ABE process [12]

When the allocation technique is based on mass, the ABE fermentation using corn grains as a substrate has the highest environmental impact, while the ABE fermentation using wheat straw has the lowest environmental impact. The worldwide environmental effect of ABE processes increases dramatically when the allocation technique is based on the economic values of products obtained, due to the lower economic value of gases released during fermentation. The price of substrates, the presence of inhibitors, and ineffective product recovery, as previously indicated, have a significant impact on the economic feasibility of ABE processes. Corn and other similar substrates can pose various challenges in human food supply and increase social repercussions from a sustainability standpoint. Because it has reduced social and environmental implications, it can be a strategic source of renewable energy to replace gasoline and other petroleum products, especially when employing subtracts like wheat straw. From an economic standpoint, it has the benefit of keeping the products wheat (straw) within the economy, which is in line with EU circular economy policy. Taking all of these variables into account, n-butanol produced from waste biomasses such as corn and wheat straw is a long-term answer.

However, the fermentation process should be further enhanced to reduce the consequences even further, which will require more investment and study [12].

2.3 Carbon foot print of Bio-butanol by ABE process

Because there are several process steps and co-products from the butanol production process, the GHG emission saving potential with butanol is still unclear, so critical analysis on GHG emission from two different bio-butanol production through ABE fermentation process from feedstocks corn and sugarcane was done by Väisänen [13]. In the study the butanol production life cycle stages included were 1) land use, 2) cultivation, 3) pretreatment and feedstock transportation, 4) biofuel conversion by the ABE fermentation and 5) distribution and use.

Biobutanol production from these two different feedstocks differ not only in the cultivation but also in the pretreatment methods and side flow generation. Sugarcane processing produces a side flow bagasse, which can be used for energy to cover the butanol production energy consumption, whereas the main side flow from corn processing is Dried Distillers Grains with Solubles (DDGS), which can be used as animal fodder. This means that the sugarcane processing plant can be self-sufficient for energy and can even supply electricity to the grid by combustion of bagasse from side flow generation of butanol from sugarcane ABE process, whereas the corn processing plant is dependent on outside energy. In order to calculate the GHG emissions related to butanol production some methodological selections have to be done in relation to the co-product acetone and ethanol from the ABE process and for the excess electricity related to bagasse combustion due to the difference in the theses two process. These products can be regarded as co-products because they have existing markets, which is the main criteria for a product to be a co-product instead of waste (GHG ISO 14040) [13].

The following five scenarios for corn butanol were investigated to see how these methodological choices affected the final GHG result.:

- C1: Emissions being allocated between butanol and ethanol by the energy allocation method. Acetone is excluded from the allocation (considered as waste); no displacement for DDGS.
- C2: Emissions being allocated between acetone, butanol, and ethanol by energy allocation method; no displacement for DDGS.
- C3: Emissions being allocated between acetone, butanol, and ethanol. In addition, DDGS is assumed to replace animal feed and a displacement credit justified.
- C4: Displacement credits being accounted for by ethanol and DDGS; acetone is considered as waste.
- C5: Displacement credits being accounted for acetone, ethanol, and DDGS

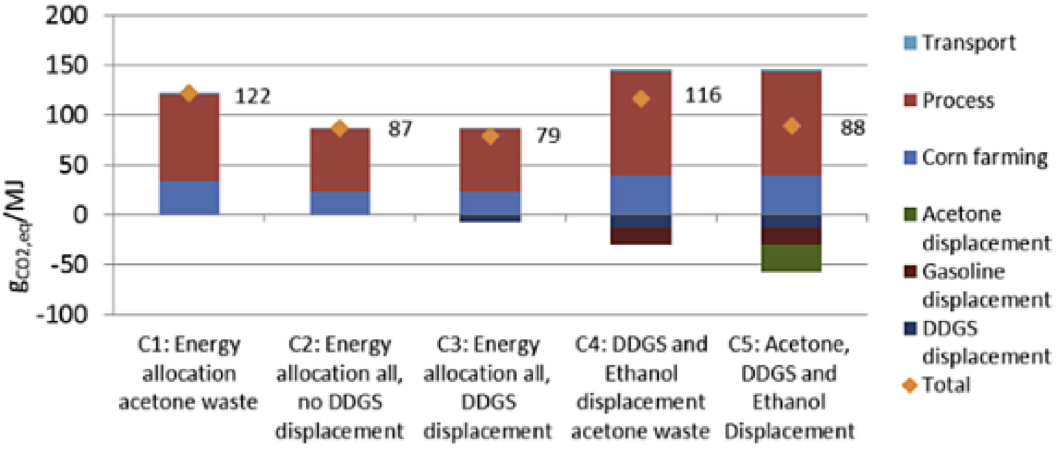


Figure 9. CO2 from Corn ABE Process [13]

In the case of sugarcane butanol, the impact of cane waste use was investigated in addition to the allocation technique chosen.

- S1: Emissions being allocated between butanol and ethanol;
cane trash is burned on the field (no utilization); acetone is
considered as waste.
- S2: Emissions being allocated between acetone, butanol, and
ethanol; cane trash is burned on the field (no utilization).
- S3: Emissions being allocated between acetone, butanol,
ethanol, and electricity produced from cane trash.
- S4: Displacement credits being accounted for by ethanol, and
Electricity production;
acetone is considered as a waste.
- S5: Displacement credits are accounted for acetone, ethanol and
electricity; cane trash is burned on the field (no utilization).
- S6: Displacement credits being accounted for by acetone, ethanol, and
electricity produced from cane trash

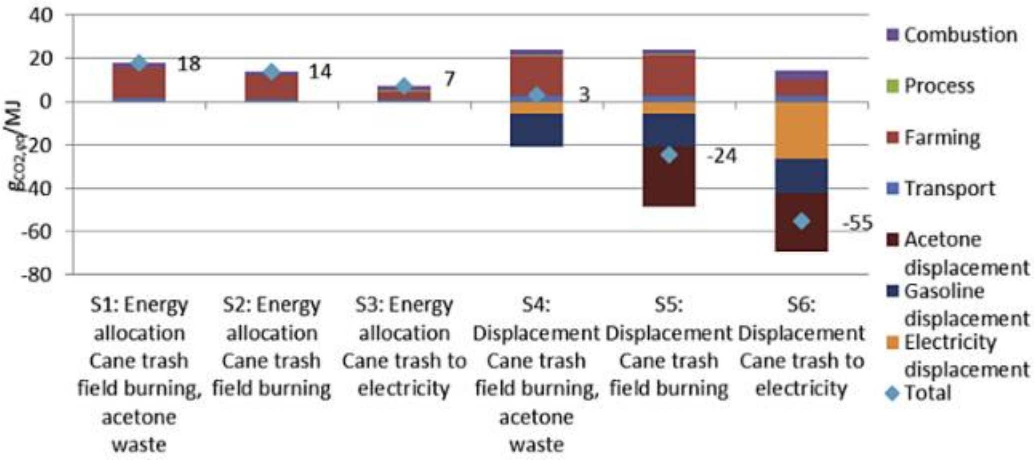


Figure 10. CO2 from Sugar Cane ABE Process [13]

Figures 9 & 10, illustrate the carbon footprint of butanol manufacturing and use from corn and sugarcane ABE process. The figures in display shows the results of the displacement and energy allocation calculations. Corn butanol production with ABE fermentation emits higher greenhouse gases than sugarcane production procedures. According to the study, corn butanol production results in significant GHG emissions, expressed as equivalent CO_2 that is converting all emission into equivalent of CO_2 emitted from the process (79 $g_{CO2\text{-}eq}$/MJ to 122 $g_{CO2\text{-}eq}$/MJ), which may exceed the emissions of fossil gasoline fuel (83.8 $g_{CO2\text{-}eq}$/MJ, (2009/28/EC). Corn butanol's key emission sources are high energy consumption, fossil fuel utilized in the process steam production, and corn growing. When compared to corn butanol production, sugarcane butanol emissions were much lower (-55 $g_{CO2\text{-}eq}$/MJ to 18g $g_{CO2\text{-}eq}$/MJ). The use of bagasse for electricity production is the key cause for the lower emissions. This also allows for the generation of extra electricity for sale in addition to energy production for the operation. When sugarcane butanol is compared to fossil gasoline, the study's findings demonstrate a reduction in global warming of more than 75% compared with gasoline. The study's findings demonstrate that sugarcane butanol emits less than 18 $g_{CO2\text{-}eq}$/MJ, representing a comparative percentage difference of more than 78 percent when compared to gasoline, which emits 83.8 $g_{CO2\text{-}eq}$/MJ. As a result, the findings for sugarcane butanol in this study are consistent with current research on butanol as a biofuel [13].

2.4 Economics of butanol

The price of oil barrels rose steadily throughout the 1990s, sparking interest in alternative fuels and production methods. With the use of new genetic engineering techniques, the incorporation of more productive reactors, and novel methods to recover the solvent, several researchers began to improve the ABE fermentation. The process economics are influenced by the feedstock, the manufacturing process, and the separation technology. Several studies have looked into the economic viability of producing butanol from corn, wheat straw, whey permeate, and molasses. Most butanol is currently generated (at a cost of

7.0–8.4 billion dollars per year) using chemical techniques such as oxo synthesis, Reppe synthesis, or crotonaldehyde hydrogenation. However, the products obtained through these processes cannot currently be considered for commercial reasons as the predominant form of butanol production uses petrochemicals as sources. The yearly combined global production of butanol from petrochemical and biomass sources was $2.49 *10^9$ kg in 1996. Butanol is currently manufactured in quantities of 12–18 billion dollars per year. The global market for n-butanol is estimated to be over three million tons per year, with a projected annual growth rate of 3.2 percent through 2025. the widespread use of bio-butanol in the production of compounds such as butyl acrylates is also fueling market expansion. It's also used to make acetates, acrylates, glycol ethers, and other industrial solvents. The present global market value of all biofuels is roughly $50 billion, with a 7.5 percent annual growth rate, at this rate the industry is predicted to increase to over $250 billion by 2040, and biobutanol is expected to become a prominent biofuel [14,15,16].

Biobutanol has a higher cost ($1.87/kg n-butanol) than petrochemical butanol ($1.52/kg n-butanol), but it has an advantage over the conventional approach due to lower feedstock processing costs and its environmentally benign character. Butanol is in high demand in North America, Western Europe, and North East Asia, especially in the United States, Germany, Japan, and China. Between 2005 and 2013, the butanol production climbed at a pace of 2.7 percent per year, and current annual global consumption is more than 5 billion liters (4 million tons), worth more than $10 billion [16], with nearly 2 billion liters of bio-butanol produced from biomass. Table 3 below highlights some of the major industries that use modified microbes on an industrial scale for feedstock processing and butanol fermentation. Since 2014, Gevo has used a commercial plant in Luverne, USA, to produce biomass-based iso-butanol via sugar fermentation, which is further converted into jet fuel. Commercial n-butanol based from biomass feedstock was produced by Green Biologics in Little Falls, USA, with the aid of using specialized Clostridia microorganisms. N-butanol has a low solubility in water and a high volumetric energy density (only 17 percent less than gasoline). This has been acknowledged by BP and DuPont, who have invested in large-scale production. DuPont and BP have spent $8.8 million on research and development for commercial butanol production utilizing seaweed biomass. Improving engines and enhancing performance through alternate fuel research can have a financial impact. Lower fuel consumption results from improved performance and efficiency. Iso-butanol blends have proven that consumption rises as a percentage of total consumption, but it remains to be seen whether that percentage replaces fossil fuel. Despite the fact that the thesis does not include research on the availability of iso-butanol on the market, the literature evaluation indicates that iso-butanol is not now available in Europe. As a result, in the United States, the opposite is true. Iso-butanol is available as a blend with gasoline with up to 16 percent iso-butanol at various gas stations there [17]. Despite the fact that commercial-scale biobutanol production is quickly expanding, industries are still faced with a number of barriers that must be overcome in order to achieve cost-effective production. The price of substrates, the presence of inhibitors, and inadequate product recovery all have a significant impact on the economic viability of butanol synthesis from ABE fermentation. Development of butanol-tolerant strains, overall cost competitiveness, reduced yield, sluggish fermentation, uneconomical product recovery, and microbe separation are all issues that must be addressed. The generation of biobutanol from algae is still in its early stages. Despite its many benefits, there are significant barriers that prevent practical usage of this biomass like cost of algae, storage, presence of inhibitors, recovery processes.

Table 3. Major Butanol Production Companies [14]

COMPANIES	COUNTRY	PRODUCTION DETAILS
GEVO	CO, USA	Using genetically engineered yeast to produce iso-butanol from glucose
BUTYL FUEL, LLC	Columbus, USA	Biobutanol manufacturing using a patented Clostridium strain which can produce large levels of butanol (1.3–1.9 times greater).
GREEN BIOLOGICS	Abingdon, UK	Biobutanol manufacturing using a genetically engineered strain that can handle approximately 4% butanol concentration.
TETRAVIATE BIOSCIENCE	Chicago, USA	Clostridium beijerinckii modified and patented for biobutanol fermentation
BUTALACO (bio-based innovations)	Zug, Switzerland	Yeast that has been genetically modified to produce more butanol and

		use C5/C6 sugars more efficiently.
METABOLIC EXPLORER	Clermont-Ferrand, France	Butanol generation from lignocellulosic biomass using designed microbes

3. Fuel properties

The characteristics of iso-butanol, n-butanol, and ethanol are listed in Table 4. For comparison, the properties of conventional gasoline and ethanol are also shown. n-butanol and iso-butanol have an approximately 30% higher volumetric energy density than ethanol, allowing butanol to qualify for 30% more credit under the US Renewable Fuel Standard law [4], if life cycle GHG emission requirements are met. The increased energy density of butanol helps by extending vehicle driving range to levels comparable to petroleum-derived gasoline.

Table 4. Comparative Fuel Characteristics of Gasoline, n-Butanol, iso-Butanol and Ethanol [18]

	Gasoline	N-Butanol	Iso-Butanol	Ethanol
Research Octane Number (RON)	95	94-96	113	110
Density [kg/m^3]	753	810	806	790
Lower Heating Value [MJ/kg]	42.9	33.3	33.3	26.8
Volumetric LHV [MJ/dm^3]	32.3	27.0	26.8	21.2
Latent Heat of Vaporization [kJ/kg]	380-500	716	579	904
Chemical Formula	Complex mixture	C_4H_9OH	C_4H_9OH	C_2H_5OH
Mass share of C [%]	86	65	65	52
Mass share of H [%]	14	13.5	13.5	13
Mass share of O [%]	0	21.5	21.5	35

Viscosity [mPa.s]	0.4-0.8	2.57	3.33	1.08
Boiling Point [°C]	199	118	108	78
Stoichiometric Air-fuel ratio	14.7	11.2	11.2	9.0
Flash Point [°C]	-43	37	28	13
Autoignition Temperature [°C]	250-300	340	415	363

These butanol isomers are less soluble in water and hold less water in solution than ethanol. In 10% ethanol-gasoline mixes, a little quantity of water is soluble. The mixture will separate into two phases if water is present above a saturation level of a few tenths of a weight percent: an ethanol-water phase and a hydrocarbon ethanol phase. Even if the ethanol-gasoline mixture is one phase at room temperature, it may separate at lower temperatures. While phase separation in the current fuel distribution system is exceedingly rare, if it does happen, the hydrocarbon-ethanol phase may no longer meet the standards for use as gasoline. A butanol-gasoline mixture may be less susceptible to phase separation because butanol is less soluble in water. This was confirmed by Christensen et al [19]. Iso-butanol has significantly higher research and motor octane numbers than n-butanol, but they are both lower than ethanol. Compared to conventional gasoline, n-butanol's anti-knock index is in the same range and thus will not cause a negative impact on engine knock. Moreover, n-butanol's high heat of evaporation provides additional charge cooling to prevent engine knock when used in gasoline direct-injection engines. This allows better engine spark timing at high loads and thus improves engine thermal efficiency. The Reid Vapor Pressure (RVP) of n-butanol is significantly lower than that of gasoline, and lower RVP helps reduce evaporative emissions, therefore RVP of gasoline is controlled to reduce unburned fuel emissions from the fuel tank and engine fuel system. While all three alcohols have a lower vapor pressure than gasoline in its pure state, they have differing effects on the vapor pressure of gasoline blends. When ethanol is blended at less than 60% by volume, the vapor pressure rises significantly. This rise is around 7 kPa for 10% mixes, as illustrated in Figure 11. Both butanol isomers, on the other hand, lower gasoline vapor pressure by around 7 kPa in the 12 percent to 15% blend range. This is a key benefit of butanol blending, as it might minimize the cost of producing low vapor pressure gasoline for summer consumption while also allowing for the blending of substantially larger amounts of lower value, high vapor pressure hydrocarbon components in the winter months [19].

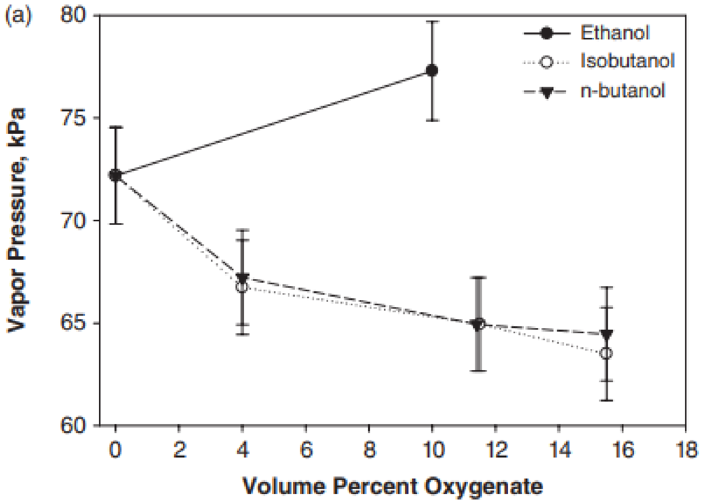


Figure 11. Effect of alcohols on gasoline vapor pressure [19]

To maintain adequate drivability in the United States, ASTM D4814 specifies restrictions on the distillation temperatures at 10%, 50%, and 90%. Blending ethanol generates a considerable drop in the 50 percent boiling temperature, as seen in Figure 12, and reformulation of the hydrocarbon blend stock may be required to achieve the standards. The 10 percent, 50 percent, and 90 percent distillation temperatures have little or no effect on the butanol isomers. None of the alcohols meet the ASTM D4814 minimum performance standards for automobile spark-ignition engine fuel, thus they can't be used directly as neat fuel [19].

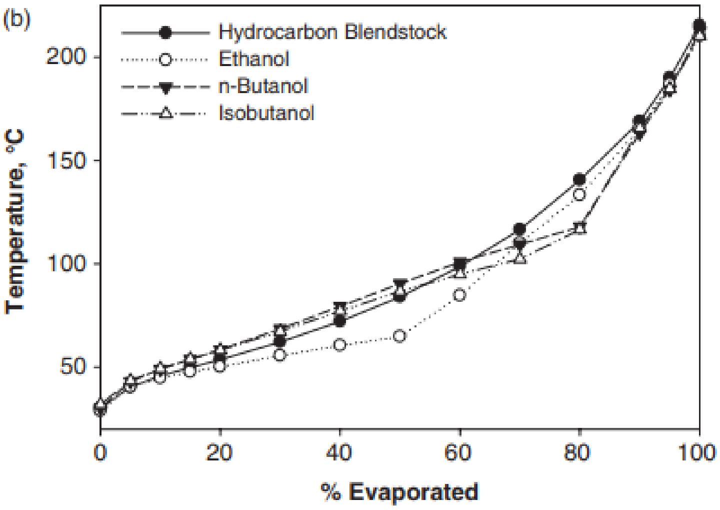


Figure 12. Effect of alcohols in gasoline blends distillation curve [19]

Combustion en-leanment ($\lambda > 1$), is one of the key problems when employing alcohol-gasoline mixes. Because fuel supply is automatically adjusted to operate near stoichiometric conditions, this is less of an issue for engines equipped with closed-loop fuel control systems. However, combustion enleanment ($\lambda > 1$), with oxygenated fuels could raise exhaust gas and engine component temperatures to levels that could damage the engine in legacy vehicles, marine, motorcycle, and small non-road engines that use fixed calibration fuel delivery systems (e.g conventional carburetors) and fixed ignition timing. Because butanol has a lower oxygen-to-carbon ratio than ethanol, at the same volumetric blending levels, it may create fewer combustion enleanment ($\lambda > 1$), issues. Another issue that needs to be addressed is material compatibility. Fuel lines, fuel tanks, fuel pumps, fuel injectors, carburetors, pressure regulators, valves, oil rings, and gaskets are among the engine components that should be examined. The compatibility of these components with ethanol blends is well established, as flex fuel vehicles capable of up to 85% ethanol have been on the market for many years. However, butanol is less corrosive than ethanol [19].

4 Fuel Quality

Before use of any fuel in the engine, its fuel qualities its material compatibility with engine, fuel systems as to be done for proper working of the engine on the fuel, also when any new fuel is feed into the engine, the engine startability that it the ability of the fuel to start the engine as to be performed and tested.

4.1 Material Compatibility

Extensive Material Compatibility of Butanol blends with gasoline was done by Oak ridge national laboratory for U.S. Department of Energy [20]. When metal specimens representing a variety of materials usually found in fuel storage and dispensing systems were immersed in nBu16 (16% n-Butanol with gasoline) and iBu16 (16% iso-Butanol with gasoline) fuel blends at 60 degrees Celsius for 28 days. The annualized corrosion rates based on weight loss were where found to be minimal, less than 1m/y corrosion rate for cartridge brass and undetectable for the other metals, and when the discolored specimens of cartridge brass and phosphor bronze were investigated, the surface of each was discovered to contain copper sulfide. The thickness of film was found to be unaffected by the amount of n-butanol iso-butanol in the fuel mix. It was found that 1100 aluminum, 1020 mild steel, 304 stainless steel, cartridge brass, phosphor bronze, 201 nickel, Cr-plated steel, Ni-plated steel, Cr-plated brass, Zn-plated steel, Ni-plated aluminum, and Pb-plated steel would be compatible with n-butanol & iso-butanol-containing fuels under the prescribed environmental conditions [4,20]. The compatibility of several elastomeric kinds with gasoline containing 16 percent n-butanol & iso-butanol was tested. Fluorocarbon, fluoro-silicone, NBR, neoprene, SBR, polyurethane, and silicone rubbers are among the materials used.

The measured mass and volume increase were found to be related to the expected solubility in general. The following is a list of elastomer kinds in order of lowest to highest degree of swelling:

- Fluorocarbon
- Fluoro-silicone
- NBR
- Polyurethane
- Neoprene
- SBR
- Silicone

In order to determine the material compatibly of the engine fuel system components and fuel wetted parts with nBu16 and iBu16 was performed by Honda, they refer to it as fuel system bench testing in their report [4]. The report concluded that all fuel system components performed within the specification after exposure to butanol test fuels as defined by test procedure and engine requirements. Changes in elastomer material properties were observed equally in baseline and butanol fuels. All fuel system components maintained in system and component function regardless of changes to material properties.

In general, we can conclude that butanol has not been found to have adverse effects on any materials typically found in gasoline fuel systems. Even though there are no adverse effects to the material compatibility of butanol, existing distribution infrastructure materials compatibility with butanol blend needs to be confirmed as well. The current producers of biobutanol (GEVO, Butamax) have done extensive materials testing through independent laboratories on existing gasoline distribution infrastructure components [4,20].

4.2 Engine Startability

Engine Startability of fuel is defined as the maximum grade that a fully laden engine combination is capable to start in and maintain the working and running on the specified fuel. Research and experimentation on engine startabilty on different blends of butanol gasoline fuels (10% n-butanol,30% n-butanol,70% n-butanol,100% n-butanol) was conducted by the author Jan Vodrážka [21], a small power generator with Spark-ignition engine KIPOR IG2000 was used for the experimentation, the ideal conditions specified by the manufacturer, i.e. an ambient air temperature of 25 °C and 30 % humidity, but also in conditions where temperatures fall below 0 °C was to be measured, so the operating the engine in the ambient temperatures in the range of -10 °C to + 45 °C was recommended by the author. On the basis of the above specified criteria, the experiment conducted by author was necessary to carry out a startability test for each fuel type to verify that the engine will run on the fuels operable at low temperatures. All the startability tests carried out, for all fuels tested, were carried out with the carburettor main jet as the default, i.e on an unmodified engine. The author mentioned that startability tests are usually carried out on specialised test stands equipped with specially modified climate chamber. Due to the unavailability of this specialised facility, the author conducted test under realistic conditions at ambient temperatures between -5 °C and +5 °C.

