INVESTIGATING THE EFFECTS OF ISOBUTANOL-GASOLINE BLENDS ON EXHAUST EMISSIONS AND ENGINE PERFORMANCE IN A SPARK IGNITION ENGINE

by

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This is the effects of isobutanol, which is an isomer of butanol, mixed in different ratios in gasoline fuel in a low-power single-cylinder spark ignition engine exhaust emissions on and engine performance according to engine load changes. The amount of isobutanol in the fuel compared to gasoline fuel reduced CO emissions. The addition of isobutanol reduced HC emissions for all engine loads. In addition, the formation of isobutanol accumulation in the fuel in the spark ignition engine significantly reduced NO_x *emissions compared to gasoline. For the highest engine load,* NO_x *emissions decreased by 39.55% for I20 fuel compared to gasoline. An increase was shown compared to brake specific fuel consumption gasoline in all mixture ratios with the use of isobutanol. The minimum brake specific fuel consumption was obtained as 383.76 g/kWh at 5000 W load with the use of I0 fuel. The maximum brake thermal efficiency value was obtained at 5000 W with the use of I0 fuel.*

Key words: *spark ignition engine performance, alternative fuel, isobutanol, emission*

Introduction

There has been a steady increase in energy consumption since the industrial revolution. Improvements in the quality of life, population growth, rapid economic growth in developing countries and industrialization are among the reasons for the increase in energy consumption [1]. Due to the high energy demand and limited resources due to developments, the interest in alternative fuels is increasing day by day [2].

Vehicle emissions cause significant negative impacts on air quality and human health at a global level. Fuel efficiency and emissions reduction are desired by the combustion industry due to environmental limitations and fuel costs [3].

Especially low power (engine power less than 25 hp) gasoline engines are air cooled, have low efficiency and high emission values because they operate with low compression ratios and rich mixtures. These engines have the potential to increase their performance and reduce emission values. Gasoline engines increase air pollution with CO, HC, and NO_x emissions. Engine emissions have a significant negative impact on air quality and human health globally. Many countries have also introduced emission limits for low-power engines. Low-power engines do not have exhaust control systems such as electronically controlled fuel system and

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catalytic converters because they increase the engine price. Therefore, emission values are high in these engines [4].

The use of alternative fuels containing oxygen in their structure is effective in reducing emission values [5]. Ethanol, methanol, butanol, liquid petroleum gas (LPG), natural gas, and hydrogen are used as alternative fuels in spark ignition engines. Due to the high pollutant emissions of petroleum fuels in spark ignition engines, researchers prefer alternative fuels that reduce pollutant emissions and increase engine performance as alternative fuels in existing engines. Researchers have been directed to evaluate the feasibility of fuels produced from biological sources as alternative fuels in current engines, which can reduce pollutant emissions and significantly increase engine performance. Alcohols are currently the most popular additives used as octane boosters in gasoline fuel, replacing all other additives. Alcohols derived from biomass fuels with high oxygen content and high octane number have an important place in alternative fuels [6, 7].

The use of ethanol and methanol as additives to gasoline in spark ignition (SI) engines results in phase separation and irregular engine operation. The use of butanol in diesel and gasoline engines shows better fuel blending properties than other alcohols. Butanol has a lower evaporation rate and an energy value 25% higher than ethanol. It is less corrosive than ethanol and can be used in existing fuel systems [8]. There are four isomers of butanol. Among them, isobutanol has a higher octane number than the others [9]. Isobutanol is present in about 16.6% by volume in fusel oil, which is a by-product of alcohol production. Isobutanol, which can be used by mixing it with gasoline in any ratio in internal combustion engines without requiring engine modification, is a four-carbon alcohol type that can be obtained by various biosynthesis methods and by distillation of fusel oil [10].

One of the major advantages of isobutanol is its adaptability to the existing gasoline infrastructure. Studies have shown that isobutanol can be blended with gasoline at higher concentrations than ethanol without requiring changes to the fuel system of conventional spark ignition (SI) engines. For example, Irimescu [11] has shown that blends containing up to 70% isobutanol (IB70) can be used effectively in unmodified engines, while pure isobutanol (IB100) presents difficulties in cold starting conditions at low ambient temperatures. This property makes isobutanol a more versatile option for fuel blending compared to ethanol, which typically requires lower blending ratios to avoid engine performance issues [12].

Although there are many studies on ethanol, methanol, and butanol in the literature, few studies have examined the impacts of isobutanol mixtures on engine performance [13-16].