Before the start of each fuel test, the fuel to be tested was accompanied by the placement of a prepared device with a given type of fuel for 12 hours in an outdoor area where it was exposed to ambient temperature. Before the actual measurements began, the following were recorded by the author the actual conditions, where the ambient air temperature range for all measurements was from 0 °C to +5 °C, and then the startability test was performed. When the start of the engine was successful, the author left the engine for running at idle speed for 180 seconds and then set to a reduced idle speed, again for the same 180 seconds. At these modes, engine operation on each fuel was monitored by the author and was compared with operation on gasoline, a repeat test of startability at ambient temperature air at 22 °C was done. After metering, was done by the author the fuel was changed, flushing the entire fuel system with a new mixture and the procedure was repeated for the other fuels. The following results from the five tests conducted by the author

The first startability test was done for gasoline, as a reference fuel, on which the equipment is designed was for. The start of the engine was measured without difficulty on the third pull of the starter. The author describes engine operation was smooth for both modes and the engine held the specified speed.

For the second test, a gasoline blend with 10% n-butanol was chosen. Here the start was similar to the petrol without any problems. The author finds the engine operation for both modes was smooth, with no noticeable changes compared to the previous fuel.

The third fuel chosen was a mixture of petrol with 30 % n-butanol. In this case the author describes that the mixture did not appear to have any deterioration in behaviour and the start was successful on the fifth stroke of starter, The starter started on the fifth stroke. In idle speed mode, the author found that the engine operation was stable with no significant changes. However, in the case of the second reduced idle speed mode, he describes the engine began to exhibit speed fluctuations and its operation was not completely regular.

The Fourth test was carried out by author on a mixture of petrol with 50 % n-butanol. For this mixture the first deterioration in startability was noted by the author, with the engine requiring more than 10 strokes of the starter. For both modes, the author describes that the engine exhibited erratic operation with noticeable speed fluctuations.

The fifth startability test was carried out by author for a mixture of petrol with 70 % n-butanol. In this the author describes start was not successful even after multiple starts. For verification, the startability was repeated in the next test, but author describes it as a failed start.

On the basis of the previous unsuccessful measurement for a mixture of petrol with 70 % n-butanol, the low-temperature engine startability test for pure n-butanol (100 %) was cancelled by the author. For all concentrations of gasoline and n-butanol mixtures in the retest at propulsion laboratory at an ambient air temperature of 22 °C was conducted by the author, and he describes that the startability test were successful. So, from the experimentation and results concluded by the author, in general we can conclude that butanol blends as fuels for unmodified gasoline engine was found to have no adverse effects on engine startablity [21].

5. Performance Characteristics of Butanol blends

5.1 In cylinder pressure and Mass Fraction Burned

The two most important metrics for assessing engine combustion are In-Cylinder Pressure (ICP) and Heat Release Rate (HRR). Typically, a pressure transducer is used to directly measure the ICP. It provides in-depth information on the combustion phenomena occurring inside the cylinder cycle by cycle, giving important insight into the properties of the entire combustion process. The HRR is a measure of how quickly combustion reactions are occurring inside the chamber. HRR can be used to determine precisely when and how quickly a combination begins to burn. Typically, the HRR data is presented in relation to the crank angle position. A crucial tool for identifying combustion irregularities like misfire and knock is the HRR-crank angle diagram. As a result, the ICP and HRR are both crucial to the combustion study.ICP measurements are presented to compare the difference in cyclic variability of combustion and to quantify the difference in combustion phasing, such as ignition delay given by 0%-10% MFB, and the fully developed combustion phase, given by 10%-90% MFB. To quantify the cyclic variability of indicated work per cycle, the Coefficient of Variation of Indicated Mean Effective Pressure (COV of IMEP) can be calculated by the formula below

$$COV_{IMEP} = \sigma_{IMEP} / \text{avg IMEP} \qquad (1)$$

where σ_{IMEP} is the standard deviation in IMEP, COV_{IMEP} is defined as standard deviation of net IMEP upon mean of net IMEP and expressed in % [22].

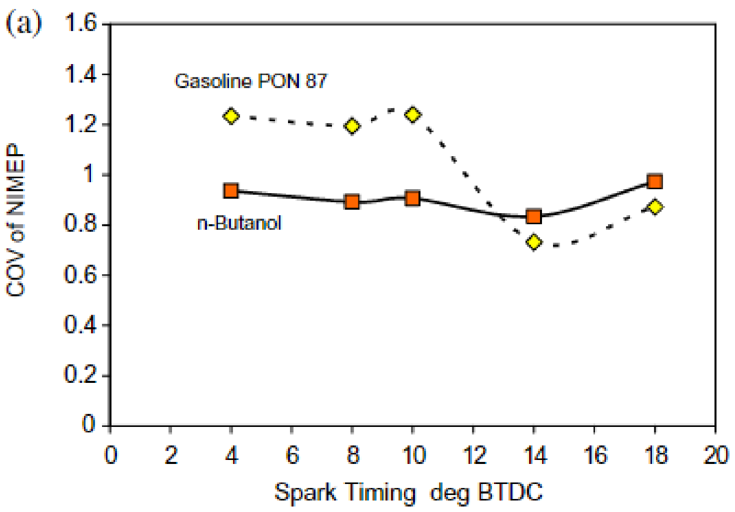


Figure 13. COV of NIMEP for n-butanol and gasoline with PON 87 vs. spark timing [22].

As presented in Figure 13, when it comes to COV value, there is minimal difference between the burning of gasoline and n-butanol. Figure 14, shows the in-cylinder pressure histories for these fuels during combustion [22].

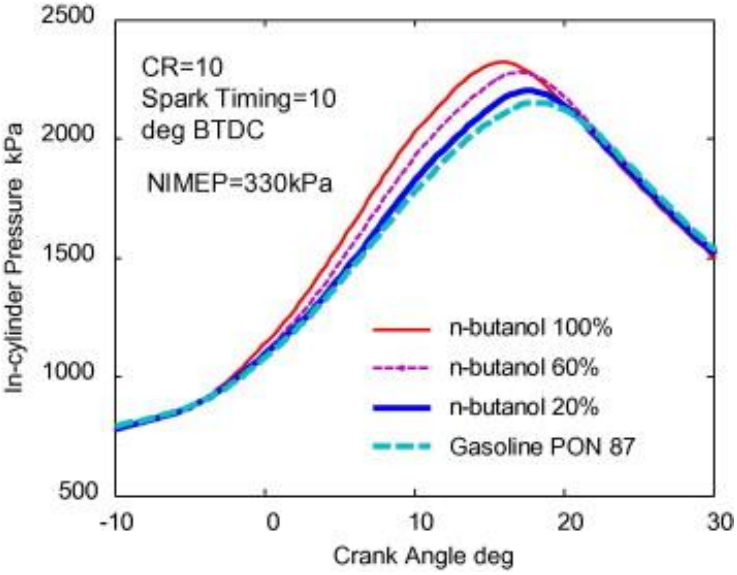


Figure 14. In-cylinder pressure traces for n-butanol-gasoline blends [22]

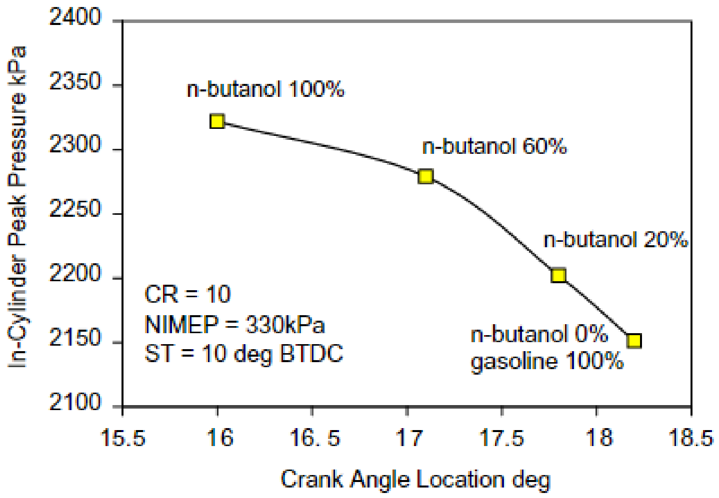


Figure 15. Location of in-cylinder peak pressure (ICP) for n-butanol–gasoline blends [22].

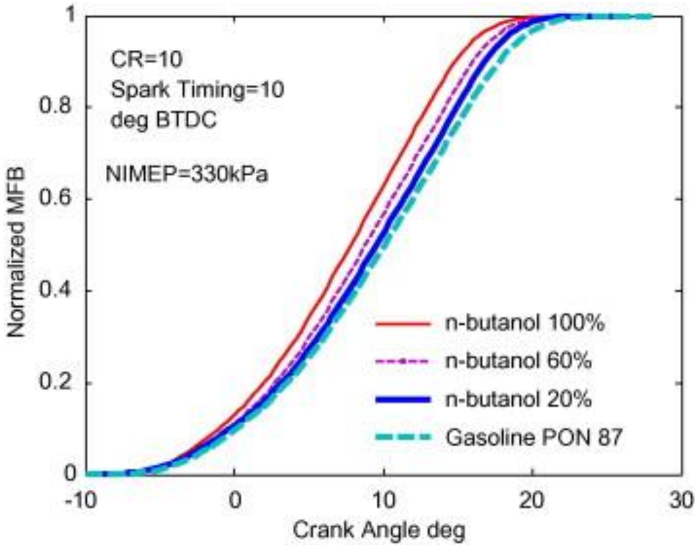


Figure 16. Normalized MFB profiles for n-butanol–gasoline blends [22].

Figure 15, demonstrates the position of the combustion peak pressure for different blends of n-butanol and gasoline fuels. As it can be observed, pure n-butanol experiences the highest peak pressure and does so earlier than other types of gasoline. This is as a result of n-butanol burning more rapidly than gasoline. Additionally supporting this conclusion are the normalized MFB (Mass Fraction Burned) profiles for these fuels shown in Figure 16. Clearly from the Figure 16, we can see n-butanol 100% burns faster or the MFB is rapid compared to gasoline, from the Figure 16, quantities as 10% MFB, 50% MFB and 90% MFB can be determined as these correspond to 0.1, 0.5 and 0.9 of normalized MFB respectively.

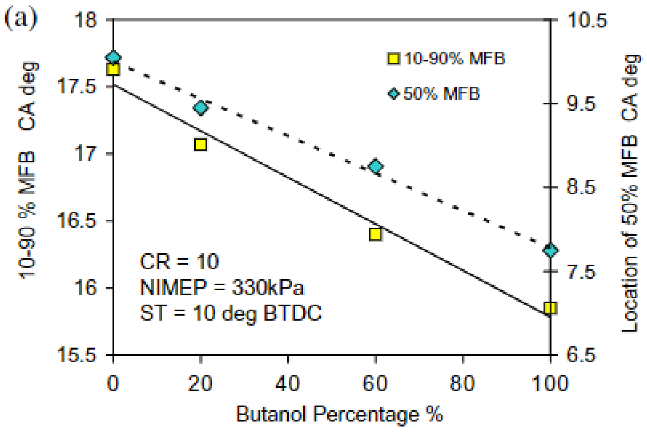


Figure 17. Combustion parameters: 10–90% MFB vs. butanol percentage [22].

From the Figure 17, when the combustion duration is calculated as a difference between 0.9 MFB and 0.1 MFB and it is expressed in degrees of crankshaft, comparing pure gasoline (17.6°) to pure n-butanol (16°), the difference in combustion period is only 10% [22]. The positioning of 50 percent MFB, which moves to an earlier position with increasing n-butanol blends, is the most crucial issue. This is due to the n-shorter butanol's ignition delay, which is shown in Figure 18.

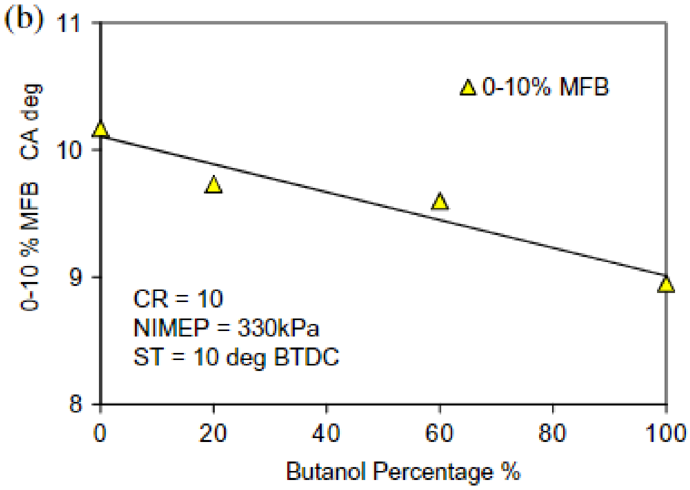


Figure 18. Combustion parameters: 0–10% MFB vs Butanol percentage [22]

The 0–10% MFB duration was used to express the ignition delay. The laminar flame speed of the fuel-air mixture affects the combustion rate during this initial phase of combustion. Later on, when the bulk flame has fully developed, turbulent flame propagation dominates the combustion. For n-butanol and gasoline, the difference between 50 percent MFB is around 2°. It has been demonstrated that the location of the 50 percent MFB, which indicates the center of combustion, has a significant impact on the engine's torque. Therefore, the spark advance needs to be changed in order to get the maximum brake torque when gasoline is substituted with n-butanol [22].

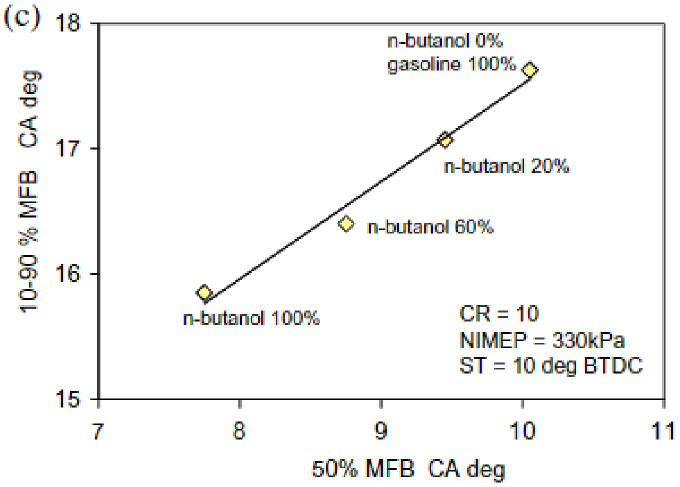


Figure 19. Combustion parameters: 0–90% MFB vs. 50% MFB butanol percentage [22].

When seen in Figure 19, as the butanol fraction in the blends increases, the ideal 50 percent MFB decreases from 10 to roughly 8° after TDC. Increased n-butanol percentage reduces the length of combustion, but the relative change in combustion rate is minimal. The rate of normalized MFB, which can be thought of as having a profile similar to heat release rate, is shown in Figure 20. As the n-butanol fraction rises, as shown in the Figure 20, the rate profile advances. However, the regular MFB peak rate doesn't change [22]. Over the range of invested n-butanol fractions, the rise in early combustion rate increases. In conclusion, it has been demonstrated that under these circumstances, the normalized MFB and MFB rate do not significantly alter with n-butanol fraction. With a higher n-butanol content, the combustion phasing relative to the spark timing does advance. The n-butanol proportion should be taken into account while adjusting or controlling the spark timing for optimal combustion phasing.

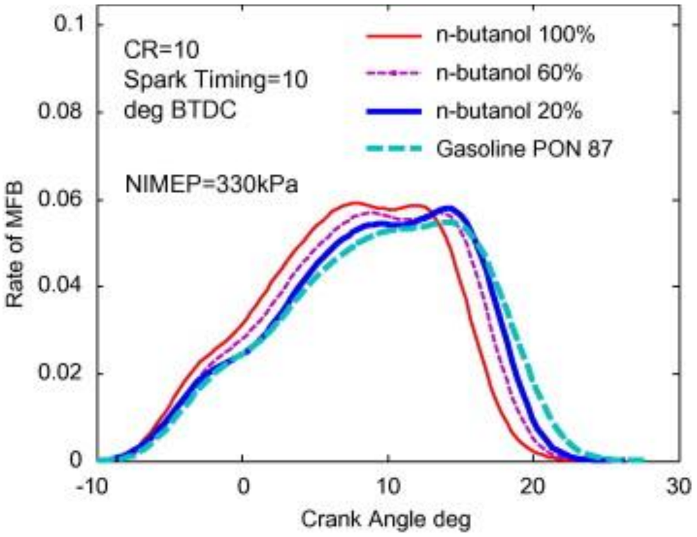


Figure 20. Rate of MFB for several n-butanol share of butanol–gasoline mixture [22].

5.2 Engine torque and brake power

Torque is a turning force produced by the pressure from the crankshaft of the piston. Engine torque depends on engine displacement, charge condition, and average effective cylinder pressure, Due to the characteristics of the fuel and the effective pressure produced, torque varies under a constant engine state when different fuels are used. According to Elfaskhany [23], the addition of n-butanol caused a minor decrease in the output torque and power, as seen in Figures 21 & 22. The author also discovered that engine performance decreased in direct proportion to the amount of n-butanol utilized in the blends. This decrease was expected because butanol had a lower volumetric efficiency than gasoline due to its lower calorific value and saturation pressure. Low percentages of butanol (0, 3, 7 and 10 vol. percent) were used in the experiment. The fuel system was left unaltered, and the single-cylinder engine operated at a range of rpms between

2600 and 3400. The performance would be drastically reduced if n-butanol was added in excess of 10% vol% without a significant reduction in exhaust emissions. Because n-butanol is more resistant to knocking than gasoline, the author suggested that increasing the compression ratio and modifying the ignition timing could improve engine performance [23].

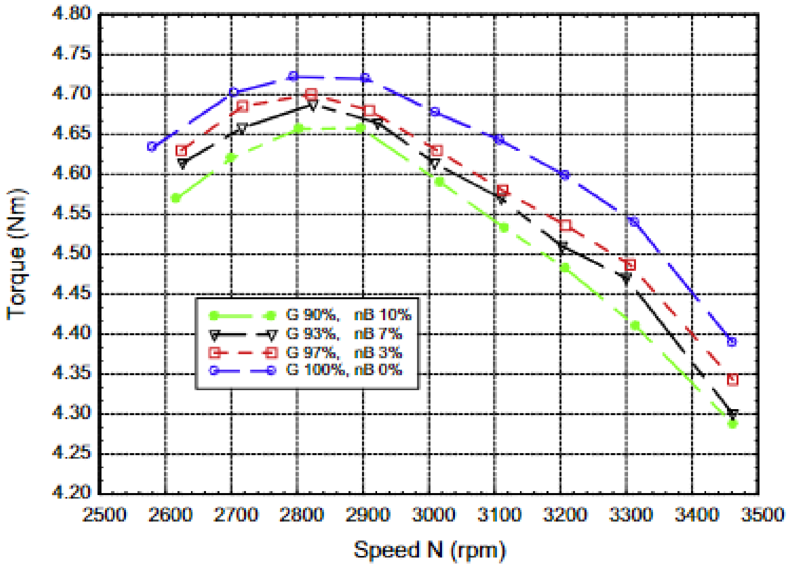


Figure 21. Variation of engine torque as a function of engine speed for different percent butanol-gasoline blends [23].

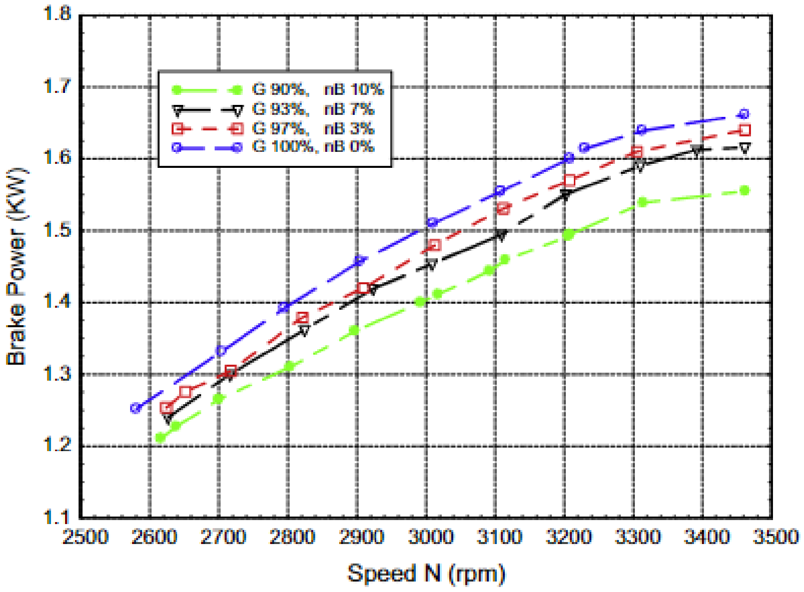


Figure 22. Variation of engine brake power as a function of engine speed for different percent butanol-gasoline blends [23].

So, from the Figures 21 & 22, we the author observed that blending butanol with gasoline reduces the engine torque and brake power as the engine speed increases from 2500 to 3500 rpm. Another study done by the author Yusoff [24] shown in the Figure 24, shows the variations of engine torque for butanol isomers gasoline blends at different engine speeds, the author concludes that the engine torque increases steadily up to 4000 rpm and decreases thereafter for all fuel blends due fuel choking. The author observed the maximum engine torque measured at 4000 rpm for the Bu0, nBu20, sBu20, tBu20, and iBu20 blends, respectively, is 132, 135, 134, 133, and 136 Nm [24].

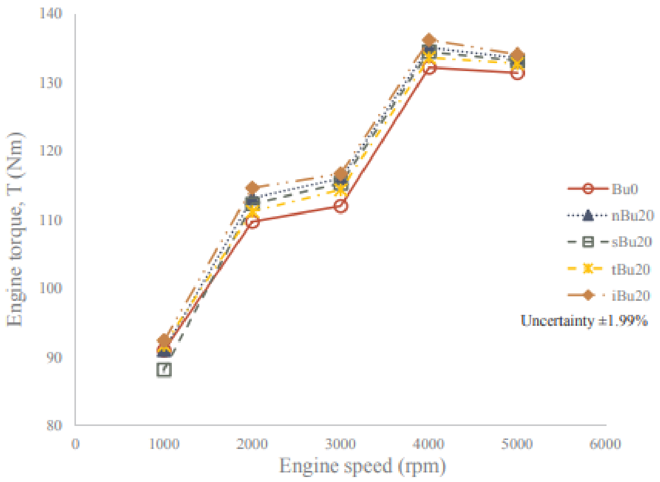


Figure 23. Variation of engine torque as a function of engine speed for all butanol isomer-gasoline blends [24].

So, from the Figure 23, the author observed that blending butanol isomers with gasoline improves the engine torque as the engine speed increases from 2000 to 5000 rpm. When calculated the nBu20, sBu20, tBu20 and iBu20 blend have higher engine torque, with an average increment of 2.19, 1.24, 1.28 and 3.08%, respectively, relative to Bu0, the high Heat of Vaporization of the fuel blends, which causes the fuel to evaporate in the intake manifold and combustion chamber, is what causes this increase in engine torque. The fact that the charge temperature drops as the alcohols evaporate accounts for the increased heat of vaporization. Additionally, butanol adds oxygen to the gasoline, making the combination leaner than with pure gasoline. This boosts the engine torque while also increasing the efficiency of fuel combustion.

Another study by a different author shown in Figure 24, gives us relationship between engine torque and spark timing for different percentage of butanol-gasoline blends Bu0, Bu10, Bu30, Bu40, Bu100, we can observe that the peak brake torque occurs almost for all percentage of butanol gasoline blends at 25 °CA BTDC [25].

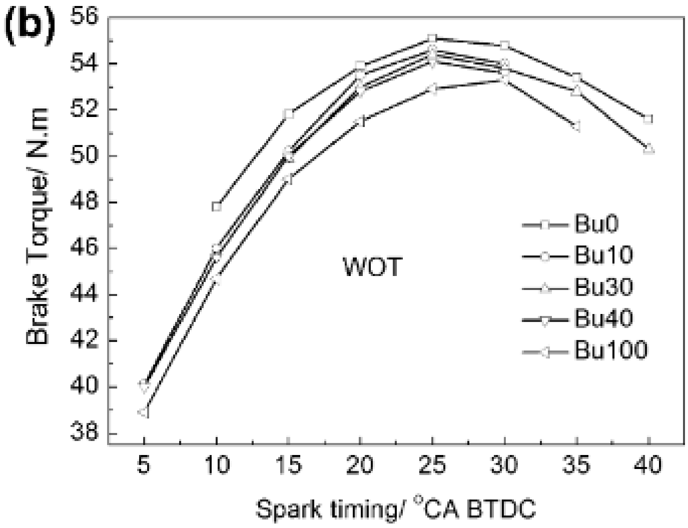


Figure 24. Variation of engine torque as a function of spark timing for different percentage of butanol-gasoline blends [25]

For all butanol isomer-gasoline blends. Figure 25, by the author Yusoff [24] illustrates how brake power varies as a function of engine speed. It is clear that as engine speed is increased from 1000 to 5000 rpm, the brake power increases approximately linearly. Similar to engine torque, the author concludes that none of the blends significantly affect brake power. In comparison to gasoline, the brake power of the nBu20, sBu20, tBu20, and iBu20 blends is higher with a slight increase of 1.36, 0.46, 0.03 percent, and 1.73 percent, respectively. Since butanol isomers are essentially oxygenates, adding them to gasoline raises the blends' octane rating, lowering their propensity for auto-ignition and raising their brake power. Additionally, the high latent Heat of Vaporization of the butanol isomers, particularly iso-butanol and n-butanol, contributes to the fuel-air charge cooling. In turn, this raises the density of the intake air, which enhances engine power [24].