Garayev *et al.* [16] presented the findings of a study investigating the emission and performance properties of gasoline-ethanol-water mixtures that include pyridine and isobutanol additives to improve water tolerance in a single cylinder gasoline engine. The researchers measured the phase equilibrium, specific fuel consumption, engine torque, effective power, and NO_x, CO, and HC emissions of blends containing different amounts of additives. The isobutanol-blended fuel mixture showed better results when compared to gasoline regarding emissions and engine performance.

Furthermore, isobutanol combustion in SI engines has been associated with cycle-to-cycle variations that can affect overall engine stability and performance, tab. 1. Shang *et al.* [17] highlighted the need for further research on the combustion dynamics of isobutanol to fully understand its impact on engine operation. This situation, with the findings of other researchers who have highlighted the importance of optimizing combustion parameters when using alternative fuels in SI engines [18].

Table 1. An insight into the impact of isobutanol use in SI engines

Source	Fuel(s) used	Brake power	BSFC	BTE	CO	CO_2	HC	NO_x	EGT
[19]	Gasoline + isobutanol	x	x	x	↓	x	↓	↑	↑
[20-22]	Gasoline + isobutanol	x	↑	↓	x	x	x	↓	↓
[23]	Gasoline + isobutanol	↓	×	×	↓≤2900min^{-1}>↑	↓	↓≤2800min^{-1}>↑	×	↓
[24]	Gasoline + isobutanol	×	↑	↓	×	×	×	×	×
[15]	Gasoline + ethanol + isobutanol	↑	↓	↑	↓	↑	↓	↑	↑
[16]	Gasoline + ethanol + water + isobuthanol	↑	↓	×	↓	×	↓	↓	×
[25]	Gasoline + isobutanol + sec-butanol + tert-butanol + n-butanol	↑	↑	↓≤3000min^{-1}>↑	↓	↑	↓	↑	↑
[26]	Gasoline + isobutanol + ethanol + methanol	x	↑	x	↓	x	↑	↓	x
[27]	Gasoline + methanol + butanol	×	↑	↓	×	×	×	×	↓
[28]	Gasoline + butanol	x	↑	↑	↓	x	↓	↑	x

" ↑" shows an increase, "↓" a decrease and "×" shows that the variable was not examined.

Table 2. Some properties of the fuels to be used in the study [23]

Specifications	Gasoline	Isobutanol
Chemical formula	C_8H_{15}	C_4H_9OH
LHV [MJkg^{-1}]	43.5	33.3
Density [kgm^{-3}]	760	802
Boiling point [°C]	25-215	108
Oxygen content [wt.%]	0.0	21.6
Saturation pressure at 38 °C [kPa]	31	2.3

Experimental

In the study, a generator with a Honda brand GX390 model carbureted single cylinder, air-cooled SI engine with SO 8.2:1 and a cylinder volume of 389 cm^3 was preferred for starting the engine tests. Technical specifications of the engine-generator unit used are given in tab. 3. In the experiments, a recessive load unit with a maximum load rating of 6 kW was used to change the engine load. Measure the emission values was used to K test brand emission measuring device. The measurement parameters and sensitivity values of the emission analyzer are given in tab. 4. Schematic representation of the setup where the experiments were performed is given in fig. 1.

Table 3. Engine technical data

Engine type	4 stroke, overhead valve, single cylinder, horizontal shaft
Bore × stroke [mm]	88 × 64
Cylinder volume [cm^3]	389,25
Compression ratio	8.2:1
Net output power (BG)	8.7 kW (11.7 hp) / 3600 rpm
Max. torque	26.5 Nm (2.7 kgfm) / 2500 rpm

Table 4. Emission emission analyzer and thermocouple technical specifications

Parameter	Measurement scale	Accuracy variables
O_2 [%]	0-25	±0.1
CO_2 [%]	0-20	±0.01
CO [%]	0-15	±0.01
HC [ppm]	0-20.000	±0.12
NO_x [ppm]	0-5000	±1
K-type thermocouple [°C]	–2000.1200	±0.004