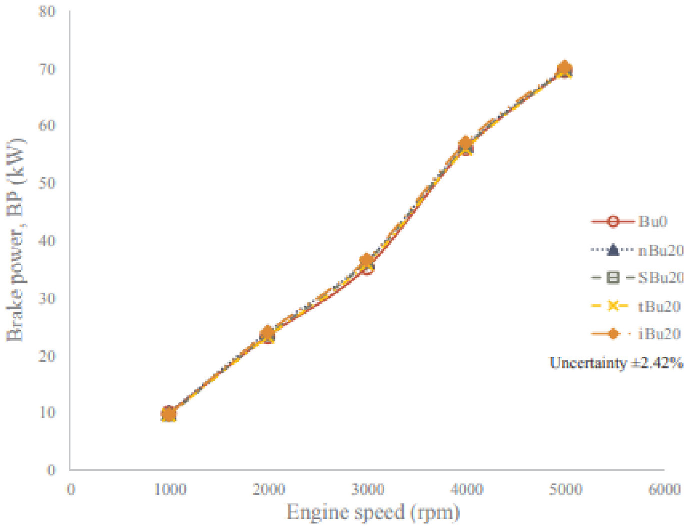


Figure 25. Variation of brake power as a function of engine speed for all butanol isomer-gasoline blends [24]

Using pre-blended alcohol-gasoline fuels throughout the entire process makes it practically hard to attain the greatest performance. We require a system that can alter the fuel ratio like closed loop oxygen feedback sensor present in modern engines. The issue might be resolved with a dual-injection system that allows for adjustment of the fuel ratio. There aren't many studies looking into two separate fuel injection systems using butanol and gasoline. The dual-injection system enables the independent injection of butanol and gasoline utilizing two distinct injection methods. While gasoline is pumped directly into the cylinders or the intake ports, butanol is supplied from the latter or the former. This allows for the autonomous ordering of fuel according to engine load and speed.

5.3 Brake thermal efficiency

The brake thermal efficiency (BTE) is the kind of engine thermal efficiency which is the ratio of the brake power at the engine crankshaft to the power generated by the combustion of the fuel. The brake thermal efficiency shows the amount of power taken by the engine crankshaft out of total power generated by the combustion of the fuel. The change of BTE for butanol isomer-gasoline blends as a function of engine rpm is depicted in Figure 26. The author states that when engine speed increases from 1000 to 5000 rpm, the BTE rises as well. The author notices that particularly at lower engine speeds that pure gasoline has a larger BTE than butanol isomer-gasoline mixtures, this is because the butanol isomers' greater auto-ignition temperatures and Heat of Vaporization decreases butanol and air mixing, which lowers combustion efficiency and thermal efficiency at lower engine speeds. However, author specifies that for all gasoline blends, especially iBu20, the BTE improves at higher engine speeds (4000–5000 rpm). The butanol fuel blends absorb heat at higher engine speeds in order to evaporate, which improves air-fuel mixing during the compression stroke and raises the BTE.

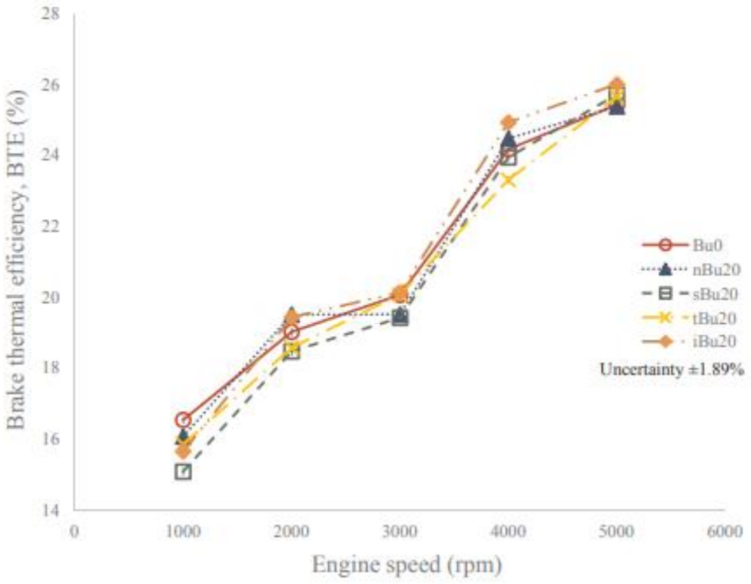


Figure 26. Variation of brake thermal efficiency as a function of engine speed for all butanol isomer-gasoline blends [24].

5.4 Brake specific energy consumption

Brake specific fuel consumption (BSFC) is the ratio of a mass flow rate of the fuel supplied to the engine to the brake power obtained at a crankshaft and it indicates how efficiently the fuel is used to produce brake power. The variations of the BSFC as a function of engine speed is shown in Figure 27, for all butanol isomer-gasoline blends. For all gasoline mixes, the author has shown that the BSFC falls off as engine speed rises up to 5000 rpm. This is a result of the rising BTE. In comparison to pure gasoline, the author indicates that there is a minor increase in the BSFC for the nBu20, sBu20, tBu20, and iBu20 blends, with average improvements of 4.95, 7.58, 6.22, and 3.75 percent, respectively. Because of this, the author states that butanol isomer gasoline blends need to use more fuel to provide the same level of engine power. Because butanol isomers have lower heating value (LHV) than pure gasoline, higher BSFC than pure gasoline was observed for butanol isomers. The LHV for pure gasoline, nBu20, sBu20, tBu20, and iBu20 are 43.46 MJ/kg, 41.96 MJ/kg, 41.90 MJ/kg, 41.77 MJ/kg, and 41.90 MJ/kg, respectively. This results in butanol blends having higher BSFC than gasoline [24].

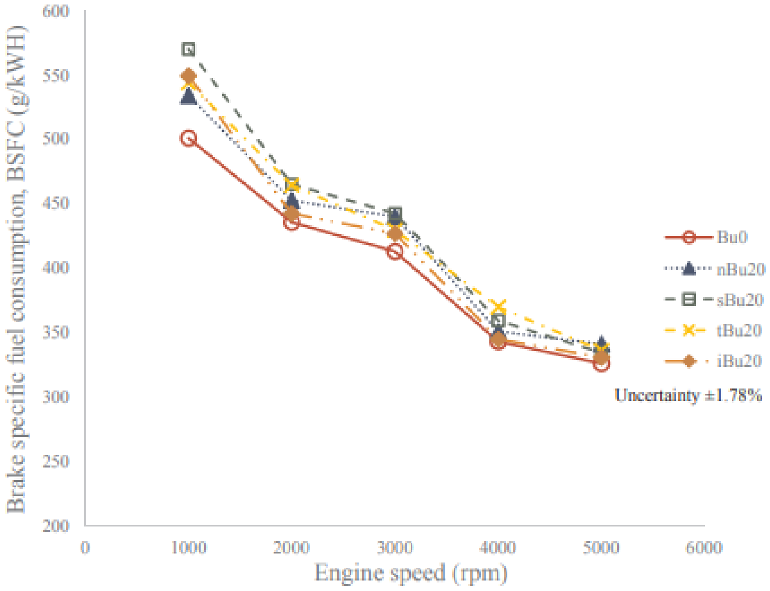


Figure 27. Variation of brake specific fuel consumption as a function of engine speed for all butanol isomer-gasoline blends [24].

Figure 28, by a different author depicts BSFC for different percentage of butanol-gasoline blends, Brake specific fuel consumptions of Bu10, Bu30, Bu40 and Bu100 are higher than that of Bu0 (gasoline pure), the author mentions that the increase in lower heating value of n-butanol is the main cause of Bu100 and its blends' increased fuel consumption. For all blends, the lowest BSFC is displayed at about 25 °CA BTDC [25].

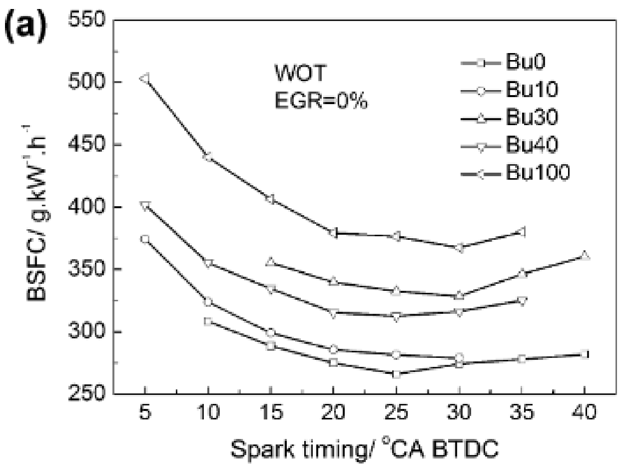


Figure 28. Variation of brake specific fuel consumption as a function of spark timing for different percentage of butanol-gasoline blends [25].

5.5 Exhaust gas temperature

For all butanol isomer-gasoline blends, the variation in Exhaust Gas Temperature (EGT) as a function of engine speed is shown in Figure 29, the author observed that at lower engine speeds, that the EGT for the butanol isomer-gasoline mixes is marginally lower than for pure gasoline, this is due to butanol isomers' higher latent heat of vaporization which causes the in-cylinder temperature to drop at the end of the compression stroke, which then lowers the EGT at the conclusion of combustion. The LHV of the butanol isomers also contributes to the decline in EGT, so the author concludes that the alcohol-gasoline mixtures improve full combustion, which lowers the combustion temperature and EGT. Intriguingly, at higher engine speeds (4000–5000 rpm), the EGT of the butanol isomer–gasoline mixtures are marginally higher than that for pure gasoline, this is due to ignition delay, fuel atomization and fuel enleanment, and the production of combustible mixtures, results in higher EGT. The iBu20 blend has the highest EGT at 5000 rpm (with a percentage difference of 3.1 percent relative to pure gasoline). All of these raise the EGT [24].

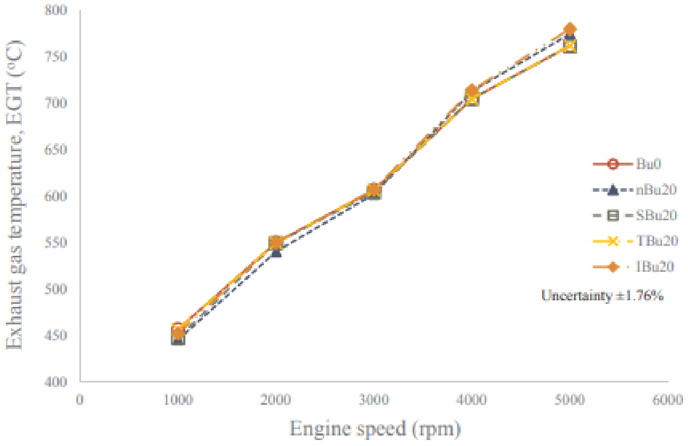


Figure 29. Variation of exhaust gas temperature as a function of engine speed for all butanol isomer-gasoline blends [24].

5.6 Knock Phenomenon

An internal combustion engine's performance and efficiency can be improved by increasing the compression and intake pressure ratios. However, knock phenomena limits the growth of those two ratios. Downsizing is also frequently chosen as a successful strategy to fulfill the two goals of increasing the fuel economy and power density of gasoline engines. On the other hand, it will raise the temperature and pressure inside the cylinder, which will cause abnormal combustion, including the knock. The knock problem must therefore be resolved as a priority in order to improve both performance and efficiency. Because of its high-octane rating, butanol is a promising alternative fuel because it has anti-knock qualities. When we analyze how n-butanol blends burn in a DI SI engine.

Study by Wei et al. [26] found that n-butanol has increased the Knock Limited Spark Timing (KLST) from 27 to 32 BTDC, which improves knock resistance, according to Figure 30. Compared to gasoline, the knock resistance of the Bu20 blend was somewhat weaker, but much higher when compared to neat butanol. Furthermore, combustion chamber resonance modes frequently affect the knock oscillation frequency. The probability distribution was employed in this study to evaluate the knock intensity variation [26]. When Wei et al. [27] sought to comprehend the impact of Exhaust Gas Recirculation (EGR) on the n-butanol knocking combustion behaviors as well as the sensitivity of the n-butanol knocking phenomena to constant intake pressure and compression ratio. The author’s findings demonstrated that EGR could lessen knock severity and postpone the timing of knock commencement due to cooling and dilution effects. The knock intensity was significantly reduced by the low EGR rate (3 percent), but the result was minimal in the pressure of combustion. The addition of n-butanol had less variance in combustion under a specific EGR rate. This was because it had a more concentrated probability distribution for knock intensity than gasoline does. This study revealed that the usage of EGR on SI with a constant high compression ratio and high input pressure [27].

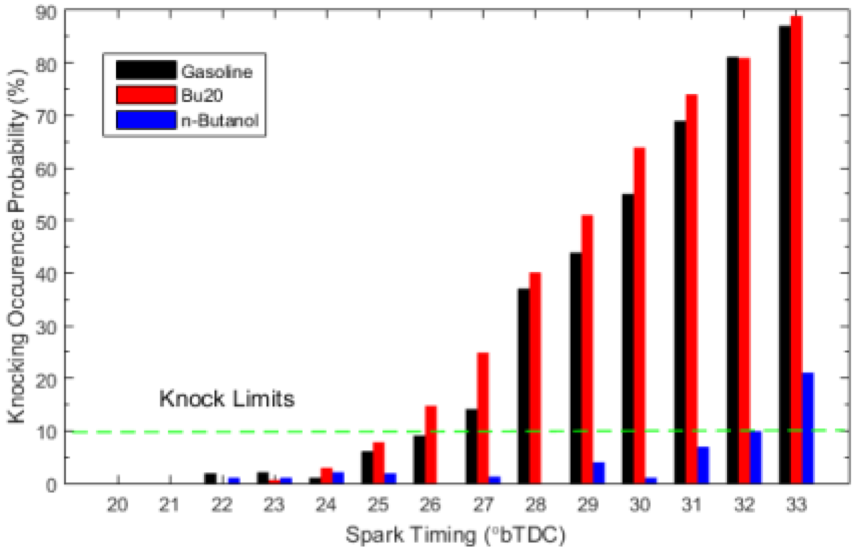


Figure 30. Knocking occurrence probability of butanol/gasoline blends [26]

6. Pollutants

Air Pollution leads to major health issues, particularly respiratory and cardiovascular issues. Growing global concern about THC (total hydrocarbon) and other combustion-related contaminants, NOx, SOx, CO, CO_2, acid rain, and photochemical pollution and particulate matter.

There are three types of vehicle emissions, shown in the Figure 31 [28].

- Exhaust Emissions- Emissions created by the combustion of petroleum fuels such as gasoline, diesel, natural gas, and LPG, which are hydrocarbon mixes. There is no such thing as a flawless engine that produces no pollution.
- Abrasion Emissions: These are emissions created by mechanical abrasion and corrosion of car parts. It is in responsible of particulate matter emissions. Mechanical abrasion of tires, brakes, and clutches, road surface wear, chassis corrosion, and other vehicle components all contribute to this issue.
- Evaporative Emissions- Emissions created by vapors evaporating from a vehicle's fuel. This occurs when VOCs are used. Whether the vehicle is stopped with the engine switched off or operating with the engine turned on, petrol fuel vapors containing various hydrocarbons attempt to escape from the fuel tank.

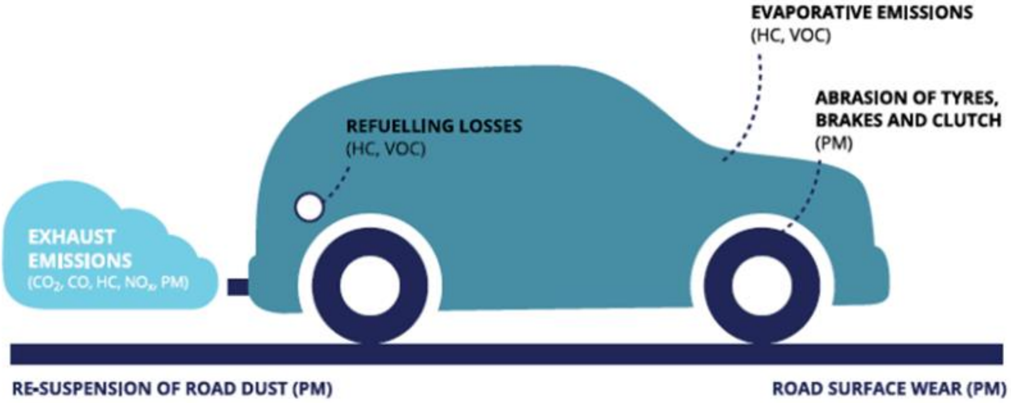


Figure 31. Types of emissions from vehicles [28]

Under EU road transport legislation, there are some ‘regulated’ pollutants [28]

- Hydrocarbons (HC), which are created when combustion is incomplete or partial, these are classified as volatile organic compounds (VOC), to ground-level ozone, which causes irritation in the skin, eyes, and respiratory tract and breathing difficulties, it also causes photochemical haze in the atmosphere which is a major source of concern.
- Carbon monoxide (CO) is a poisonous gas created by incomplete (or partial) combustion, when the carbon is partially oxidized, resulting in incomplete oxidation of CO owing to a lack of oxygen. CO exposure could cause a decline in flow of O_2 levels in the bloodstream. It's a colorless, odorless, and poisonous gas.
- Carbon dioxide (CO_2) is formed when fuel is completely burned and complete oxidation of CO. It is the most significant source of greenhouse gases, which affects climate change and, indirectly, human health and the environment.
- Nitrogen oxides (NOx), produced during the combustion of fuel in presence of air inside the engine. NOx is made up of two compounds: Nitric Oxide (NO), a colorless gas and created in the combustion process, and Nitrogen dioxide (NO_2), a toxic reddish-brown gas that has an adverse effect on human health and the environment. In modern diesel cars, NOx is particularly prevalent.
- Particulate Matter is a term used to describe very small particles created by incomplete combustion or tyre and brake wear. These are harmful to human health since they can enter the respiratory system and cause cardiovascular and pulmonary disorders, as well as lead to cancer [29].

6.1 Pollutant Formation

6.1.1 Formation of NO_x

The majority of NOx is created by automobiles, railways, shipping, airways, and factories, with a small amount coming from agriculture using nitrate fertilizers

[30]. NOx is generated when oxygen and nitrogen split into their atomic states at temperatures above 1800K [30]. In three equations, Zeldovich extended mechanism has demonstrated this:

$$N_2 + O = NO + N \qquad (2)$$

$$N + O_2 = NO + O \qquad (3)$$

$$N + OH = NO + H \qquad (4)$$

Zeldovich developed the first two equations for NO production, while Lavoie contributed the third equation. NO_2, which is emitted from the exhaust of diesel engines, is also considered toxic. At high temperatures in the flame area, NO_2 is generated from NO. The formation of NO_2 is depicted below.

$$NO + HO_2 = NO_2 + OH \qquad (5)$$

$$NO_2 + O = NO + O_2 \qquad (6)$$

In the second equation, local quenching and cooling cause NO_2 to dissolve into NO in the presence of atomic oxygen. The major elements in the creation of NO are a higher temperature and the presence of oxygen. The majority of NOx generation occurs during the combustion process, when air and fuel are mixed, igniting combustion quickly and resulting in a high temperature. Similarly, because of the prolonged period of combustion, Similar to the high temperature scenario, prolonged combustion duration results in the generation of NOx, but in larger concentrations.

6.1.2 Carbon Monoxide CO

Carbon monoxide is an odourless, colourless, flammable gas. It is a highly poisonous component of exhaust fumes and is fatal to humans if inhaled. It is formed from the combustion of carbon fuels at low temperatures and in the absence of combustion air (oxygen) without complete oxidation of the hydrocarbons to carbon dioxide and water vapour. The amount of this gas is dependent on the richness of the mixture (λ air/fuel ratio value), with decreasing air/fuel ratio (lambda value), the CO content increases in direct proportion. At normal concentrations in air, it oxidises to harmless carbon dioxide (CO_2).

6.1.3 Carbon dioxide CO_2

This non-toxic, colourless gas is the product of complete combustion (oxidation) of the carbon contained in hydrocarbon fuels. At higher concentrations it becomes a dangerous to humans, with the risk of unconsciousness and death. Rising CO_2 levels contributes to the so-called greenhouse effect, which is the cause of rising temperatures of the atmosphere.

6.1.4 Unburned Hydro Carbons UHC

Exhaust gases include various types of hydrocarbons such as unburned hydrocarbons contained in the fuel, their oxidation products and hydrocarbons produced by thermochemical reactions during combustion. Similar to carbon monoxide, they are produced by hydrocarbons from incomplete combustion. Unburned hydrocarbons are the result of incomplete oxidation reactions in certain zones of the combustion chamber (cooling in close to the cylinder walls) or by a malfunction or even an omission of combustion. Contents of unburned hydrocarbons is greatly influenced by the engine temperature regime, engine misfire, the design of the combustion chamber, the physical properties and chemical composition of the fuel and in last but not least, the richness of the fuel mixture (air excess coefficient λ). Unburned hydrocarbon content, the optimum mixing ratio is in the slightly around lean mixture ($\lambda = 1{,}1 \div 1{,}2$), with both higher and lower values of the air excess coefficient leads to an increase in the concentration of unburned hydrocarbons in the exhaust gases. Among most dangerous hydrocarbons in exhaust gases are polycyclic aromatic hydrocarbons (PAHs), which are formed by the polymerisation of other hydrocarbons with ring bond and by pyrolysis of HC. This group of the heaviest hydrocarbons belongs to the group of cancer-causing substances. These hard-to-evaporate hydrocarbons are found in the exhaust gases, which are often bound to another pollutant, particulate matter PM. Unburned hydrocarbons, together with nitrogen oxides, contribute significantly to smog formation and tropospheric (ground-level) ozone [29].

6.1.5 Particulate Matter

Particulate Matter is made up of a variety of particle sizes and chemical compositions. Particulate matter is divided into several categories based on their size. PM10 and PM2.5 are very minute particles that can be ingested. Particles having an aerodynamic diameter of 10µm or less are classified as PM10, and particles with an aerodynamic diameter of 2.5µm or less are classified as PM2.5, Figure 32, shows the sizes and classifications in further detail [29].

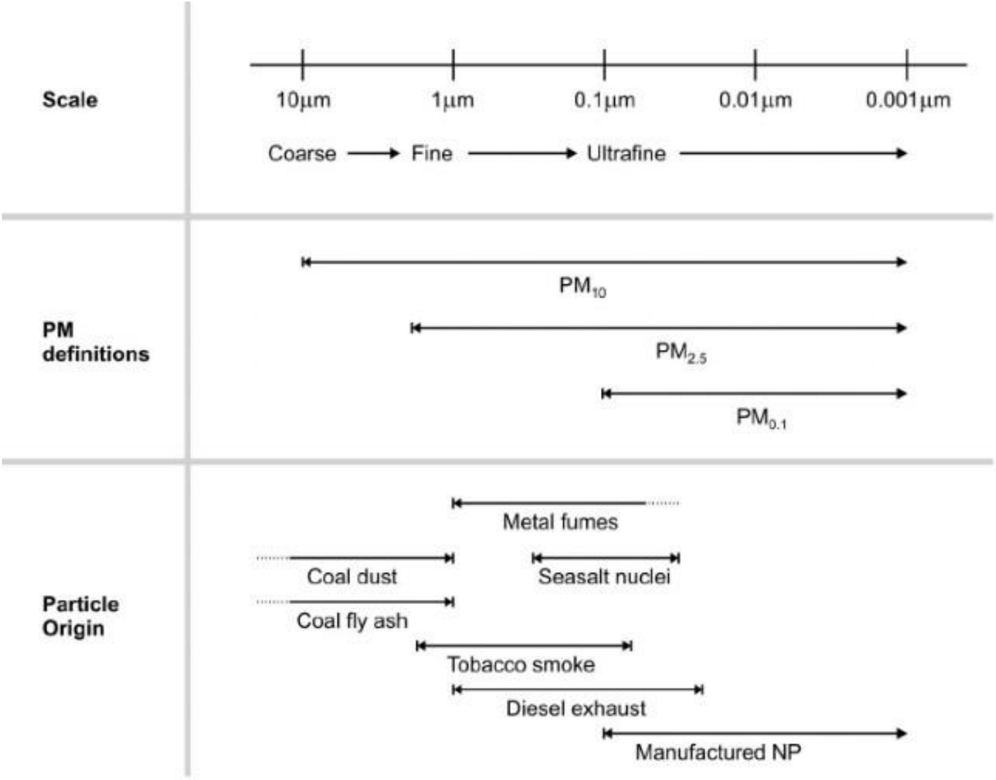


Figure 32. Particle Matter sizes and classification and common sources [Mühlfeld, Christian, et al (2008)][29]

.