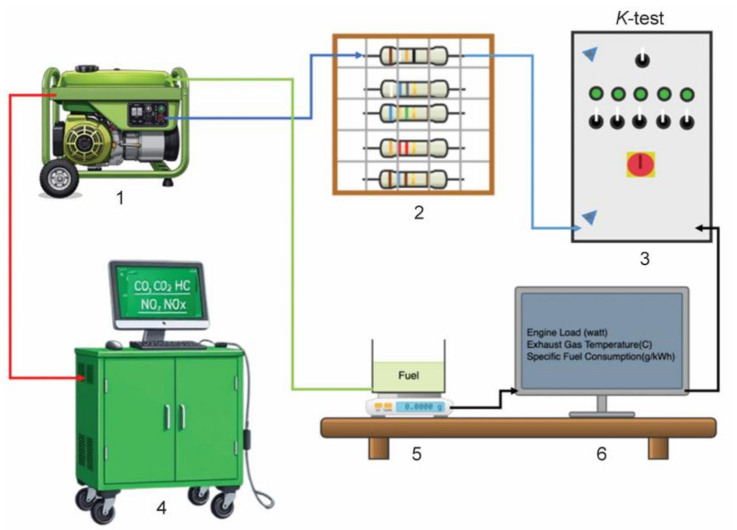

Figure 1. Schematic view of the test system; *1 - experiment motor generator group, 2 - load resistors, 3 - experiment set control panel, 4 - emission device, 5 - precision balance, and 6 - computer*

A Radwag brand WLC X2 model 0.1 g precision electronic scale was used to measure fuel consumption. Since alcohol is volatile, in order to obtain high precision measurements, fuel mixtures were created and filled into the tank when the experiment was started, and instantaneous fuel consumption measurements were made using the mass method. In the experiments, a control panel with a programmable logic controller was used to systematically collect instantaneous fuel consumption and exhaust gas temperature (EGT) data. For specific fuel consumption data, time-dependent fuel status information obtained from the precision scale and thermocouple data used for measuring EGT were instantly transferred to the test screen. They were also saved as .xls files in the data files.

In this study, isobutanol, which does not cause phase separation when mixed with gasoline and has a high octane number, was preferred. The effects of gasoline-isobutanol (isobutanol additives to gasoline 5%, 10%, 15%, and 20% by volume) mixtures on engine performance and emission parameters in a single-cylinder spark ignition engine were investigated.

Results and discussion

Performance and emissions

Brake specific fuel consumption (BSFC) is a parameter that shows the amount of fuel consumed per unit power. The effect of studies conducted with isobutanol-gasoline mixtures and gasoline on BSFC is shown in fig. 2. The BSFC decreased for all fuel types as the engine load increased. In addition, BSFC increased at all loads as isobutanol addition increased. Since the lower heating value (LHV) of alcohols is lower than gasoline, more fuel must be used to obtain the same output power [29]. For this reason, BSFC is higher when alcohols are used as fuel than when gasoline is used. The lowest BSFC value was obtained with I0 fuel at 5000 W engine load. This value was measured 19% more BSFC for I20, which has the highest isobutanol solids in the study at the same engine load.

Brake thermal efficiency (BTE) is an indicator of the rate at which fuel energy is converted into useful work. The calculated BTE values are given in fig. 3. It is seen that FEV values increase with increasing engine load. The maximum BTE value was recorded for I0 fuel at 5000 W engine load where the lowest BSFC was recorded. As the isobutanol ratio increased at the same engine load, the BTE value decreased. Compared to the I0 fuel consisting of pure gasoline, the increase in isobutanol content in the blends caused a decrease in the BTE values [30].

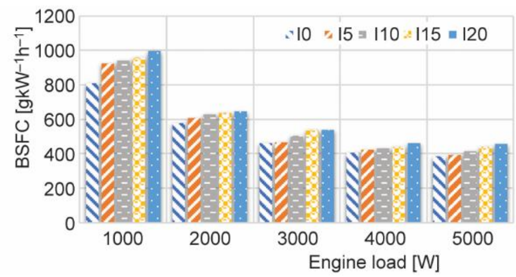

Figure 2. The BSFC

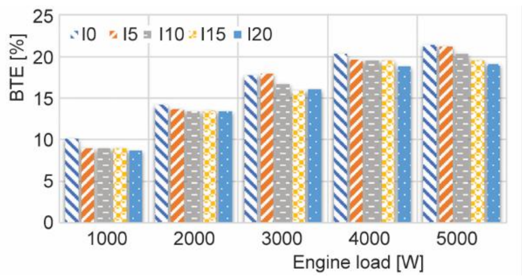

Figure 3. The BTE

The EGT given in fig. 4 increased for all fuels as the engine load increased. When the engine load increased, the combustion chamber temperature increased and this increased the EGT. The EGT decreased as the isobutanol content in the fuel blends increased, slowing down combustion at all engine loads. The effect of isobutanol on EGT was more pronounced at low engine loads than at high engine loads. Especially for I10 fuel, the lowest EGT was obtained at all loads. At the 5000 W engine load where the highest EGT was obtained, the EGT value decreased by 4.6% compared to I10 fuel and I0 fuel without isobutanol additive. This decrease is due to the high latent heat of vaporization of alcohol [31].