Soot particles are pollutants produced by internal combustion engines. These are generated at a temperature of 1000K to 2500K and a pressure of 50atm to 100atm in the presence of enough air to complete the fuel combustion. Nucleation, growth, agglomeration, and adsorption and condensation are the four stages of soot formation shown the Figure 33 [30]. The condensed materials from the fuel are formed in the nucleation phase by oxidation or pyrolysis products, which are mostly unsaturated hydrocarbons and polycyclic aromatic hydrocarbons. This interaction produces nuclei, which are the smallest identifiable particles with a diameter of less than 2nm.

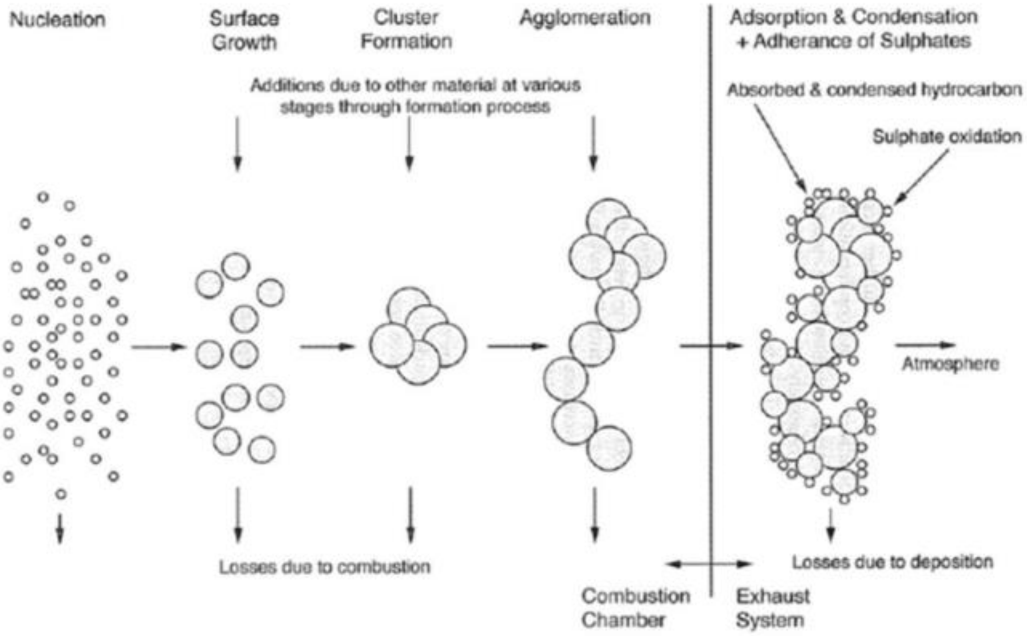


Figure 33.Phases of formation of diesel soot particles [30]

6.2 Health Effects of Pollutants

The respiratory system is adversely affected by NOx. This produces inflammation in the respiratory system's airways, leading in decreased lung function, infections, and an increased allergic response. Not only is a high level of NOx harmful to one’s health, but it also harms the ecosystem. Disease and frost damage become increasingly prevalent in the vegetation. The leaves are damaged as a result, and the plant's growth is slowed. In the presence of sunshine, NOx combines with other pollutants to generate ozone, which is extremely toxic to plants. Long-term exposure to particulate matter is also fatal as it can cause harm to the heart and lungs. Premature death, nonfatal heart attacks, irregular pulse, worsened asthma, impaired lung function, and respiratory infections are all possible outcomes.

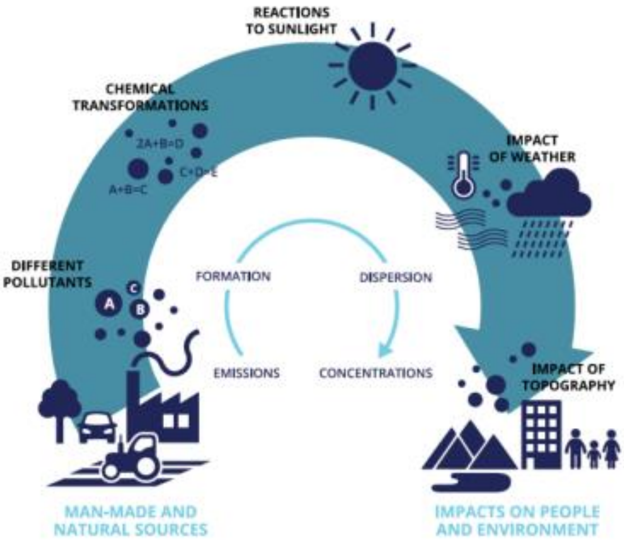


Figure 34.Process of impact of emissions

The smaller the particle size, the more probability of entering the human body and cause damage. The presence of particulate matter in atmosphere reduces visibility. These are occasionally carried by the wind and settle on the land and water, causing acidification of water bodies, depletion of soil nutrients, crop damage, and acid rain shown in Figure 34.

6.3 European Legislation

6.3.1 Air quality Standards

The biggest environmental health risk in Europe is air pollution, which causes respiratory and cardiovascular illnesses that shorten healthy life spans and, in the worst circumstances, result in premature death. According to both EU air quality standards and the WHO recommendations, which were amended in 2021, this briefing shows the state of pollutant concentrations in ambient air in 2020 and 2021, broken down by pollutant. The analysis demonstrates that concentrations frequently surpass the most recent WHO recommendations for air quality throughout the EU. However, in 2020, lockdown measures put in place to stop the spread of COVID-19 temporarily reduced the amount of air pollution generated by vehicular transportation and improved air quality.

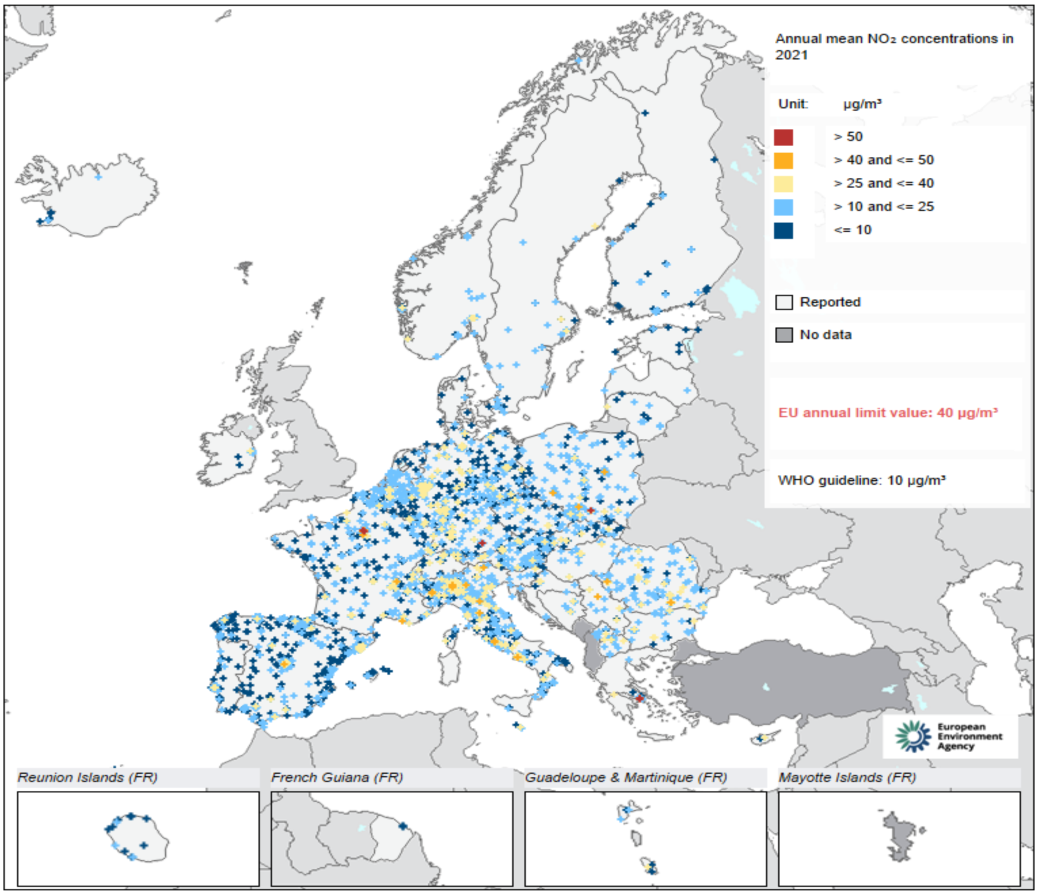


Figure 35. Annual mean concentrations of NO2 in 2021 [31]

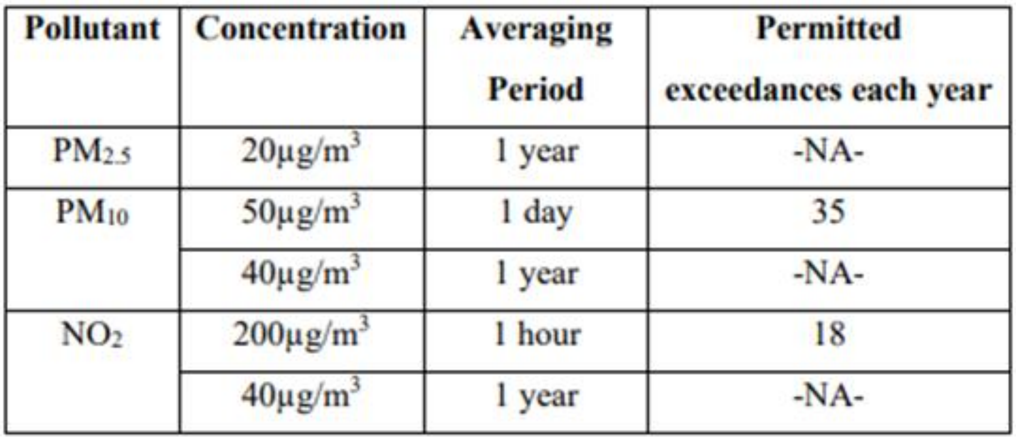
Road transportation is the main source of nitrogen dioxide (NO_2), which it emits near to the ground, primarily in densely populated areas, increasing population exposure. Energy supplies and industrial combustion processes are further significant sources. In larger, more heavily populated cities around Europe, the largest concentrations were discovered. This air pollutant definitely felt the effects of the COVID-19-related lockout measures in 2020 because the amount of its primary source, road transport, was drastically decreased shown in the Figure 35. The average decline in annual mean NO_2 concentrations ranged from 10% to 19% in the 10 EU Member States most impacted by the first wave of lockdowns (ETC/ATNI, 2021/16, forthcoming). NO_2 annual mean levels decreased by as much as 25% in France, Italy, and Spain (EEA, 2020)[31].

Concentrations of NO_2 in 2021

From Figure 35

- 8 reporting countries, including 7 EU Member States, registered values above the annual limit value of 40 µg/m^3
- All 35 reporting countries registered values above the WHO annual guideline of 10 µg/m^3
- All reporting countries registered values above the WHO daily guideline of 25 µg/m^3

Table 5. Air quality standards for PM2.5, PM10, NO2 [30]



Pollutant	Concentration	Averaging Period	Permitted exceedances each year
$PM_{2.5}$	20µg/m^3	1 year	-NA-
PM_{10}	50µg/m^3	1 day	35
	40µg/m^3	1 year	-NA-
NO_2	200µg/m^3	1 hour	18
	40µg/m^3	1 year	-NA-

Table 5. details the maximum limit for European Air quality standards for PM2.5, PM10, NO_2

6.3.2 Emission Standards

The European commission has set standards for emission of pollutants from non-road small Spark Ignition Engines considering air pollution level which should be followed by the manufacturers. Below are the emission standards for SH (hand-held small SI engines) and SN (Non-handheld small SI engines) in g/kWh are shown in Tables 6, 7 & 8.

Table 6. EU Stage I/II emission standards for small SI engine below 19KW [32]

Stage	Date	Displacement [cm^3]	CO[*g/kWh]*	HC[*g/kWh]*	NOx[*g/kWh]*	HC+NOx [*g/kWh]*
SH:1	2004.08.11	$V < 20$	805	295	5.36	-
SH:2	2004.08.11	$20 \leq D < 50$	805	241	5.36	-
SH:3	2004.08.11	$V \geq 50$	603	161	5.36	-
SN	2004.08.11	$V < 66$	519	-	-	50
SN	2004.08.11	$66 \leq V < 100$	519	-	-	40
SN	2004.08.11	$100 \leq V < 225$	519	-	-	16.1
SN	2004.08.11	$V \geq 225$	519	-	-	13.4
SH:1	2007.08	$V < 20$	805	-	-	50
SH:2	2007.08	$20 \leq D < 50$	805	-	-	50
SH:3	2007.08	$V \geq 50$	603	-	-	72
SN	2007.08	$V < 66$	610	-	-	50
SN	2007.08	$66 \leq V < 100$	610	-	-	401
SN	2007.08	$100 \leq V < 225$	610	-	-	16.1
SN	2007.08	$V \geq 225$	610	-	-	12.1

* Additionally, NOx for all engine classes must not exceed 10 g/kWh

Table 7. Stage V emission standards for hand-held SI engines below 19 kW (NRSh) [32]

Category	Displacement [cm^3]	Date	CO[*g/kWh]*	HC+NOx [*g/kWh]*
NRSh-v-1a	V < 50	2019	803	50
NRSh-v-1b	V ≥ 50	2019	602	72

Table 8. Stage V emission standards for non-hand-held SI engines below 56 kW (NRSh)[32]

Category	Power [kW]	Displacement [cm^3]	Date	CO[*g/kWh]*	HC+NOx [*g/kWh]*
NRS-vr/vi-1a	P < 19	80 ≤ V < 225	2019	610	10
NRS-vr/vi-1b	P < 19	V ≥ 225	2019	610	8
NRS-v-2a	19 ≤ P < 30	V ≤ 1000	2019	610	8
NRS-v-2b	19 ≤ P < 30	V > 1000	2019	4.4	2.
NRS-v-3	30 ≤ P < 56	any	2019	4.4	2.7

** Or any combination of values satisfying the equation (HC+NOx) × CO0.784 ≤ 8.57 and the conditions CO ≤ 20.6 g/kWh and (HC+NOx) ≤ 2.7 g/kWh

7. Experimental Setup

In this experiment four different fuels gasoline, iso-butanol, n-butanol and for comparative study on alcohols ethanol was used in small SI engine, subjected to detect combustion emissions with the help of three different instruments. The experiment was conducted on 27th and 28th of August. A four-stroke, petrol engine is used to power this inverter power plant, air-cooled single-cylinder engine, Kipor IG2000 mobile inverter power plant show in Figure 36 with ignition engine is used with variable speed and variable load, subjected three instruments used were PEMS (Portable On-Board Emissions Monitoring System), AMA, FTIR (Fourier Transform Infrared Spectrometer).

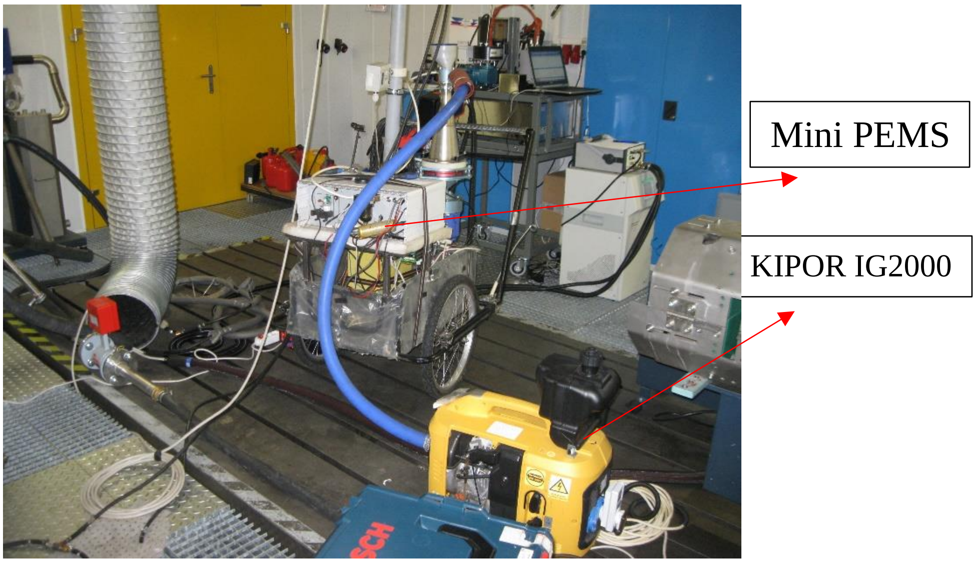


Figure 36. Experiment Setup

7.1 Electric Generator KIPOR IG2000 inverter

An electric generator is a device that produces electric current by means of an alternator. This device serves as an independent source of electricity or as a backup source in in the event of a power failure. Power generators are available in many designs as mobile digital generators, usually single-phase, stationary three-phase generators, depending on the type of fuel, then with petrol, LPG or diesel engine. The different types generators differ from each other in their power, dimensions and weight. Electric generators find their application in a wide range of fields and professions, from domestic use to professional use. Power generators equipped with AVR control can also supply appliances sensitive to voltage fluctuations, such as computer technology or medical equipment. For this work, the Kipor IG2000 shown in Figure 37, mobile inverter power plant with ignition engine is used. A generator is a device that consists of two main parts, namely the combustion engine and the multipole alternator. This alternator is directly connected on a common shaft with the engine and replaces the flywheel. During rotation, a high-frequency three-phase current is indicated, which is fed into the inverter unit where it is rectified. By means of an invertor, it is converted to a single-phase electric current output at a frequency of 50 HZ [33]. The IG2000 power plant uses inverter technology, which consists in the precise control of voltage and frequency, which produces a precise sinusoidal alternating current.

Figure 37. Electric generator Kipor IG2000 [33].

The KG158 gasoline internal combustion engine used in the power plant meets the emission standard, Stage II according to Directive 2002/88/EC. The system is cooled by means of a labyrinth forced cooling, which ensures optimum cooling of all components of the power plant. Technical specifications are listed below in the Table 9.

Table 9. Technical specifications of the power plant [34].

Model	IG2000
Rated Voltage (V)	230
Rated Current (A)	7.0
Nominal Frequency (Hz)	50
Rated Power Output (kW)	1.6
Max. Output Power (kW)	2.0
Compression Ratio	8.5:1
Minimum Fuel Consumption (g/kW*h)	420
Maximum Engine Power (kW/rpm)	2.2 / 4500
Fuel Tank Volume (l)	3.7
Dimensions [L*W*H] (mm)	520 x 300 x 425
Dry Weight (kg)	22
DC Output (V/A)	12 V/ 5 A
Rated Speed (rpm)	4500

7.1.1 Operating conditions of the Generator

An air-cooled single-cylinder engine four-stroke petrol engine is used to power the generator, The engines in these mobile generators is in conjunction with a multipole alternator, do not need to maintain a constant speed, but are capable of operating in different speed modes, depending on the actual consumption of electrical appliances connected to the generator. This is provided by an electronic PWM unit. Generators of conventional design do not allow this and need to produce electricity at constant engine speed. This electronic control has a significant effect on reducing the weight, noise and fuel consumption of the generator with improved performance engine performance. This system was developed by Honda, a Japanese company that is a leading manufacturer of engines for these types of equipment. The multipole alternator is a manufacturer of is integrated directly into the engine instead of the conventional flywheel. The working areas of the internal combustion engine can be divided into four operating states, with in which the engine is most often operated. The first is idling, the so-called idling mode. In this the engine is adapted to run at idle, rated speed (4500/min-^{1}) and reduced idle speed mode (3200/min-^{1}), here the engine does not perform any usable work and any energy supplied to the engine in the form of fuel is wasted on heat and mechanical losses. Here the emphasis is primarily on the sustainability of operation of the engine while maintaining the lowest possible fuel consumption. The next condition is the part-load mode, in which the engine operates at a range of speeds depending on the current consumption of the connected electrical appliances. In this mode, the engine operates most frequently, and is therefore designed to achieve the lowest fuel consumption in this region at optimum composition of pollutants in the exhaust gases. The third condition is the full load mode, where the engine has a full flow of mixture available and is therefore the emphasis is on maximum engine performance. The engine should remain in this mode only for a limited period of time. The last condition listed here is cold starting. engine and its subsequent warm-up. A cold engine has higher mechanical losses and should be more energy to be supplied. This is achieved by enriching the fuel mixture supplied. Minimum The manufacturer's stated specific fuel consumption of this engine is 420 g/kWh.

7.2 Portable On-Board Emissions Monitoring System (PEMS)

Portable on-board emissions monitoring technology is being used for this task. This System takes raw, undiluted exhaust samples and uses Electrochemical cells are used to test the concentrations of oxygen, nitrogen monoxide, and nitrogen dioxide. Non-dispersive infrared (NDIR) analyzers are used to detect the concentrations of hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide (CO_2), Two heated ionization chambers (241Am, 30 kBq), the reading of which has been demonstrated to correlate to total particle length; and a semi-condensing integrating nephelometer (635 nm, 45° forward scattering) calibrated to yield reading roughly proportionate to particle mass concentrations. The system weighs approximately 14 kg and operates on 9-14 Volts [35].

7.3 Ama Gas Analyzer

The AVL AMA i60 comprises a gas analyzer bench for diluted modal and bag exhaust gas analysis. The concentration readings from the analyzer bench together with the volume flow measured with miniature CVS system is used to calculate the exhaust mass emissions in a very simple, reliable and accurate way. The analysis of the diluted sample gas is performed by means of NDIR, FID and CLD gas analyzers for THC, CH4, NO/ NO_2/NOx, CO, CO_2, N_2O, O_2, and SO_2 concentration analysis. Depending on the application various analyzer types can be used with the AMA i60 exhaust measurement system. Integrated pumps draw in the measurement gas from the sample point, which can be located at a distance of up to 20 m, or up to 60 m with a heated boost pump. Heated lines and pre-filters or sample point selector units are used in the vicinity of the sample point. The analysis of the measurement gas is implemented by means of sophisticated conventional gas analyzers.

7.4 Fourier Transform Infrared Spectrometer (FTIR)

An FTIR analyzer uses an infrared source shown in Figure 38, such as a heated tungsten wire, to produce light with a broad and continuous range of wavelengths. In a Michelson type interferometer, a beam splitter separates the beam into two beams, one of which reflects from a stationary mirror and the other of which reflects from a mirror moving in the direction of the beam. Following their joining, the two beams produce an interference pattern for each variation in optical path length. The generated beam is directed through a multi-pass sample cell containing the investigated exhaust, and a detector records the overall intensity for each variation in optical path lengths. A Fast Fourier Transform converts the interferogram into a transmission spectrum in the frequency domain. Compared to when the transmission at each wavelength is examined independently, this method yields a higher signal to noise ratio [36]. The spectra can be interpreted (deconvoluted) to obtain concentrations of specific compounds or concentrations of compounds belonging to characteristic groups. In this study, a Nicolet Antaris IGS FTIR instrument with a 5meter optical path length cell was used. The concentrations of HC, CO, NO, NO_2, CO_2, formaldehyde and acetaldehyde were obtained from the spectra using software provided by the instrument manufacturer. During the data analysis, several anomalies in the FTIR spectra were found, i.e., results being markedly different between the two test days and also inconsistent with the readings of the AMA gas analyzers. For this reason, only formaldehyde and acetaldehyde emissions are reported here, with these results being only qualitative.

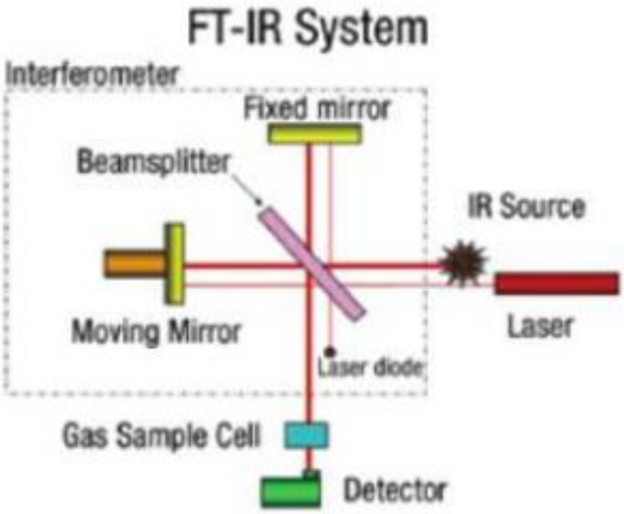


Figure 38. Schematic diagram of FTIR working

7.5 Engine Exhaust Sampling

Before the instruments measure the exhaust and its chemicals, an engine exhaust sample is taken. To ensure that the initial conditions of the measuring instruments, such as temperature, concentration, and pressure, are met, the exhaust sample is pre-conditioned, minimizing the presence of volatile chemicals and moisture (to reduce mistakes) avoiding any physical or chemical change while measuring exhaust gases.

7.5.1 Raw Gas Sampling

Undiluted Gas Sample, also known as Raw Gas Sampling, is a straightforward sampling method. However, the presence of a high concentration of moisture, particles, and high temperatures presents a challenge to this sample process, making it difficult to acquire data that can be relied upon. Raw gas sampling is mostly used for field testing of naval engines and stationary power plants. This type of sample technique is utilized with devices like opacity meters, which work at high temperatures to prevent condensation. In this experiment raw gas sampling is done by PEMS (Portable On-Board Emissions Monitoring System)

7.5.2 Diluted Gas Sampling (full-flow dilution tunnel):

The system for diluted gas sampling consists of full-flow dilution tunnel, from which the emissions are sampled. The flow in the tunnel is maintained by an adjustable power blower. As all gases leaving the engine are sampled, uncertainties of ratio of total dilution tunnel flow to extracted sample flow is eliminated, and constant flow through the dilution tunnel does not have to be maintained for gas emissions sampling purposes. The flow through the tunnel is measured by a thermal mass flow meter placed downstream of the filter. In this experiment the sampling of diluted exhaust through the full-flow dilution tunnel was analyzed by a set of standard laboratory analyzers (HC - heated flame ionization detector, CO CO_2 –non-dispersive infrared analyzers, NOx – chemiluminiscence analyzer), FTIR and AMA i60, AVL.

7.6 Experiment Test Cycle

7.6.1 Fuels used in the Test

The test was conducted on august 27th by using three different fuels in which two fuels (iso-butanol 30%, n-butanol 30%) are alcohol blended in a proportion of 30% to vol with gasoline and the other fuel is gasoline and on august 28th four different fuels in which three fuels (iso-butanol 70%, n-butanol 70%, 70% ethanol) are alcohols blended in a proportion of 70% to vol with gasoline and 25% n-butanol with gasoline was also tested with the reference fuel been gasoline.

7.6.2 Alcohol Fuel Engine Modification

When alcohol is used as fuel for engine, few modifications have to been performed on fuel metering system and air/fuel ratio to due to changes in the physical and chemical properties of alcohol when compared with gasoline.

7.6.2.1 Modification of the fuel metering system

Alcohol fuels, like any other type of fuel, have their specific physical and chemical properties. From the point of view of combustion, the calorific value of the fuel is important, which alcohols are generally lower compared to petrol. For ethanol, the calorific value is even lower than for n-butanol. In view of this fact, the use of these fuels, it is necessary to increase the amount of fuel that the carburetor can deliver to the engine in order to match the mixing ratio. The amount of fuel delivered to the engine is given by the cross-section of the carburetor main jet. It follows from the above that in order to maintain the same richness of mixture, i.e to increase the fuel rate, it is necessary to modify the carburetor, by increasing the cross-section of the main jet.

7.6.2.2 Air fuel ratio

An important indicator for mixture formation and combustion in internal combustion engines is the ratio between the amount of air and fuel in the mixture. This ratio is expressed by air excess coefficient λ, which indicates the deviation from the stoichiometric mixture.

It is calculated as:

$$\lambda = \frac{m_{air}}{m_{fuel} \times L_t} \qquad (7)$$

When ($\lambda = 1$), the mixture is one with a stoichiometric composition (so-called 100% richness). This is the mode in which the vast majority of today's spark-ignition engines operate. This mixing ratio must be maintained for the fuels tested. In the ($\lambda > 1$), regime (so-called lean mixtures with excess air), a small depletion ($\lambda \approx 1.1$), almost ideal combustion. However, this combustion results in dangerous oxidation of the nitrogen in the air is accompanied by the formation of poisonous nitrogen oxides. In the ($\lambda > 1$) regime, only certain groups of gas engines operate in the spark-ignition regime and all diesel engines. At ($\lambda < 1$) (so-called rich mixtures with insufficient air), imperfect combustion due to the lack of oxygen in the rich mixture, with a significant increase in the production of harmful substances in the exhaust gases. These are particular for emission component of CO. For the reasons mentioned above, it is not desirable for internal combustion engines to operate in ($\lambda < 1$) rich mixture mode. Another reason for the unsuitability of this mode is that it does not make use of the energy potential of the fuel.

7.6.2.3 Calculation of the theoretical air quantity:

In order to achieve a stoichiometric mixture, the correct amount of air must be brought to 1 kg of fuel the theoretical air quantity Lt which is determined computationally on the basis of the chemical composition of the fuel. The calculation was performed for all the selected fuels.

The theoretical amount (consumption) of air

$$Lt = 1/0,23(8/3M_c + 8M_{h2} - M_{o2}) \quad [kg_{air}/kg_{fuel}] \quad (8)$$

Where M_c is mass of carbon in fuel, M_{h2} is mass of hydrogen in fuel and M_{o2} is mass of oxygen in fuel. The mass fractions of the individual components contained in the fuels are taken from the Table 4 from fuel properties. The exact determination of the mass fraction of each component in a given fuel is can only be obtained by chemical analysis. Gasoline, the trade name of which is BA 95 Natural, contains approximately 85.5 % C and 14.5 % H by weight assuming no ethanol or oxygenates. Theoretical air consumption for the combustion of 1 kg of petrol using the formula (8) was found to be: 14.95 kg_{air}/kg_{fuel}. To achieve perfect combustion of the stoichiometric mixture, it is necessary to add λ = 1 to formula (7), As a result, for perfect combustion of the stoichiometric mixture, for 1 kg of gasoline 14.95 kg of air must be supplied. Ethanol as a representative of alcohol fuels, consists of 52.2% C, 13% H and 34.8% O. For these measurements, commercial E85 blend has been chosen, taking into account for the calculations the content of ethanol content in blend is 70%, by setting λ = 1 when calculated for E85 blend theoretical air consumption for 1 kg of E85 we need 10.74 kg_{air}. Butanol was the main alcohol fuel considered in this work. Pure n-butanol (100% concentration) contains 64.8% C, 13.6% H and 21.6% O. Theoretical air consumption for the combustion of 1 kg of pure n-butanol, we need 11.29 kg_{air}. when setting λ = 1, we obtain, for perfect combustion of the stoichiometric mixture. Based on the previous calculations, it is possible to compare the individual fuels with gasoline and obtain the required fuel dosage amounts to maintain the stoichiometric composition of the mixture. In the case of the nBu30 blend, 13.92 kg of air is required for perfect combustion with 1 kg of this fuel mixture. When compared with gasoline, which is a mixture of 15.95 kg (1 kg of gasoline + 14.95 kg of air), Similarly 1 kg of nBu70 requires 12.54 kg of air. This shows that there is a 19.2% increase in the weight of the fuel and the volume of the nBu70 blend increased by 12.78 % compared to petrol. The theoretical air volumes were calculated in an identical way and compared the weight and volume increases for the remaining fuels, namely the mixture of gasoline with n-butanol, iso-butanol in different concentrations. The results of all theoretical air consumption and the increases of the individual fuels, including the density of the fuels, are given in Table 10.

Table 10. Comparison of theoretical air consumption and fuel volume increase

Blend	Theoretical amount of air required for 1 kg of fuel [kg_{air}/kg_{fuel}]	Required fuel mass for stoichiometric mixture [kg]	Excess volume of fuel required [%]	Density [kg/m^3]
Gasoline	14.95	1	0	753
Ethanol 70	10.74	1.392	34.5	779
Iso-butanol 30	13.92	1.074	5.2	769
n-butanol 30	13.92	1.074	5.2	770
Iso-butanol 70	12.54	1.192	12.7	790
n-butanol 70	12.54	1.192	12.7	793

7.7 Emissions Test Cycle

The experiment was conducted on two days august 27th and august 28th, experiment matrix is show in Table 11. Figure 39, shows Kipor IG2000 mobile inverter power plant with ignition engine connected to three different emissions analyzers PEMS, AMA, FTIR. The test cycle consists of nine steady-state operating regime for 22 minutes duration as shown in the Table 11, for different rated power from idle, 500W, 1000W, 1500W, 2000W, and fast idle for varied amount of time duration. The only modification made to the engine was that of carburetor nozzle diameter, in order to supply more alcohol fuel for higher percent alcohol fuel blends. the carburetor main nozzle diameter of 0.60mm was used for lower percent alcohol fuel blends and 0.72mm diameter was used for higher percent alcohols to delivery more fuel, for comparative study on carburetor main nozzle diameter the experiment was also run on 25% n-butanol with a larger, carburetor main nozzle diameter of 0.66mm for evaluation of effects of air/fuel ratio and the effect of fuel used. The length of all test regimes was at least one minutes, during which data stability has been visually checked to ensure that an equilibrium state has been reached. Data have been averaged over the last 30 second of each mode. On august 27th the engine was run on three fuels blends (Gasoline, 30% iso-butanol, 30% n-butanol) with nozzle diameter of 0.60mm, and on august 28th the engine was run on five different fuels blends (70% iso-butanol, 70% n-butanol, 70% ethanol), with nozzle diameter of 0.72mm, gasoline with 0.60mm and for comparative study on nozzle diameter, 25% n-butanol was run on with nozzle diameter of 0.66mm, the nine steady state cycle was followed for these fuels test runs. In this thesis, discussions pertaining to nozzle diameters refer to the main nozzle diameter of the carburetor.

Table 11. Experiment Text Matrix

Date and start time		**Wed Aug 27 17:25**	**Wed Aug 27 18:22**	**Wed Aug 27 19:36**	**Thu Aug 28 12:17**	**Thu Aug 28 13:31**	**Thu Aug 28 14:56**	**Thu Aug 28 15:50**	**Thu Aug 28 17:00**
Rated power	**Time length**	**Gasoline 0.60 jet**	**iso-butanol 30% 0.60 jet**	**n-butanol 30% 0.60 jet**	**n-butanol 70% 0.72 jet**	**i-butanol 70% 0.72 jet**	**n-butanol 25% 0.66 jet**	**E70 70% ethanol 0.72 jet**	**Gasoline 0.60 jet**
idle	**1**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
500 W	**1**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
1000 W	**1**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
2000 W	**1**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
1500 W	**4**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
1000 W	**5**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
500 W	**5**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
fast idle	**1**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**
idle	**1**	**x**	**x**	**x**	**x**	**x**	**x**	**x**	**x**

Figure 39. Experiment Setup

7.7.1 Test procedure

At the beginning of each measurement, for each fuel type, the following shall be put into operation the exhaust gas analyzers. The analyzers shall be allowed to warm up for a minimum of 15 minutes, to bring them to the operating condition and adjust them to the initial values (zeroing). During this time, the fuel type shall be prepared and a change of fuel nozzle of the selected carburetor diameter. After all the operations necessary for preparation of the generator, the generator can be put into operation. The engine and system must be warmed up before the engine parameters can be stabilized in order to achieve steady state measurement from the test. This is done at maximum power and rated speed. Subsequently, individual measurements of the prescribed modes for the specified type of fuel and selected nozzle diameters. This procedure is repeated for each individual fuel type fuel and the corresponding carburetor nozzle diameters selected. The data obtained from the exhaust gas analyzers were processed for each selected mode individually. Based on the evaluation of these data, the resulting pollutant concentrations for all fuel types and selected nozzle combinations. From the measured and processed concentrations of the gaseous of pollutants, a mixture richness calculation was performed for each fuel type, with the selected carburetor main nozzle diameter, it can be seen that the change in carburetor main nozzle cross section has a significant effect on the richness of the fuel mixture, with increasing main nozzle cross-section the fuel mixture becomes progressively richer. Raw and undiluted exhaust emissions are measured by PEMS and to measure of diluted exhaust emissions, to determine specific pollutant production, specific fuel consumption and overall efficiency, the diluted emissions were measured by AMA.

8. Comparative Study on Emission Characteristics of Butanol-Gasoline Blends v/s pure Gasoline

The aim or goal of the experiment is to test and compare gas emission characteristics of different blends of butanol isomers with gasoline mainly n-butanol and iso-butanol gasoline blends, for comparative study on alcohols ethanol gasoline blend was also tested. For the selected six steady state regimes of the cycle, time average concentrations of gas emissions for diluted and undiluted gas, for the six steady state regimes was done for the described fuel blends, Data have been averaged over the last 30 second of each mode for the whole cycle duration of 22 minutes.

8.1 CO emissions

8.1.1 CO emissions PEMS

Figure 40, below shows calculated time average points of CO emission concentration done for the nine steady state regimes of ibu30 for undiluted raw CO gas emission, detected by PEMS instrument, the averaging was done from the start of idle at 15:00 minute to the end of cycle at 37:00 minute.

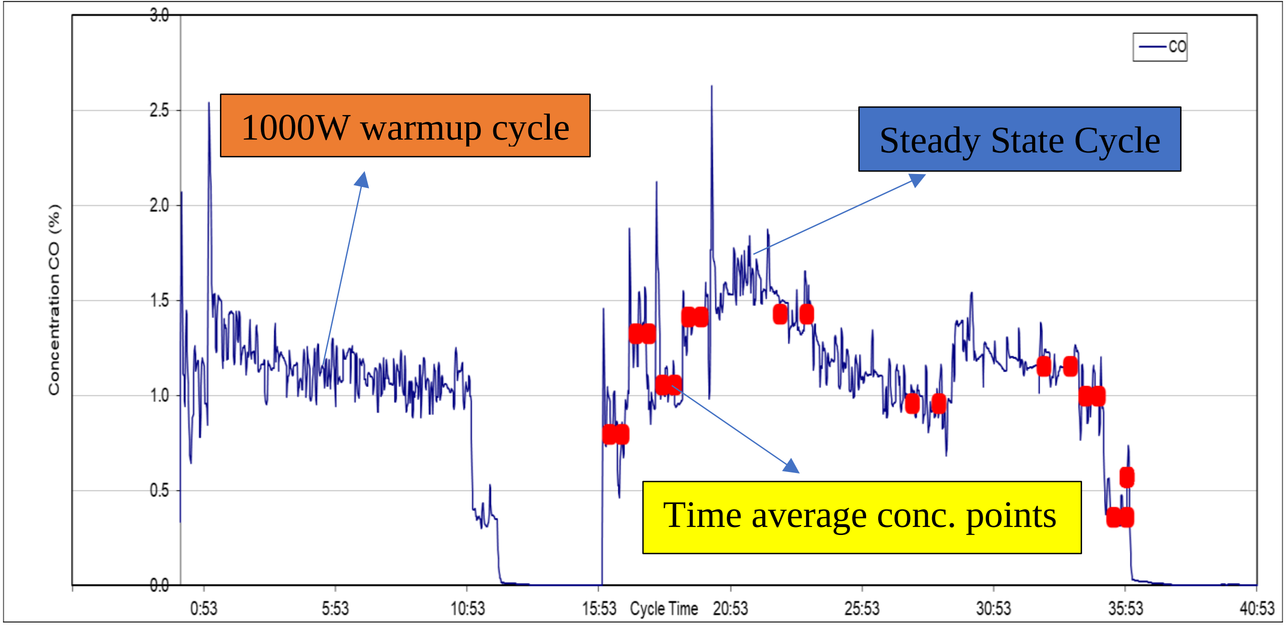


Figure 40. Time average concentration of CO emissions(ppm) for nine steady regimes of iso-butanol30 blend (PEMS)

From Figure 40, we can observe that the time average concentration values of CO emissions for the individual steady state can clearly be seen over the 22 minutes cycle duration. When the time averaging of CO emissions were done for the remaining fuel gasoline blends the following time average points of CO emission concentration for different steady power is show in Table 12.

Table 12. Time average raw CO emission concentration (%) of fuel blends over the steady state cycle (PEMS)

Fuel	gas wed	ibu30 wed	nbu30 wed	nbu70 thur	ibu70 thur	gas thur	e70 thur	nbu25 thur
Test rated power.	**CO(%)**	**CO(%)**	**CO(%)**	**CO(%)**	**CO(%)**	**CO(%)**	**CO(%)**	**CO(%)**
inde	1.7	0.8	0.7	0.4	0.6	2.0	0.5	1.2
500W	4.9	1.3	1.9	3.7	3.3	5.0	2.6	6.0
1000W	5.1	1.1	1.5	5.4	5.0	4.8	3.8	6.0
2000W	4.9	1.4	1.7	7.2	6.9	4.9	5.5	6.6
1500W	5.6	1.4	1.7	5.9	5.4	5.5	4.8	6.5
1000W	5.1	1.0	1.5	5.6	5.2	5.3	3.9	6.1
500W	4.8	1.1	1.4	2.6	2.6	5.1	2.4	5.9
fast idle	3.6	1.0	1.2	1.2	1.5	1.7	0.8	3.0
idle	1.5	0.4	0.7	0.3	0.4	3.8	0.4	1.6

When Table 12. is graphically represented it is shown in the Figure 41, here we can observe CO emissions from alcohol gasoline fuel blends are reduced compared to gasoline in the low load region, this low CO emissions at low load in alcohol fuel blends is due to the presence of excess oxygen content in these alcohols which helps in more oxidation of CO to CO_2, but at rated power of 2000W nBu70 and iBu70 with nozzle diameter of 0.72mm clearly emit higher concentration of CO emissions then pure gasoline and rest of the fuel blends this is due to over-enrichment($\lambda < 1$) of the mixture during the combustion of the fuel blends. The over-enrichment ($\lambda < 1$) results in an imperfect combustion, i.e; imperfect oxidation of the elements contained in the fuel and a corresponding increase in CO emissions. When 25% n-butanol with 0.66mm nozzle diameter and 30% n-butanol with 0.60mm nozzle diameter and no change in stoichiometric ratio of the mixture are compared, we observe that the increase of fuel supply by larger nozzle diameter 0.66mm results in enrichment ($\lambda < 1$) of fuel supplied during combustion which results improper or incomplete combustion and subsequent reduction in oxidation of CO to CO_2. Also use of alcohol fuels, particularly in higher concentrations in the fuel mixture, due to the lower calorific value of alcohol fuels in general, where it is necessary to increase the fuel rate, larger nozzle diameter are used which results in more supply of fuel to the combustion chamber and subsequent over-enrichment of fuel ($\lambda < 1$). Hence 30% iso-butanol and 30% n-butanol fuel blends with nozzle diameter of 0.60mm emit quite substantially low CO emissions compared with the rest of the fuel blends, this is due to both more complete combustion of mixture and presence of excess oxygen which helps in more oxidation of CO to CO_2. We also observe that higher percent alcohol fuel blends with larger nozzle diameter of 0.72mm results in over-enrichment of fuel ($\lambda < 1$) and increased CO emissions compared to 0.60mm nozzle diameter used for lower alcohol concentration fuel. From Figure 41, we also observe that the concentration CO emission from pure gasoline fuel tested on both august 27th Wednesday and august 28th Thursday is almost similar which indicates good repeatability of the experiment.

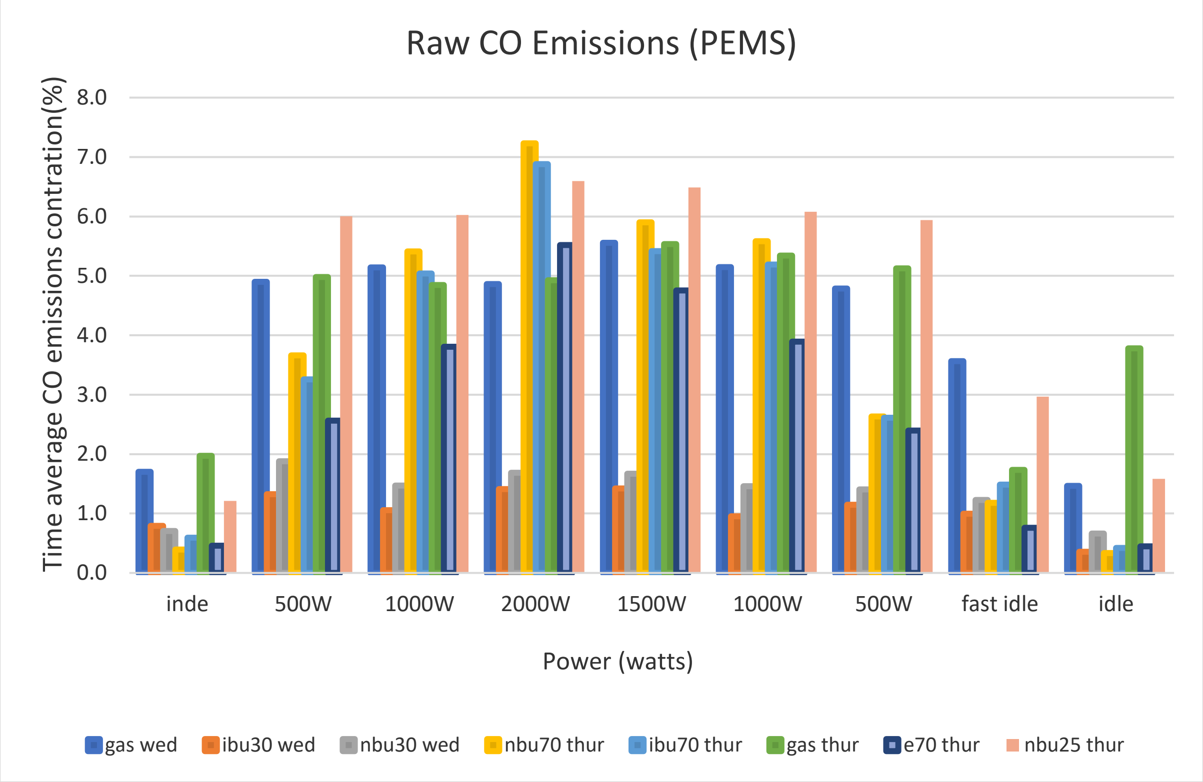


Figure 41. Raw CO emissions time averaged over the steady cycle for all fuel blends (PEMS)

8.1.2 CO emissions AMA

Figure 42, below shows calculated time average points of CO emission concentration done for the nine steady state regimes of iBu30 for diluted raw CO gas emission, detected by AMA instrument, the averaging was done from the start of idle at 15:00 minute to the end of cycle at 37:00 minute.

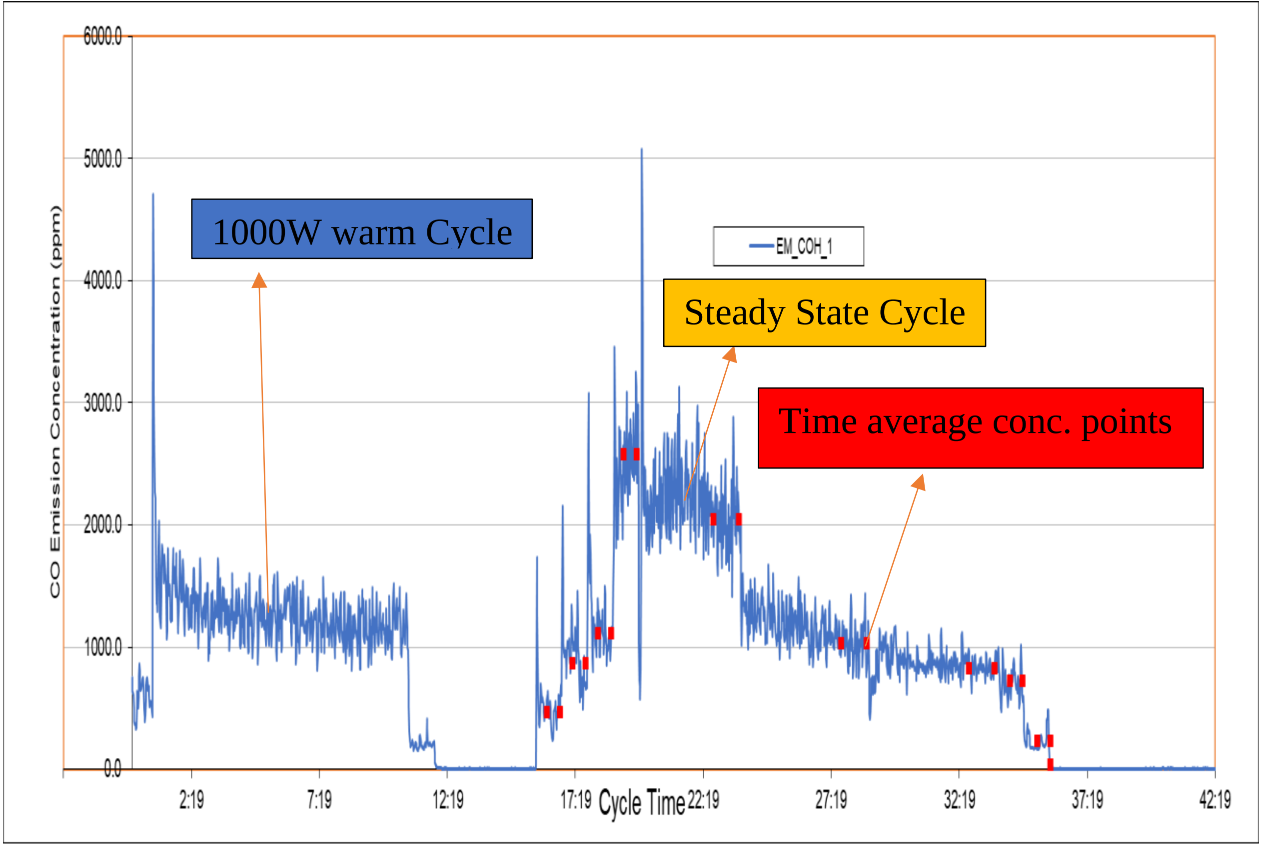


Figure 42. Time average Concentration of CO emissions(ppm) for nine steady regimes of iso-butano370 blend (AMA)

From Figure 42, we can observe that the time average concentration values of CO emissions for the individual steady state can clearly be seen over the 22 minutes cycle duration. When the time averaging of CO emissions were done for the remaining fuel gasoline blends the following time average points of CO emission concentration for different steady power is show in Table 13.

Table 13. Time average diluted CO emission concentration of fuel blends over the steady state cycle (AMA)

Fuel	gas wed	ibu30 wed	nbu30 wed	nbu70 thur	ibu70 thur	gas thur	e70 thur	nbu25 thur
Test Power	**CO(PPM)**	**CO(PPM)**	**CO(PPM)**	**CO(PPM)**	**CO(PPM)**	**CO(PPM)**	**CO(PPM)**	**CO(PPM)**
inde	923	459	418	233	302	1081	269	642
500W	3730	867	1247	2636	2266	3664	1786	4324
1000W	5657	1105	1576	5842	5447	5277	3939	6521
2000W	9002	2570	2972	13388	12739	8680	9602	12218
1500W	8547	2038	2531	8476	7740	7969	6664	9446
1000W	5801	1029	1550	6028	5647	5722	4112	6715
500W	3529	827	962	1857	1897	3670	1665	4342
fast idle	2480	717	838	831	1111	899	516	2009
idle	766	227	361	203	265	2495	264	890

When Table 13. is visualized graphically, it is shown in Figure 43. Like the CO emissions detected from raw exhaust emission, by PEMS we can observe that at low load, we have reduced CO emission from alcohol fuel blends compared with pure gasoline, like raw exhaust emission at rated power of 2000W the higher alcohol percent fuel blends nBu70 and iBu70 with nozzle diameter 0.72mm emit higher concentration of CO emission among the tested fuel blends, this is due to over-enrichment of fuel blends $(\lambda < 1)$ and subsequent incomplete combustion of fuel and oxidation of CO to CO_2. Similar to the CO emissions detected from raw exhaust, iBu30 and nBu30 emit reduced CO emissions compared with the rest of the fuel blends, due to addition of 30% alcohol to gasoline which is burns slightly rich, blends the fuel close to stoichiometric air/fuel ratio $(\lambda=1)$, hence we observe lower CO emissions in 30% n-butanol and 30% iso-butanol when compared with the rest of the fuel blends, and when comparison of 25% n-butanol with 0.66mm nozzle diameter and 30% n-butanol with 0.60mm nozzle diameter and no change in stoichiometric ratio of mixture is done, we can observe that the increase of fuel supply by larger nozzle diameter 0.66mm results in enrichment $(\lambda < 1)$ of fuel supplied during combustion which results improper or incomplete combustion and subsequent oxidation of CO to CO_2, also we can observe that the CO emission from gasoline run on both the test days indicate good repeatability of the experiment.

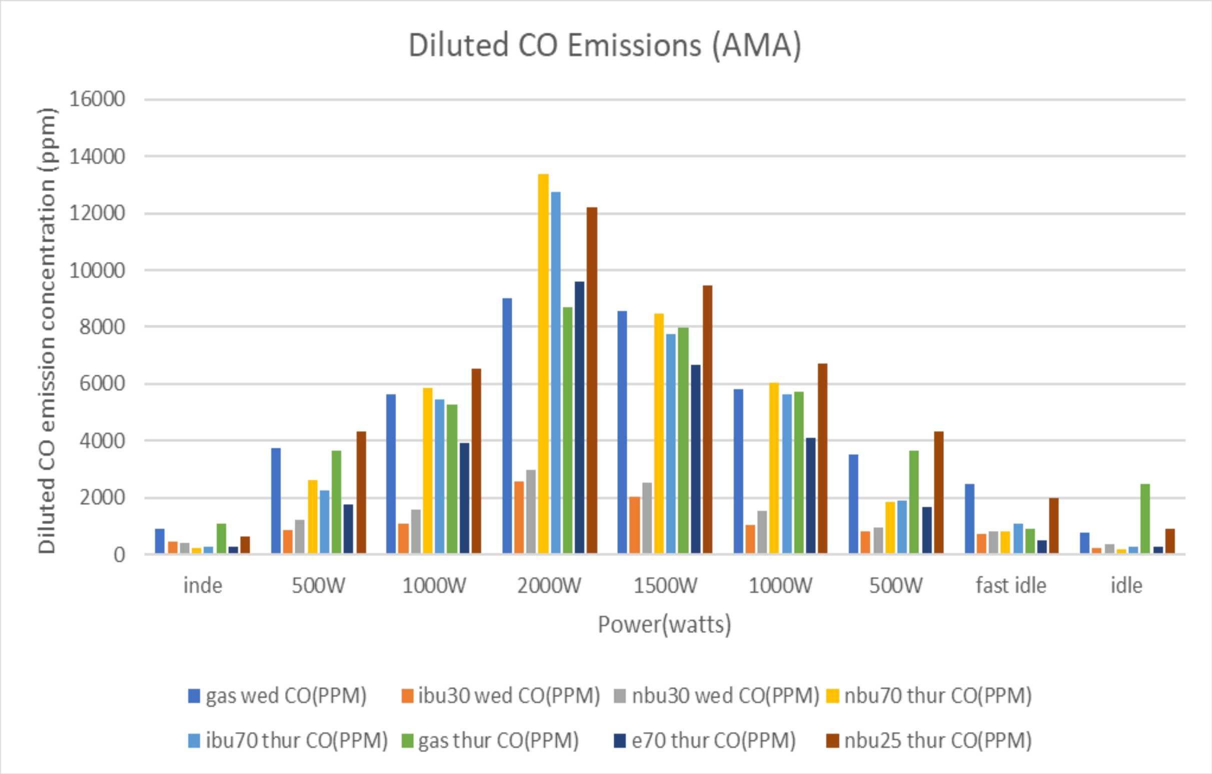


Figure 43.Diluted CO emission concentrations time averaged over the steady cycle for all fuel blends (AMA)

8.2 Hydro Carbon (HC) Emissions

8.2.1 Hydro Carbon (HC) Emissions PEMS

The flame range inside the cylinder is precisely described by the Hydro Carbon (HC) emission. The mixture found in crevices and unburned fuel vapour that are absorbed by the oil as a result of quenching close to the cylinder walls are the main sources of HC emissions.

When the time average of HC emissions over the nine steady regime for the fuels blends is done the following results were obtained which are tabulated into Table 14, we can observe that unburned hydrocarbons are also, like CO, the product of imperfect combustion. From the graph in Figure 44, a decrease in HC emissions for lower percent alcohol mixtures can be observed, with the lowest values being achieved when burning a mixture of gasoline with 30 % iso-butanol. This decrease was most pronounced in the medium to high load regimes. This reduction of HC emissions was achieved due to the presence of excess oxygen content in the butanol which improves the oxidation of HC to CO_2 and H_2O. also, HC emissions increased as the percentage of alcohol in the fuel was increased, this increment of HC emissions is due the fuel over enrichment ($\lambda < 1$) which results in incomplete or partial burning or oxidation of fuel. High percentage alcohol fuel blends like 70% ethanol, 70% iso-butanol and 70% n-butanol with nozzle diameter 0.72mm emit higher HC emissions from low to high load when compared with pure gasoline due to previously mentioned fuel enrichment ($\lambda < 1$) and insufficient air, but lower percentage alcohols 30% iso- butanol and 30% n-butanol with nozzle diameter 0.60mm have decreased HC emissions compared with gasoline, this can be attributed due to the presence of excess oxygen content in 30% butanol fuel blends which improves oxidation of HC, and when comparison of 25% n-butanol with 0.66mm nozzle diameter and 30% n-butanol with 0.60mm nozzle diameter and no change in stoichiometric ratio of the mixture is done, we can observe that the increase of fuel supply by larger nozzle diameter 0.66mm results in enrichment ($\lambda < 1$) of fuel supplied during combustion which results in improper or incomplete combustion and subsequent decrease in oxidation of HC. The sudden increase in high HC emissions seen for all fuel blends at the end of steady cycle during idle when observed it was due to over lean ($\lambda > 1$) fuel mixture and decrease in load which results in decrease in temperature, pressure and incomplete combustion.

Table 14. Time average raw HC emissions concentration of fuel blends over the steady state cycle (PEMS)

Fuel	gas wed	ibu30 wed	nbu30 wed	nbu70 thur	ibu70 thur	gas thur	e70 thur	nbu25 thur
Test desc.	HC(ppm)	HC(ppm)	HC(ppm)	HC(ppm)	HC(ppm)	HC(ppm)	HC(ppm)	HC(ppm)
inde	785	782	925	817	1099	924	1238	785
500W	628	473	583	694	929	526	757	594
1000W	654	452	564	758	946	510	796	586
2000W	626	441	569	790	951	477	846	580
1500W	649	427	502	794	846	514	803	624
1000W	651	342	429	757	730	505	609	611
500W	633	324	390	616	583	478	478	583
fast idle	529	274	314	525	514	700	378	431
idle	625	348	913	1273	869	332	1434	907

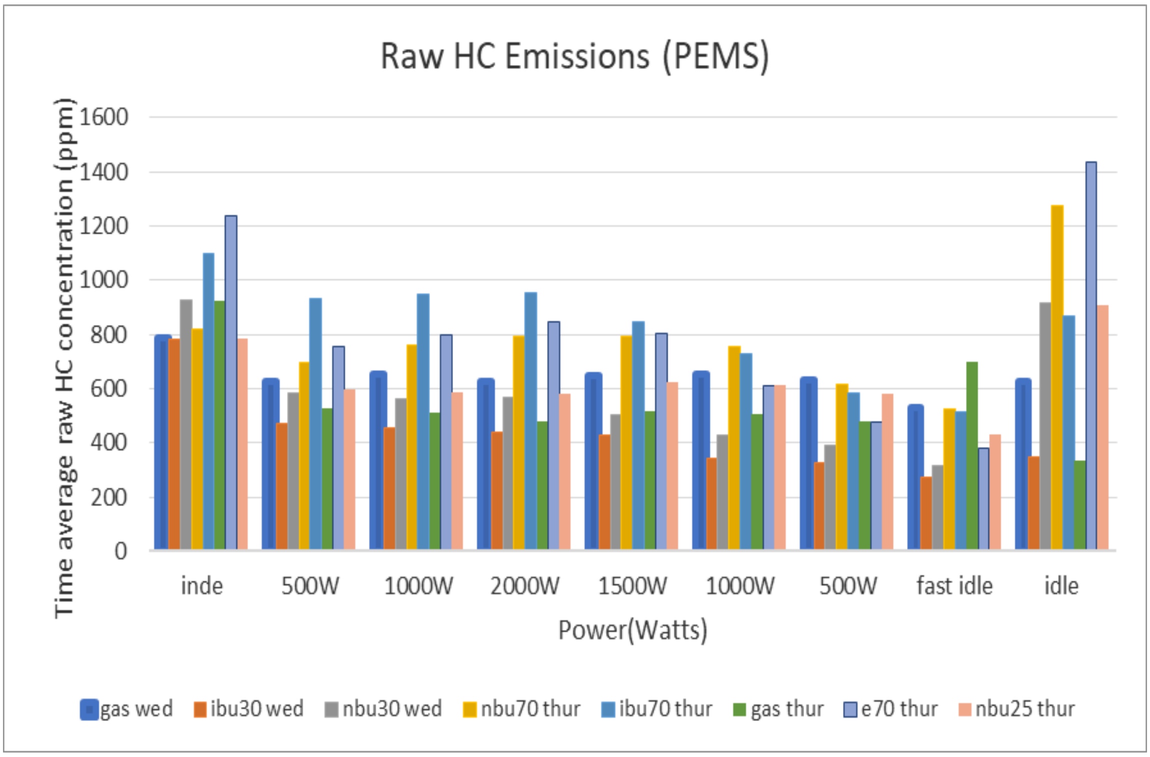


Figure 44. Time average HC emissions concentration of fuel blends over the steady cycle (PEMS)

8.2.2 Hydro-Carbon (HC) Emissions AMA

The diluted HC emissions were measured using the instrument AMA i60, and similar time average of the concentrations are done and tabulated in the Table15, below and graphically represented in the Figure 45. We can observe from the Figure 45, that as we go from low load to high load conditions lower percent alcohols fuel blends 30% n-butanol and 30% iso-butanol emit lower HC emissions compared with higher percent 70% n-butanol 70%iso-butanol and gasoline, this is due to over enrichment of fuel ($\lambda < 1$) for high percent alcohol fuel blends and availability of excess oxygen for 30% alcohol gasoline fuel blends. And when we consider the rated power of 2000W higher percent alcohol blends are shown to emit higher HC emissions than the rest of the fuels this is due to incomplete combustion and oxidation of fuel because of above mentioned fuel enrichment ($\lambda < 1$) and addition of 30% alcohol to gasoline which is burning slightly rich, blends the fuel close to stoichiometric air/fuel ratio ($\lambda = 1$) show reduced HC emissions, also when comparison of 25% n-butanol with 0.66mm nozzle diameter and 30% n-butanol with 0.60mm nozzle diameter and no change in stoichiometric ratio of the mixture is done, we can observe that the increase of fuel supply by larger nozzle diameter 0.66mm results in enrichment ($\lambda < 1$) of fuel supplied during combustion which results in improper or incomplete combustion and subsequent reduced oxidation of HC, hence we observe lower HC emission from 30% n-butanol compared to 25%n-butanol with larger nozzle diameter.

Table 15. Time average diluted HC emissions of fuel blends over the steady cycle (AMA)

Fuel	gas wed	ibu30 wed	nbu30 wed	nbu70 thur	ibu70 thur	gas thur	e70 thur	nbu25 thur
Test desc.	**EM HC (ppm)**	**EM HC (ppm)**	**EM HC (ppm)**	**EM HC (ppm)**	**EM HC (ppm)**	**EM HC (ppm)**	**EM HC (ppm)**	**EM HC (ppm)**
inde	85	107	107	113	142	111	192	91
500W	94	56	65	71	70	91	57	94
1000W	131	75	87	121	114	123	87	130
2000W	198	127	146	216	214	186	159	200
1500W	179	111	112	154	149	180	127	179
1000W	135	76	82	122	118	133	90	136
500W	91	55	57	60	62	92	50	95
fast idle	72	39	38	34	46	84	23	59
idle	65	97	118	204	159	70	249	117

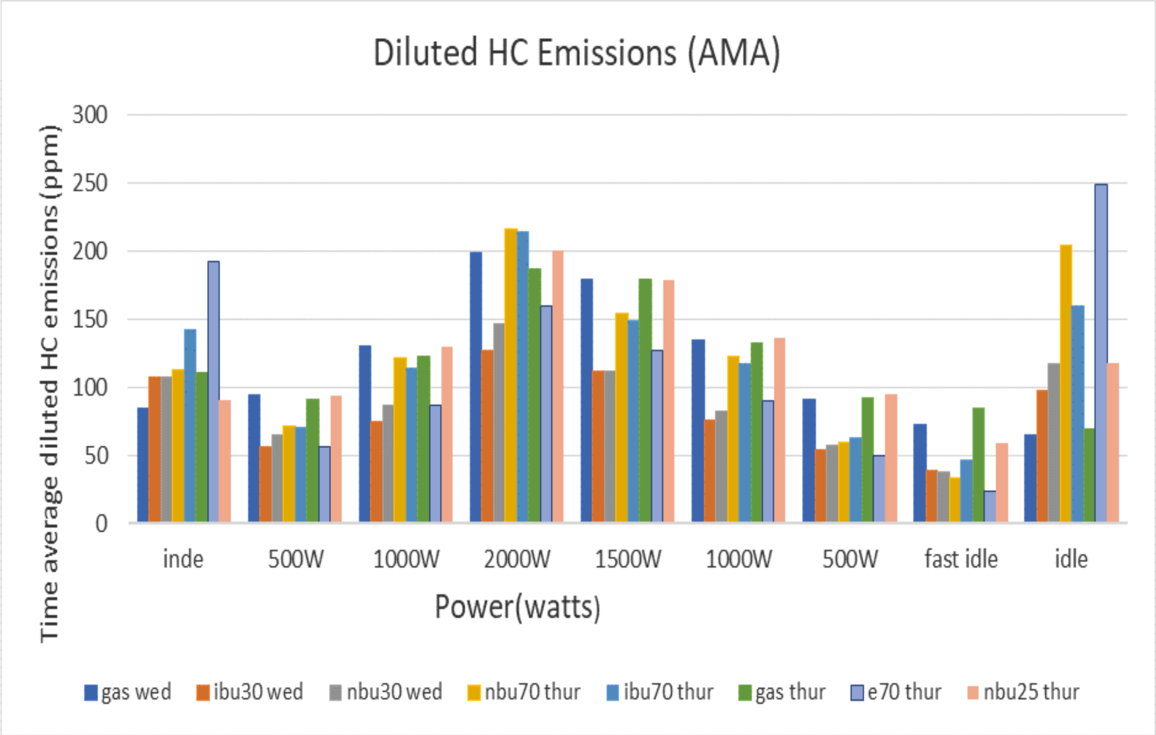


Figure 45. Diluted HC emissions time averaged over the steady cycle for all fuel blends (AMA)

8.3 NO_X Emissions

8.3.1 NOx PEMS

Nitrogen oxides NOx are formed at high combustion temperatures, which means that the higher the combustion temperature, the more NOx is produced. Time average NOx emission over the steady cycle is shown in the Table 16. Figure 46, shows the increase in NOx emissions for lower percent alcohol fuel blends 30% n-butanol, 30% iso-butanol compared to gasoline due to the leaning of the fuel blend ($\lambda > 1$) excess availability of oxygen and probably an increase in in-cylinder temperatures due to better combustion. While the fuel mixture of 30% alcohol blend, as gasoline burns slightly rich, with 30% addition of alcohol to the fuel, fuel blends were close to stoichiometric air/fuel ratio in composition. Due to the increase in of the oxygen concentration in the mixture, the combustion and high loads, the higher emissions were achieved for lower percent alcohol content in fuel , NOx emissions were measured highest for fuel blend with a mixture of gasoline and 30 % n-butanol, and at the rated power of 2000W the highest emissions values were recorded for 30% n-butanol, and when comparison of 25% n-butanol with 0.66mm nozzle diameter and 30% n-butanol with 0.60mm nozzle diameter and no change in stoichiometric ratio of the mixture, we observe that the increase of fuel supply by larger nozzle diameter 0.66mm results in enrichment ($\lambda < 1$) of fuel supplied during combustion, which results in improper or incomplete combustion and subsequent reduction in formation NOx, probably due to lower in-cylinder temperature an after effect of incomplete combustion which is an important factor for NOx formation. NOx emissions for higher percent alcohol content in fuel blends 70% n-butanol, 70% iso-butanol and 70% ethanol compared to gasoline are lower due to over enrichment of the fuel blend ($\lambda < 1$) and probably decrease in combustion temperatures. While the fuel mixture of 70% alcohol blend as gasoline burning slightly rich, with 70% addition of alcohol to the gasoline, causes supply of excess oxygen to fuel. But higher percent alcohol fuel blends produce reduced NOx when compared with lower percent alcohol fuel blends due to the enrichment of the fuel concentration in the mixture ($\lambda < 1$), and probable decrease in in-cylinder temperatures lowers NOx production. Among the higher percent alcohol fuels 70% ethanol as shown to emit higher NO_x than 70% n-butanol and 70% iso-butanol.

Table 16. Time average NOx emissions concentration of fuel blends over the steady state cycle (PEMS)

fuel	gas wed	ibu30 wed	nbu30 wed	nbu70 thur	ibu70 thur	gas thur	e70 thur	nbu25 thur
Test desc.	**Nox(ppm)**	**Nox(ppm)**	**Nox(ppm)**	**Nox(ppm)**	**Nox(ppm)**	**Nox(ppm)**	**Nox(ppm)**	**Nox(ppm)**
inde	47	40	40	32	35	48	45	38
500W	78	124	142	63	62	73	76	46
1000W	224	569	654	131	132	250	206	120
2000W	557	1261	1338	155	157	547	246	240
1500W	387	1128	1170	242	244	396	309	240
1000W	284	720	754	163	163	267	254	167
500W	95	161	185	99	88	88	96	59
fast idle	68	62	66	52	51	58	50	50
idle	56	43	53	46	44	61	60	48

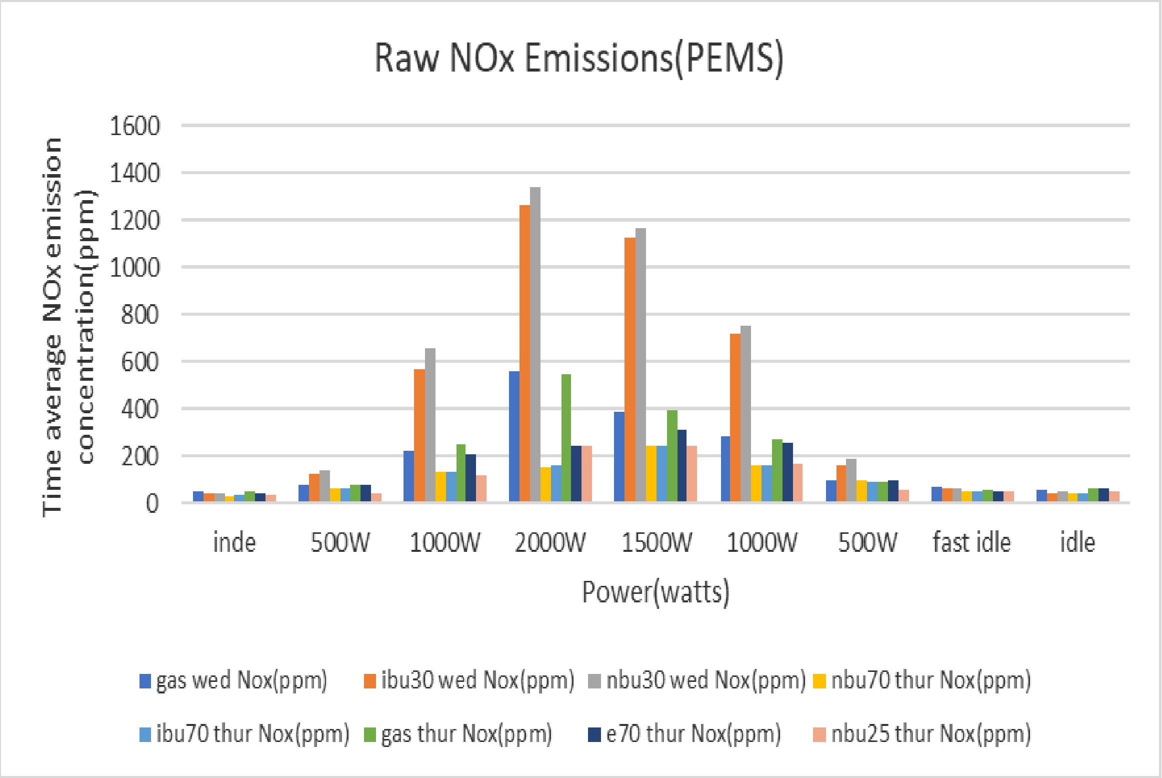


Figure 46. Time average NOx raw emissions time averaged over the steady cycle for all fuel blends (PEMS)

8.3.2 NOx AMA

When the diluted NOx emission from AMA were analyzed, because Nitrogen oxides are formed at high combustion temperatures, the higher the combustion temperature the more NOx that is produced. Table 17, displays the time average NOx emission over the steady cycle. Figure 47, illustrates the rise in NOx emissions for lower alcohol fuel blends (30% n-butanol, 30% iso-butanol) as compared to gasoline. This rise is caused by the fuel mix becoming leaner ($\lambda >$ 1), and higher combustion temperatures. While gasoline with a 70 percent alcohol blend burned significantly richer, fuel blends with a 30 percent alcohol in volume were almost stoichiometric in composition. The largest NOx emissions were produced by 30% alcohol blends as a result of the mixture's increased oxygen concentration, more complete combustion which probably results in higher in-cylinder temperature, and high loads. The blends of gasoline and 30% n-butanol produced the highest levels of NOx emissions, which peaked at 2000W of rated power, due to enleanment of the fuel blend ($\lambda >$), and a probable increase in combustion temperatures. And when comparison of 25% n-butanol with 0.66mm nozzle diameter and 30% n-butanol with 0.60mm nozzle diameter and no change in stoichiometric ratio of the mixture is done, we observe that the increase of fuel supply by larger nozzle diameter 0.66mm results in enrichment ($\lambda < 1$) of fuel supplied during combustion which results in improper or incomplete combustion and probable reduction in the in-cylinder temperature which is an important factor for formation NOx, hence reduction in NOx emission was observed for 25% n-butanol compared to 30% n-butanol. Higher percentage alcohol fuel blends like 70% ethanol, 70% n-butanol, and 70% iso-butanol emit lower NOx emissions than regular gasoline does, due to the supply of excess fuel to the engine and change in air/fuel ratio probably results in lower in-cylinder temperatures then gasoline and also the unavailability of oxygen leads to lower NOx, by the fact that gasoline blended with a 70% alcohol content burned significantly richer ($\lambda < 1$), than usual. And higher percent alcohol content fuel blends produce reduced NOx when compared to lower percent alcohol content fuel blends, due to the enrichment of the fuel concentration in the mixture ($\lambda<1$), and probably results in the decrease of combustion temperatures and thus lower NOx production. 70% ethanol among the highest alcohol concentrations has been demonstrated to emit more NOx than 70% n-butanol and 70% iso-butanol.

Table 17. Time average diluted NOx emissions of fuel blends over the steady cycle (AMA)

Fuel	gas wed	ibu30 wed	nbu30 wed	nbu70 thur	ibu70 thur	gas thur	e70 thur	nbu25 thur
Test desc.	EM NOX (ppm)	EM NOX (ppm)	EM NOX (ppm)	EM NOX (ppm)	EM NOX (ppm)	EM NOX (ppm)	EM NOX (ppm)	EM NOX (ppm)
inde	4	4	4	4	4	4	4	4
500W	12	18	17	9	10	9	9	7
1000W	43	103	107	29	30	48	39	29
2000W	154	336	343	55	58	157	76	81
1500W	92	237	240	60	62	90	72	60
1000W	48	113	118	31	32	45	42	31
500W	10	19	20	12	12	10	10	7
fast idle	6	6	7	5	5	4	4	5
idle	4	3	5	4	4	5	5	4

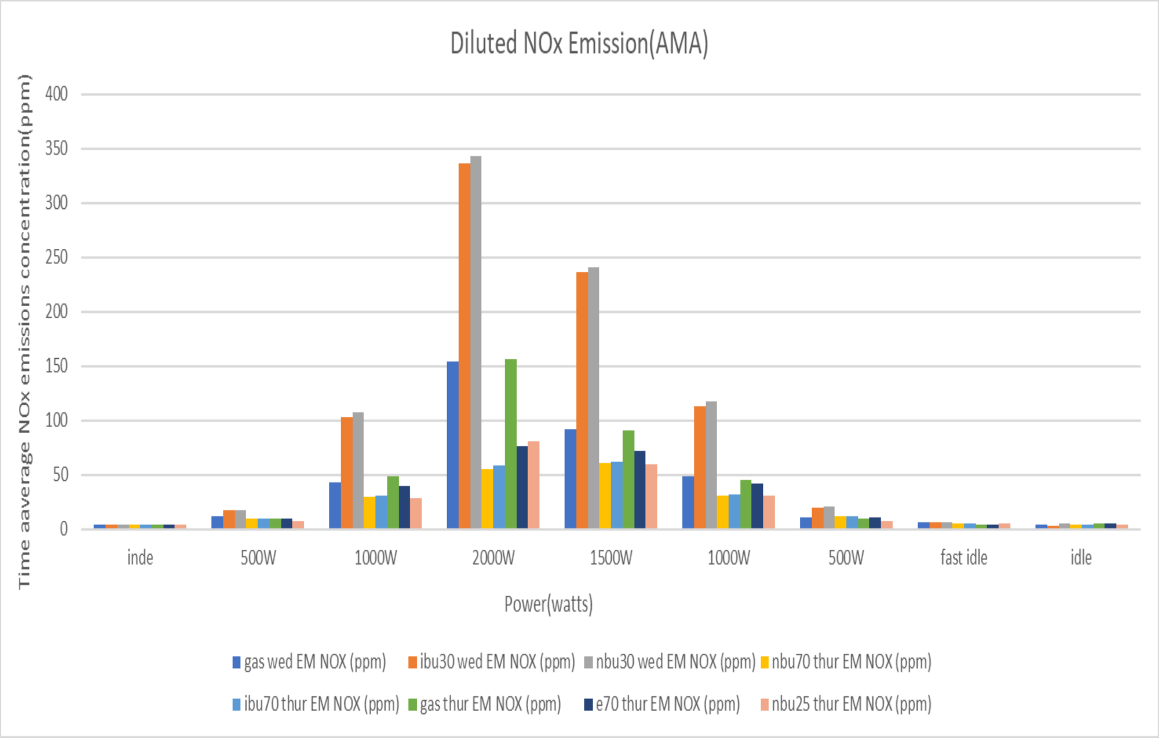


Figure 47. Diluted NOx emissions time averaged over the steady cycle for all fuel blends (AMA)

8.4 Aldehyde Emission

Formaldehyde, acetaldehyde and other aldehydes are produced when alcohols are oxidized, addition of butanol to gasoline as fuel increase the formation of formaldehyde and acetaldehyde. During the data analysis, several anomalies in the FTIR spectra were found, i.e., results being markedly different between the two test days and also inconsistent with the readings of the AMA gas analyzers Hence the time average concentrations of formaldehyde & acetaldehyde emitted by the all fuels over the steady state cycle are tabulated in Table 18 & 19 respectively and illustrated separately for the two experiment days august 27th (Wednesday) and august 28th (Thursday) for formaldehyde in the Figures 48 & 49, and acetaldehyde in the Figures 50 & 51, due to anomalies in test FTIR spectra.

8.4.1 Formaldehyde

From the Figures 48 & 49, we can observe consistent increase in formaldehyde emissions when alcohol as addition to gasoline with 30% n-butanol alcohol fuel blend emitting higher concentrations then the rest of the fuel over two days of test days, with lowest concentrations observed for 25% n-butanol with nozzle diameter of 0.66mm.

8.4.2 Acetaldehyde

From the Figures 50 & 51, we can observe consistent decrease in acetaldehyde emissions as load increase when lower percent alcohol as addition to gasoline with 25% n-butanol with 0.66mm nozzle diameter and 30% n-butanol alcohol fuel blends emitting lower concentrations then the rest of the fuel over two days of test days, with lowest concentrations observed for 25% n-butanol with nozzle diameter of 0.66mm.

Table 18. Time average Formaldehyde emission concentration (FTIR)

Fuel	gas wed	ibu30 wed	nbu30 wed	nbu70	ibu70 thur	gas thur	e70 thur	nbu25 thur
Test desc.	**Formaldehyde**	**Formaldehyde**	**Formaldehyde**	**Formaldehyde**	**Formaldehyde**	**Formaldehyde**	**Formaldehyde**	**Formaldehyde**
inde	4.5	8.2	8.8	6.7	8.2	3.3	7.5	1.2
500W	3.7	5.2	5.3	4.4	4.3	2.4	2.7	0.9
1000W	6.5	8.8	9.5	8.2	7.6	4.0	5.2	0.8
2000W	11.8	15.5	17.2	13.6	13.6	7.2	9.4	0.8
1500W	10.0	12.9	13.1	10.8	10.6	6.3	8.0	0.9
1000W	6.9	9.0	8.9	8.2	8.0	4.1	5.5	0.7
500W	3.7	5.1	5.3	3.8	4.0	2.6	2.8	0.8
fast idle	3.3	3.8	3.7	2.7	3.2	2.7	1.8	0.8
idle	3.4	6.3	8.0	7.7	8.4	1.6	8.0	1.4

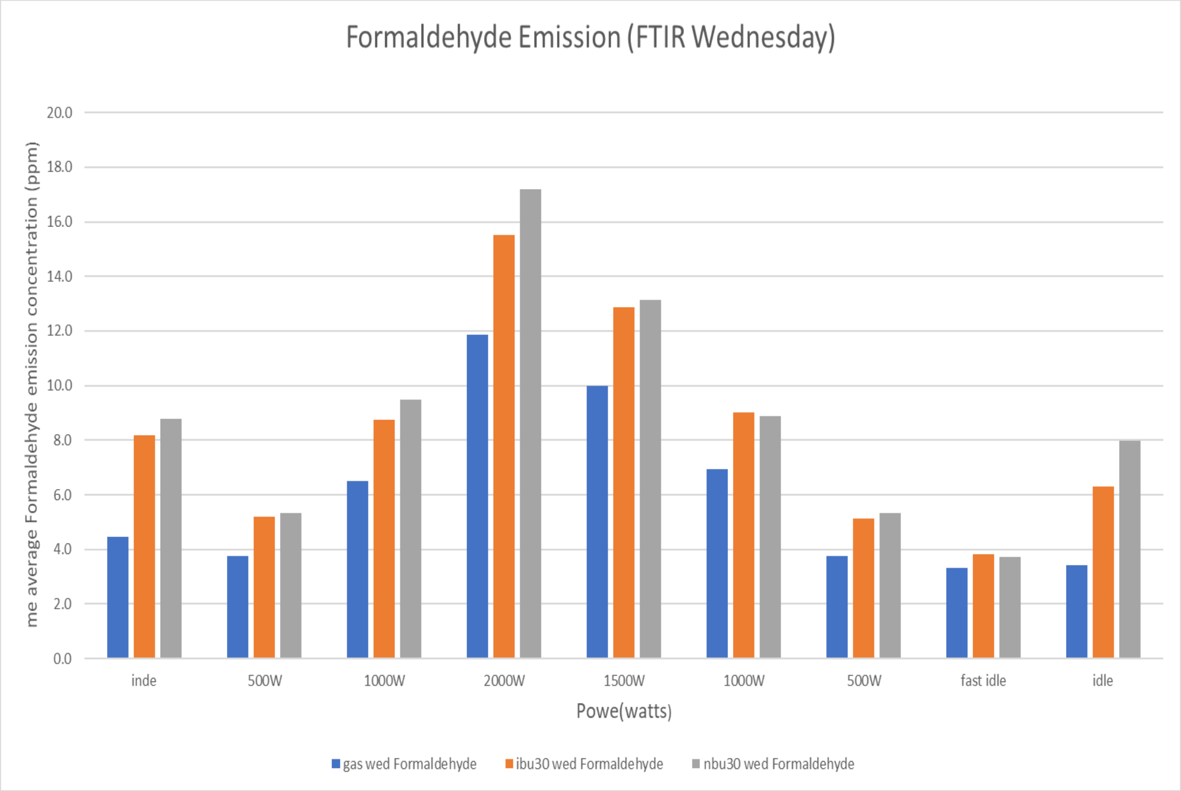


Figure 48. Time average Formaldehyde emission concentration (FTIR Wednesday)

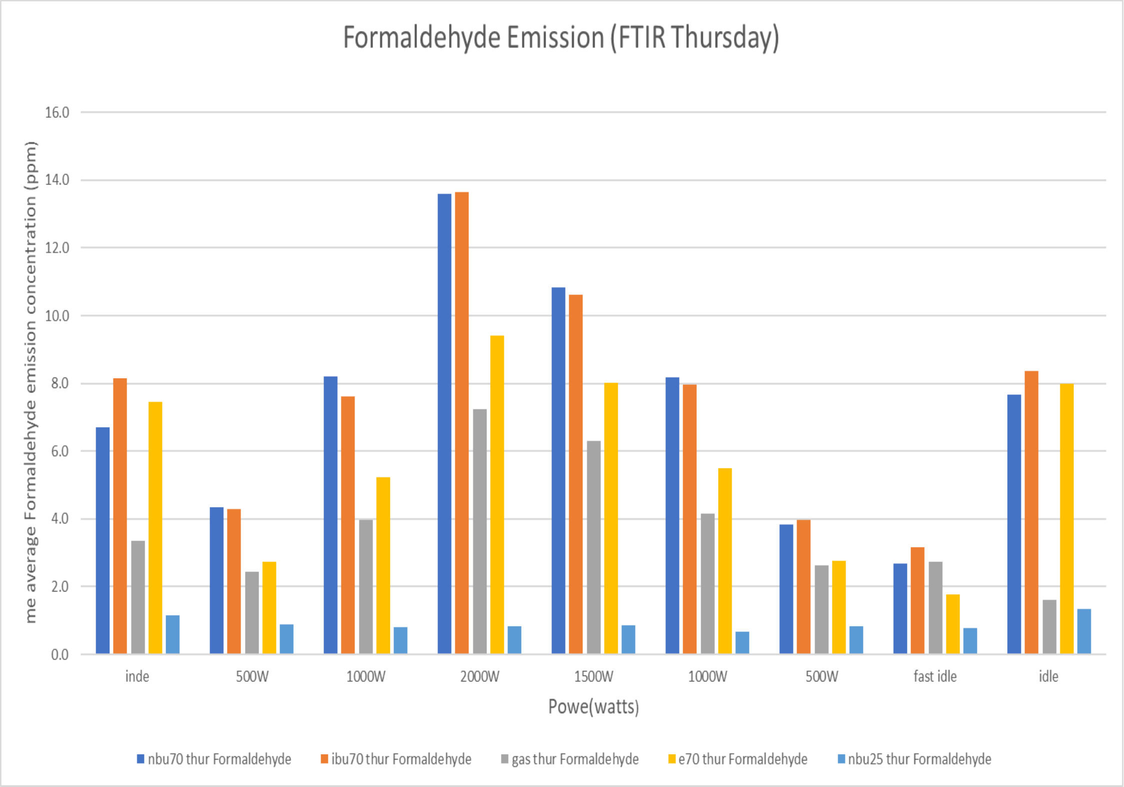


Figure 49. Time average Formaldehyde emission concentration (FTIR *Thursday*)

Table 19.Time average Acetaldehyde emission concentration (FTIR)

Fuel	gas wed	ibu30 wed	nbu30 wed	nbu70	ibu70 thur	gas thur	e70 thur	nbu 25 thur
Test desc.	**Acetaldehyde**	**Acetaldehyde**	**Acetaldehyde**	**Acetaldehyde**	**Acetaldehyde**	**Acetaldehyde**	**Acetaldehyde**	Acetaldehyde
inde	2.7	4.6	2.5	5.4	6.6	4.2	7.6	2.3
500W	3.3	2.7	1.8	3.5	4.2	2.2	5.2	2.0
1000W	4.7	3.7	1.4	6.3	6.1	4.0	7.8	1.9
2000W	8.3	6.7	2.1	10.3	12.0	6.5	13.0	2.0
1500W	7.8	6.6	1.8	9.4	7.9	5.4	12.7	2.0
1000W	5.4	4.1	1.4	6.7	6.9	4.3	8.7	2.1
500W	3.1	2.2	1.7	3.7	3.9	2.4	4.5	2.1
fast idle	2.2	0.8	1.8	1.9	2.9	2.9	2.0	1.5
idle	2.2	2.3	2.3	6.3	7.8	1.8	7.1	2.0

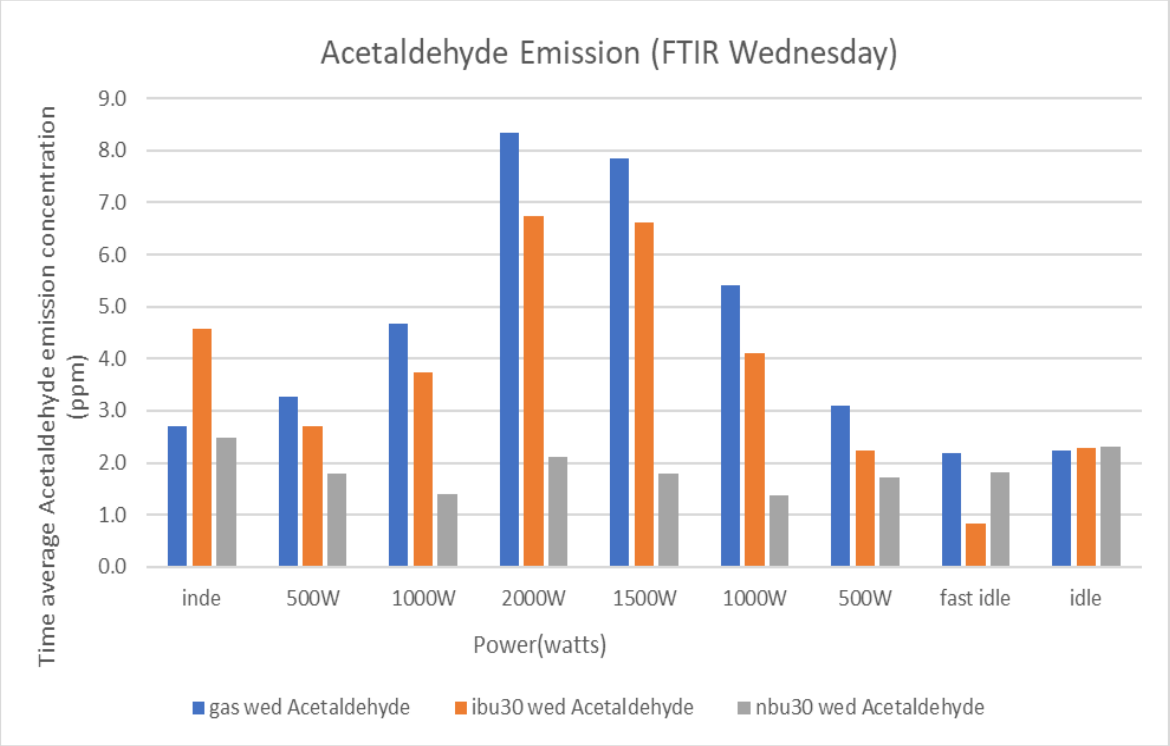


Figure 50. Time average Acetaldehyde emission concentration (FTIR Wednesday)

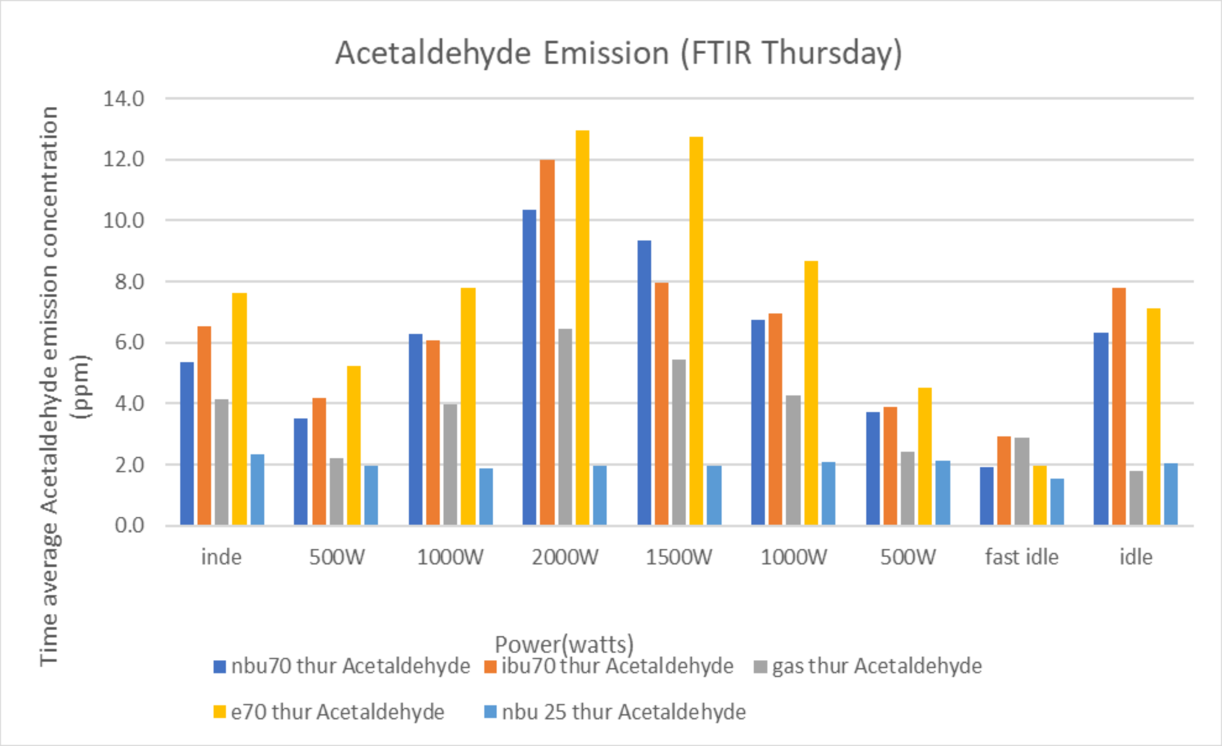


Figure 51. Time average Acetaldehyde emission concentration (FTIR Thursday)

8.5 Calculations of Specific Emissions g/kg $_{\text{fuel}}$ and g/kWh

From the measured data obtained from the analysers, the average volumetric concentrations of the monitored exhaust gas components for the individual tested fuels are measured in all cycle states. These average concentrations were converted using correction factors, according to the response of the analysers to the calibration and measurement gas. The resulting average concentrations of the individual exhaust gas components for the selected fuels and selected nozzle diameters are shown in the appendix 8. Diluted mass flow rate sample was measured with a thermal mass flow meter. To determine the specific emissions (CO, NOx, HC), specific fuel consumption and the overall efficiency of the power plant is the mass flux of the gaseous substances of interest need to be determined.

8.5.1 Calculation of the mass fluxes of the exhaust gas components

The mass fluxes of the gaseous species of interest are calculated as the product of the instantaneous flux of the diluted exhaust sample and the average concentrations of the pollutants of interest.

molecular volume of the gas is taken as 22400cm3 /mole.

$$m_{gas} = (\dot{m}_{flowrate} * conc_{gas} * M_{gas}) \div 10^6 \quad [\text{g/h}] \qquad (9)$$

In this way, all mass fluxes of the individual components (HC, CO, NOx, CO2) for the tested fuels across all modes are calculated. The resulting mass fluxes of the individual exhaust gas components that were required for the following calculations are presented in appendix.

8.5.2 Calculation of Specific Emission Factors

The specific emission factor of the individual exhaust gas components is calculated by dividing the mass flow of the component of interest, by the cycle average power input of the load appliance.

For the calculation of Emission Factor, certain parameters were considered certain parameters were considered

a. Carbon content in fuels is taken from the fuel properties Table 4

b. Presence of CO and CO2 in gasoline were assumed.

c. Molecular volume of gas was assumed as 22400cm3 /mol.

$$Emission\ Factor[EF] = \dot{m}_{flowrate} \div power \quad [\text{g/kWh}] \qquad (10)$$

8.5.3 Calculation of specific consumption

To determine the specific fuel consumption, it is necessary to determine the total carbon flux in sample, i.e in the CO, CO2 and THC (Total Hydro Carbons) components (PM neglected), for calculation carbon content in the fuel is taken from the fuel properties Table 4

$$\dot{m}_{c_{co}} = (\dot{m}_{co} * \frac{M_c}{M_{co}}) \quad [\text{g/h}] \qquad (11)$$

$$\dot{m}_{c_{co_2}} = (\dot{m}_{co_2} * \frac{M_c}{M_{co_2}}) \quad [\text{g/h}] \qquad (12)$$

$$\dot{m}_{c_{THC}} = (\dot{m}_{THC} * \frac{M_c}{M_{THC}}) \quad [\text{g/h}] \qquad (13)$$

$$\dot{m}_{c_{c}=} \dot{m}_{c_{co}} + \dot{m}_{c_{co_2}} + \dot{m}_{c_{THC}} \ [\text{g/h}] \qquad (14)$$

$$EF_{spec} = \dot{m}_{c_c} \Big/ P * m_c \qquad \text{[g/kWh]} \qquad (15)$$

$$EF\ (g/kWh) = EF\ (g/kgfuel\ )/1000 * BSFC \qquad (16)$$

Where, $EF_{specific}$= Emission Factor in [g/kWh]

$\dot{m}_{c_{co}}$= Mass of Carbon in CO concentration [g/h]

$\dot{m}_{co}$== Concentration of CO measured using AMA [g/h]

$\dot{m}_{c_{co_2}}$ = Mass of Carbon in CO_2 concentration [g/h]

$\dot{m}_{co_2}$ = concentration of CO_2 measured using AMA [g/h]

$\dot{m}_{c_{THC}}$= Mass of Carbon in THC [g/h]

$\dot{m}_{THC}$= Concentration of THC measured using AMA [g/h]

$\dot{m}_{c_c}$= Total Mass of Carbon from CO, CO_2, THC concentration [g/h]

M_c=Molecular Weight of Carbon [g/mol]

M_{co_2}=Molecular Weight of CO_2 [g/mol]

M_{THC}=Molecular Weight of THC [g/mol]

Where BSFC is Brake Specific Fuel Consumption, the molecular weight of carbon is 12g/mol, CO is 28g/mol and THC is considered as methane with molecular weight 16g/mol and molecular volume of the gas is taken as 22400cm3 /mole

8.5.4 Diluted exhaust emission results

The results of the calculated specific emissions are shown in the Tables 20 & 21 when observed we detect fuel mixtures of gasoline with 30% n-butanol and 30% iso-butanol have higher NOx specific emissions, while specific emissions of CO and HC decrease but, higher percent alcohols with gasoline emit lower NOx emission compared to the rest of the fuel blends. CO_2 emissions is not shown here as it is not currently a regulated emission and is not for emission limits are not set for this component. When comparing the results of specific fuel consumption, the it is clear that there is a decrease in specific fuel consumption for both alcohol fuel blends compared to the baseline fuel, i.e gasolin

Table 20. Specific Emission Factors for Different Fuel Blends [g/kWh]

Fuel	% C in fuel	CO [g/kWh]	NO_x [g/kWh]	THC [g/kWh]	BSFC [g/kWh]
iso-Butanol 30%	84	61	9.2	3.2	385
n-Butanol 30%	84	77	9.5	3.5	404
n-Butanol 70%	81	163	2.3	4.8	462
Iso-Butanol 70%	81	155	2.4	4.7	435
Ethanol 70%	75	180	3.0	4.5	448
Gasoline (Thursday)	87	253	4.2	4.8	429
n-Butanol 25%	85	277	3.0	5.0	430
Gasoline (Wednesday)	87	259	9.0	5.0	443

Table 21.Specific Emissions Factors for Different Fuel Blends [g/kgfuel]

Fuel	% C in fuel	CO [g/kg$_{fuel}$]	NO$_x$ [g/kg$_{fuel}$]	THC [g/kg$_{fuel}$]
iso-Butanol 30%	84	158	23.8	8.3
n-Butanol 30%	84	191	23.5	8.7
n-Butanol 70%	81	480	5.7	10.0
Iso-Butanol 70%	81	482`	5.9	11.0
Ethanol 70%	75	401	6.7	10.0
Gasoline (Thursday)	87	590	9.8	11.2
n-Butanol 25%	85	644	6.0	11.0
Gasoline (Wednesday)	87	584	10.0	11.0

8.5.5 Graphical Representation of Specific Emissions

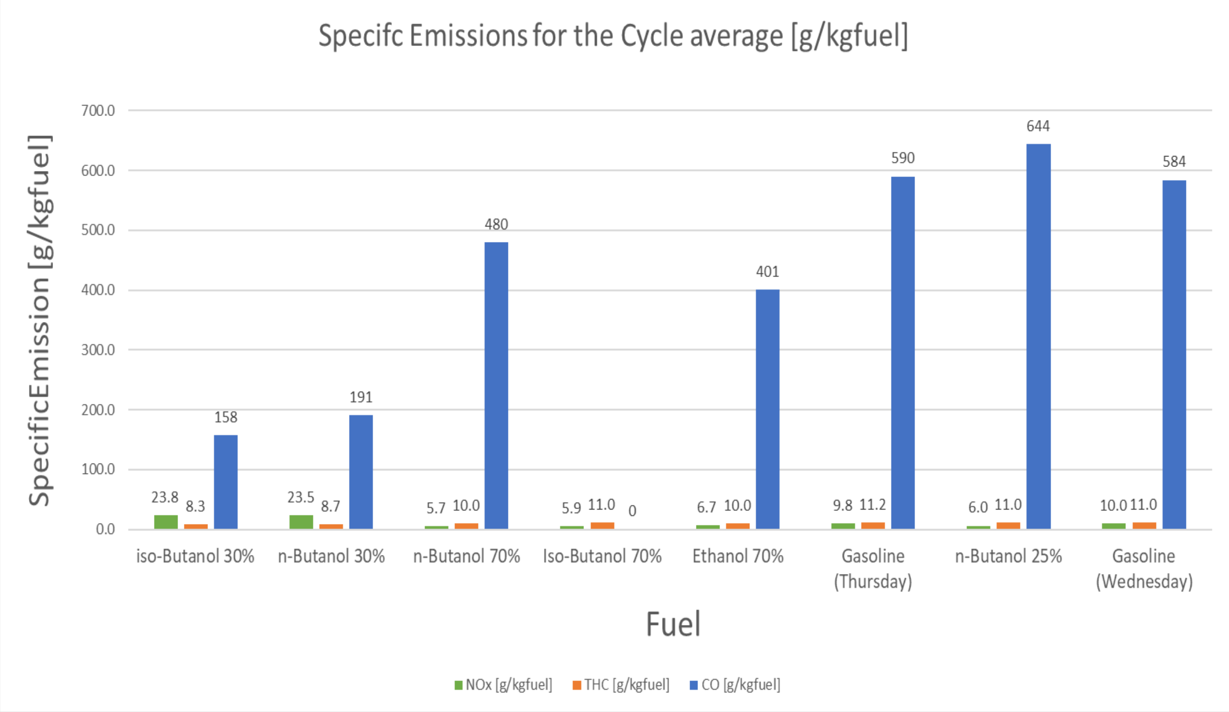


Figure 52. Specific Emission over the Cycle [g/kgfuel]

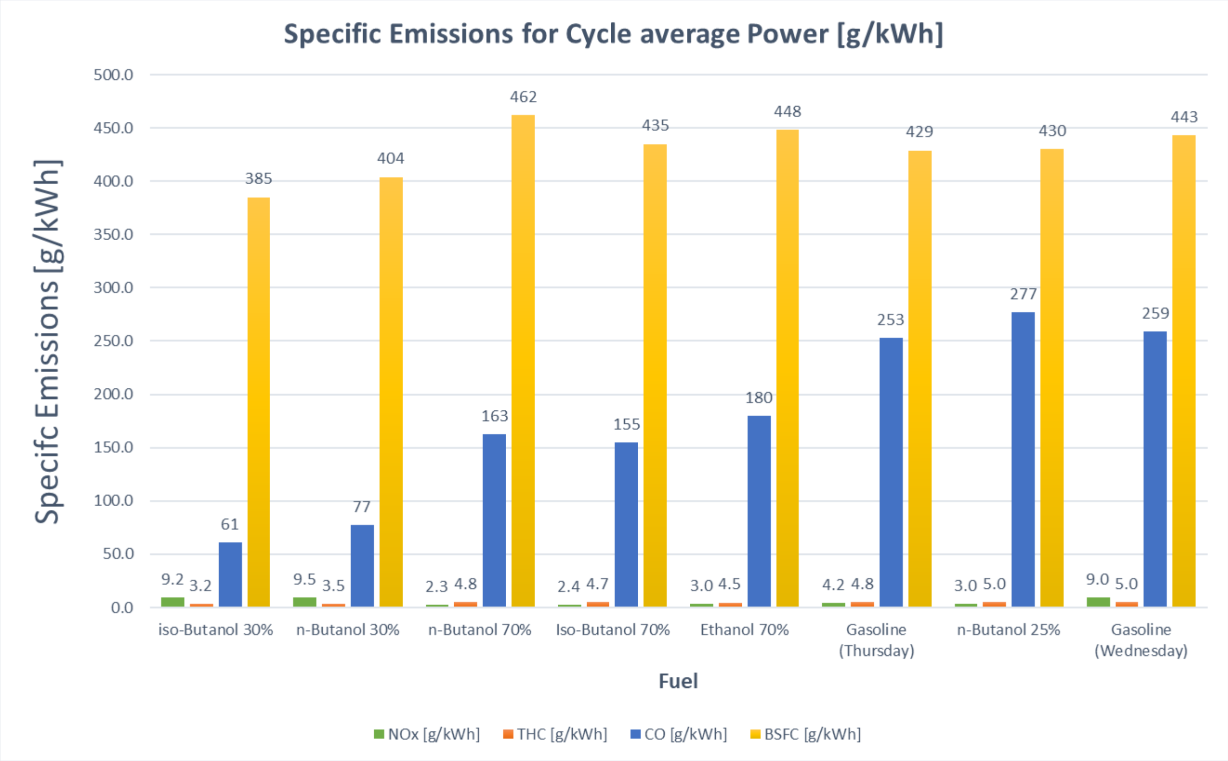


Figure 53.Specific Emission over the Cycle [g/kWh]

A comparison of the specific emissions in Figures 52 & 53, shows the combustion of butanol-gasoline mixtures, specific CO emissions are reduced compared to gasoline, especially in lower percent alcohol fuel blends. The increase of CO emissions between gasoline and the mixture of gasoline with 70 % n-butanol was up to 1.5 times as large, due to over-enrichment ($\lambda < 1$), of the mixture during the combustion of the fuel. The over-enrichment results in an imperfect combustion, i.e imperfect oxidation of the elements contained in the fuel and a corresponding increase in specific CO emissions, we also observe that 25% n-butanol with gasoline with nozzle diameter of 0.66mm emits higher specific CO emissions, this when compared to 30% n-butanol with nozzle diameter 0.60mm when the stoichiometric ratio of the mixture was unchanged, due to increase in nozzle diameter more fuel mixture was supplied resulting in over-enrichment ($\lambda < 1$) of fuel. Unburned hydrocarbons are also a product of imperfect combustion as CO. From the Figures 52 & 53, a decrease in specific HC emissions for lower percent butanol blends and an increase in higher percent butanol fuel blends can be observed, with the lowest values being achieved when burning a mixture of gasoline with 30 % iso-butanol and the highest specific HC emission values were achieved by gasoline with 70% n-butanol, due to its significant enrichment of the fuel mixture ($\lambda < 1$). when specific HC emissions for alcohol fuel blends 25% n-butanol and 30% n-butanol with nozzle diameters of 0.66mm and 0.60mm respectively, with no change in stoichiometric ratio of the mixture are compared, we then observe that over-enrichment of fuel ($\lambda < 1$), due to supply of more fuel through increased nozzle diameter and subsequent change in air/fuel ratio to 25% n-butanol fuel emits increased the HC specific emissions compared to 30% n-butanol fuel. NOx is probably formed at high combustion temperatures, which implies that the more higher the combustion temperature, the more NOx is produced. Figures 52 & 53, shows an increase in specific NOx emissions for lower percent alcohol fuel blends compared to gasoline, due to the leaning of the fuel blend ($\lambda > 1$), better stoichiometric combustion and probably an increase in combustion temperatures. While the fuel mixture when burning gasoline was slightly rich, the addition of 30% alcohol content to fuel, blends it very close to stoichiometric air/fuel ratio ($\lambda = 1$). Due to the increase in of available oxygen concentration in the mixture, and probable increase in in-cylinder temperature results in higher NOx production. 30% n-butanol and 30% iso-butanol have shown to emit higher NOx specific emissions when compared to baseline fuel gasoline. When 25% n-butanol was compared with 30% n-butanol and no change in stoichiometric ratio of the mixture, the over enrichment of 25% n-butanol due increased nozzle diameter results in decreased specific NOx emissions. Also, higher percent alcohol fuel blends have shown to emit significantly lower specific NOx emissions compared to gasoline.

8.5.6 Summary of test results

The aim of this part of the experiment was to determine the specific pollutant production contained in the exhaust gases produced by different butanol gasoline blends and for comparative study of alcohol ethanol was also tested, on a small SI engine present in KIPOR 2000IG together with the determination of specific power consumption. From the measured data obtained from the analyzers, the average volumetric concentrations of the individual exhaust gas components for each of the fuels tested is calculated for all cycle regimes. From these time average concentrations, the following calculations were made of mass fluxes of the gaseous substances monitored. Based on these calculation of the mass fluxes of the individual gaseous components, the specific emissions (CO, NOx, HC), specific fuel consumption are calculated, the resulting values of which are given in Tables 15,16. From the results of the specific emissions it is clear that, when 25% n-butanol and 30% n-butanol with no change in air/fuel ratio and different nozzle diameter was compared we can observe that the increase of fuel supply by larger nozzle diameter results in enrichment $(\lambda < 1)$ of fuel supplied and subsequent higher specific emissions of CO, HC. Due to the leaning of the fuel mixture $(\lambda > 1)$ for lower alcohol fuel blends, there is a reduction in carbon monoxide CO and unburned hydrocarbons HC. NOx, on the other hand, increases with increasing leanness of the blends for alcohol fuels. A comparison of the specific fuel consumption results shows that an increase in specific fuel consumption for higher alcohol fuel blends compared to the reference gasoline fuel, due to the lower energy value (calorific value) of n-butanol, where it was necessary to increase the cross section of the main nozzle and thus increase the fuel supply to match the mixing ratio. Results of specific consumption shows decreased consumption in lower percent alcohols which can be attributed to the enleanment of fuel mixture $(\lambda > 1)$ due to the presence of excess oxygen in alcohol fuel and subsequent change air/fuel ratio of the mixture.

9. Discussion & Conclusion

The aim of thesis is to review potential prospects of utilization of Butanol produced from biomass (Bio-Butanol) as fuel in small Spark ignition engines, the studies done on butanol are divided into three parts, firstly production of butanol from biomass, material compatibility of fuel, engine startability, and comparison of performance and emissions characteristics of butanol fuel blends with gasoline as baseline or reference fuel.

The first part of the thesis goal or study is done on critical review on production of butanol from biomass was done with additional life cycle and carbon foot assessment on production of butanol through different feedstock and chemical synthesis process are presented in Chapter 2, from this chapter 2 we can conclude that, bio-butanol that is butanol produced by means of utilization biomass as feedstock in its production, is a potential viable alternative fuel, its production technology, storage technology and transportation technology are becoming more and more advanced. Even though ABE process is constrained by the high cost of fermentation substrates, butanol-induced process inhibition, and low butanol concentration in the product, as well as high downstream processing costs. Use of continuous one-step coupling of bioethanol and butanol is one of the most promising chemical solutions, but price has a significant impact on the economic sustainability of butanol generation using ABE fermentation. The use of bio-butanol as a fuel has a lot of promise in the energy systems, especially in the transportation sector, and it can assist EU countries meet their national emission requirements.

The second part of the study was done on material compatibility of butanol with the relevant materials coming into in contact with the fuel and engine startablity which are explained in Chapter 4. The chapter 4 consists of extensive studies and results done on material compatibility and engine startability by various authors. Results of the compatibility studies show that the different parts of the fuel system of engine are able to withstand the effects of butanol blended fuels and therefore the materials used in the fuel system and engine components can be operated at various concentrations of butanol mixtures without adverse effects on the material. The results of engine startability were reported from the study mentioned in the section 4.2 of Chapter 4. The study included a test of the startability of an unmodified small SI engine at low temperatures, the results of study show that for gasoline blends with lower n-butanol concentrations, up to 30%, no engine startability problems were observed, but at 30% n-butanol concentration, the author observed engine began to exhibit degraded performance compared to operation gasoline operation. For gasoline blends with higher concentrations of n-butanol, when operating at low temperatures, complications arise not only with engine operation but also with startability. Based on the experimental measurements carried out in the study by the author, it can be concluded that it is possible to use n-butanol blends as fuel for this type of internal combustion engine, provided the necessary modification of the fuel system. For mixtures with n-butanol content up to 10 % the study concludes no modification is necessary and they can be operated without any problems.

For third part of the thesis, studies on performance characteristic of butanol in small SI engines were presented in Chapter 5, these studies conclude that performance characteristics like torque and power have shown to be reduced while an increase in BTE (Brake Thermal Efficiency) and BSFC (Brake Specific Fuel Consumption) was observed when using butanol has fuel, this effect can explained due to lower heating value of butanol when compared to gasoline and subsequent increase in fuel supply to maintain same power of the engine. To understand the emission characteristics of butanol on small SI engine, emissions test was performed on different blends of butanol gasoline, ethanol gasoline with gasoline as baseline or reference fuel which are explained in chapters 7 & 8, in these chapters (30% n-butanol 30% iso-butanol) with original carburetor main nozzle diameter 0.60mm and higher percent alcohol fuel blends (70% iso-butanol, 70% n-butanol) with a larger, 0.72mm carburetor main nozzle diameter and for comparative study on alcohols (70% ethanol) with 0.72 nozzle diameter was also tested, also test of 25% n-butanol with 0.66mm nozzle diameter for comparative study on effect of air/fuel ratio and fuel was also run on the engine. From the results of the experiments, we can conclude that lower percent alcohol content blends (30% iso-butanol and 30% n-butanol) with gasoline and original carburetor main nozzle diameter of 0.60mm emit reduced CO, HC specific emissions and higher NOx specific emissions. Higher percent alcohol content blends (70% iso-butanol, 70% n-butanol, 70% ethanol), which used the larger nozzle diameter 0.72mm emit higher specific emissions for CO and HC and reduced NOx emissions when compared with reference fuel gasoline. When emissions from 25% n-butanol blend with the larger, 0.66mm nozzle diameter were observed there was an increase in CO, HC specific emissions and decrease in NOx specific emissions and when compared to 30% n-butanol with 0.60mm nozzle diameter, with no change in the stoichiometric ratio of the mixture for these two blends, the increase in nozzle diameter results in over-enrichment of 25% n-butanol compared to 30% n-butanol which results in incomplete or improper combustion of fuel and oxidation CO,HC and reduced in-cylinder temperature which is important factor for NOx production. Also, when compared with the European emission standards stage V, the results analyzed from the emission measurement test, we clearly observe that there is a substantial reduction nearly 90% reduction in the specific emissions of CO & THC [g/kWh] for both butanol isomers (n-butanol & iso-butanol) when blended in 30% volume with gasoline, an increase in specific emissions of NOx [g/kWh] for lower percent alcohol fuel blends is observed, but higher percent alcohol fuel blends emit reduced NOx specific emissions. Hence use of butanol alcohol as fuel with little to no modification (carburetor jet diameter) to engine and change in air/fuel ratio accordingly can reduce specific emissions.

Butanol blended fuel has been considered a new generation of alternative fuels for IC engines (SI engines) in the future, compared to traditional fossil fuels. Butanol blended fuel can be utilized in a wide range of IC SI engines, including:, SI engines with inlet port injection, GDI SI engines,. In today's SI engines, the butanol mixed fuel combustion technology is commonly used. This use of butanol fuel in engines will gradually increase in the future. The study of butanol as fuel for engines has a lot of practical utility and a lot of potential, butanol is an excellent alternative fuel to traditional fossil fuels. Butanol has distinct advantages over methanol and ethanol as an alcohol alternative fuel. It has a low hydrophilic index, less corrosion, and is easy to transfer via pipeline. It has a promising future application potential has potential alternate fuel in small SI engines.

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11. List of Figures

12. List of Tables

13. List of Abbreviations

ASTM : American Society for Testing and Materials
ABE : Acetone, Butanol and Ethanol
Bu : Butanol
BSFC : Brake Specific Fuel Consumption
BTE : Brake Thermal Efficiency
CO : Carbon Monoxide
CO_2 : Carbon Dioxide
COV : Coefficient of Variation
CLD : Chemiluminescence Detector
DDGS : Dried Distillers Grains with Solubles
EEA : European Environment Agency
EF : Emission Factor
EGR : Exhaust Gas Recirculation
EPA : Environmental Protection Agency
EU : European Union
FID : Flame Ionization Detector
FTIR : Fourier Transform Infrared Spectrum
GHG : Greenhouse Gases
H_2 : Hydrogen
HC : Hydrocarbon
HO_2 : Hydrogen Dioxide
HRR : Heat Release Rate
iBu : Iso-Butanol
ICP : In Cylinder Pressure
IR : Infrared Ray
KLST : Knock Limited Spark Timing
LCA : Life Cycle Assesment
LHV : Lower Heating Value
LPG : Liquified Petroleum Gas
MFB : Mass Fraction Burnt
N: Nitrogen
nBu : N-Butanol
NDIR : Non-Dispersive Infrared
NO : Nitric Oxide
NO_2 : Nitrogen Dioxide
NO_x : Nitrogen Oxides
O_2 : Oxygen
OH : Hydrogen Oxide
PAH : Poly Aromatic Hydrocarbons
PEMS : Portable Emissions Measurement System

PM : Particulate Mass
PM10 : Particulate Matter with diameter >10 µm
PM2.5 : Particulate Matter with diameter >2.5 µm
PN : Particulate Number
RVP : Reid Vapor Pressure
sBu : Secondary Butanol
SI : Spark Ignition
tBu : Tertiary Butanol
THC: Total Hydrocarbon
UHC : Unburnt Hydrocarbon
VOC : Volatile Organic Compounds
WHO : World Health Organization

14. Appendix

1. Calculated cycle average weight of individual gas emissions (AMA)

30% n-butanol Wednesday						
POWER	**EM_CO2_1 [g]**	**EM_NO_1 [g]**	**EM_NOX_1 [g]**	**EM_THC_1 [g]**	**CO [g]**	**Total C [g]**
index	537.6	0.3	0.39	4.0	22.0	159.4836
500W	778.6	1.1	1.66	2.4	66.9	243.1145
1000W	1227.5	6.6	10.26	3.2	85.2	374.0654
2000W	2063.0	21.2	32.75	5.5	160.6	636.1231
1500W	1681.7	14.9	22.98	4.2	136.8	520.8316
1000W	1249.8	7.2	11.24	3.1	83.8	379.3933
500W	807.1	1.2	1.94	2.1	50.9	243.7964
fast idle	780.0	0.4	0.63	1.4	44.3	232.9059
idle	548.9	0.3	0.44	4.4	19.1	161.6389

	30% Iso- butanol Wednesday					
POWER	**EM_CO2_1 [g]**	**EM_NO_1 [g]**	**EM_NOX_1 [g]**	**EM_THC_1 [g]**	**CO [g]**	**Total C [g]**
index	523.5	0.3	0.42	4.0	24.5	156.7053
500W	785.6	1.1	1.70	2.1	46.2	235.8705
1000W	1205.2	6.3	9.83	2.8	59.0	356.392
2000W	2017.2	20.9	32.12	4.7	138.9	613.7184
1500W	1637.8	14.6	22.62	4.2	110.1	497.4279
1000W	1210.5	7.0	10.83	2.8	55.1	356.1882
500W	784.0	1.2	1.81	2.0	43.9	234.3686
fast idle	753.7	0.4	0.62	1.4	37.9	223.0278
idle	479.1	0.2	0.33	3.6	12.1	138.9626

	70% n-butanol Thursday				
POWER	**EM_CO2_1 [g]**	**EM_NO_1 [g]**	**EM_NOX_1 [g]**	**EM_THC_1 [g]**	**CO [g]**
index	523.4	0.2	0.35	4.2	12.2
500W	684.4	0.6	0.88	2.7	144.7
1000W	990.6	1.8	2.86	4.6	320.7
2000W	1552.2	3.4	5.30	8.1	540.0
1500W	1295.5	3.6	5.68	5.7	451.8
1000W	962.2	1.9	2.93	4.5	322.2
500W	735.4	0.8	1.20	2.3	105.3
fast idle	756.3	0.3	0.51	1.3	45.9
idle	492.4	0.2	0.37	8.1	11.5

70% Ethanol Thursday						
POWER	**EM_CO2_1 [g]**	**EM_NO_1 [g]**	**EM_NOX_1 [g]**	**EM_THC_1 [g]**	**CO [g]**	**Total C [g]**
idle	479.9	0.2	0.43	7.3	14.6	143.3726
500W	719.7	0.6	0.96	2.2	99.7	240.8693
1000W	1040.4	2.5	3.96	3.3	218.0	380.0536
2000W	1621.3	4.8	7.53	6.0	519.3	669.8733
1500W	1330.8	4.4	6.86	4.6	351.8	517.6894
1000W	1038.3	2.6	4.17	3.4	221.9	381.1855
500W	723.0	0.7	1.06	1.9	93.5	238.9244
fast idle	745.5	0.3	0.45	0.9	28.8	216.4341
idle	462.5	0.3	0.51	9.7	14.7	140.7759

	70% iso-butanol Thursday					
POWER	**EM_CO2_1 [g]**	**EM_NO_1 [g]**	**EM_NOX_1 [g]**	**EM_THC_1 [g]**	**CO [g]**	**Total C [g]**
idle	541.9	0.2	0.39	5.4	16.4	159.4826
500W	719.2	0.6	0.95	2.7	125.9	252.4069
1000W	1032.4	1.9	2.99	4.4	305.9	416.4558
2000W	1536.3	3.5	5.57	8.0	478.0	630.7079
1500W	1316.9	3.7	5.84	5.5	410.8	539.8984
1000W	1001.7	1.9	3.02	4.4	305.6	407.937
500W	752.1	0.7	1.13	2.4	105.0	252.1824
fast idle	757.8	0.3	0.53	1.8	60.8	234.2519
idle	555.6	0.2	0.42	6.2	14.8	163.1834

	Gasoline Thursday				
POWER	**EM_CO2_1 [g]**	**EM_NO_1 [g]**	**EM_NOX_1 [g]**	**EM_THC_1 [g]**	**CO [g]**
idle	513.6	0.2	0.39	4.4	61.3
500W	696.0	0.6	0.96	3.7	213.7
1000W	1087.7	3.1	4.91	4.9	303.0
2000W	1748.0	9.7	15.14	7.1	474.4
1500W	1346.0	5.5	8.53	6.6	425.7
1000W	1025.5	2.8	4.38	5.1	317.9
500W	669.1	0.6	0.97	3.6	208.7
fast idle	517.4	0.2	0.40	3.3	50.5
idle	661.5	0.3	0.55	2.8	142.6