The CO emission, which is an important indicator of combustion in the cylinder, is the product of incomplete combustion caused by oxygen deficiency. The number of carbon atoms in the chemical composition of the fuel directly affects CO emission. Figure 5 shows the CO emissions obtained with engine load variation. As the engine load increased, the CO emission values decreased until the highest engine load of 5000 W. It was observed that isobutanol blended fuels reduced CO emission values compared to I0 fuel. Alcohol fuels have fewer carbon atoms in their chemical composition compared to gasoline and have lower C/H ratios, thus providing cleaner combustion and reducing CO emissions [32]. The lowest CO value was obtained as 0.138 %V for 5000 W engine load. When compared with I0 fuel at the load where the lowest CO emission value was obtained, it reduced CO emission by 93.72%.

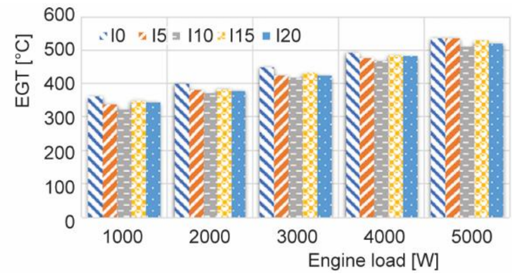

Figure 4. The EGT

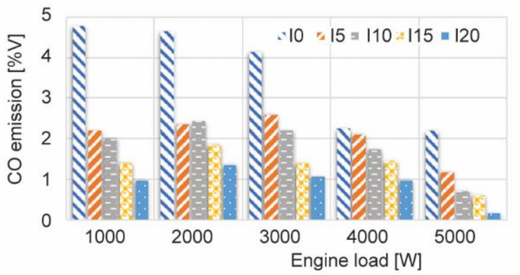

Figure 5. The CO emissions

The HC emissions occur due to incomplete combustion in the cylinder for any reason. The HC emissions generally increase as engine load increases. At high engine loads, the combustion chamber temperature rises and combustion occurs faster. This increases the likelihood of the formation of unburned HC and increases HC emissions. The effect of isobutanol additive on HC emissions is more pronounced at low engine loads than at high engine loads. This is due to the fact that combustion is slower and more homogeneous at low loads and isobutanol stabilizes the combustion process better. This is due to the fact that isobutanol has a higher oxygen content than gasoline as indicated in tab. 2 [25]. Figure 6 shows that the lowest HC value of isobutanol additive at 4000 W engine load is obtained for I20 fuel. When the HC value of I0 fuel is compared for the same load value, a decrease of 89.07% is observed.

Nitrogen is the most abundant element in the air. The air taken into the cylinder combines with oxygen at the time of combustion when the temperature in the cylinder rises above 1800 °C and forms NO_x emission [33]. As the engine load increases, the combustion chamber temperature increases and NO_x formation increases. It has been observed that as the isobutanol contribution increases, it reduces the combustion temperature for all loads and prevents NO_x formation. Isobutanol has a high specific heat capacity and absorbs more heat in the combustion chamber, limiting the temperature increase in the combustion chamber. This reduces the temperature of the exhaust gases in the combustion chamber, reducing NO_x formation [34]. The highest NO_x value was measured as 2771 ppm at 5000 W engine load for I0 fuel. It was observed that the NO_x value was reduced by 39.55% when I0 and I20 fuels were compared at the engine load where the highest NO_x value was observed. For the highest engine load, the NO_x value obtained with I20 fuel decreased by 71.95% compared to I0 fuel.

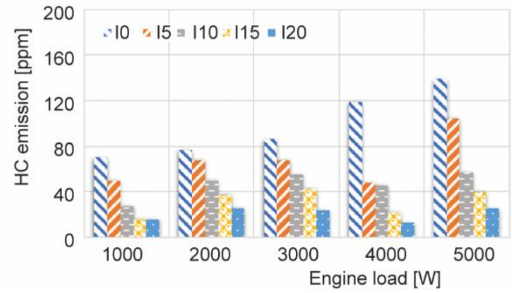

Figure 6. The HC emissions

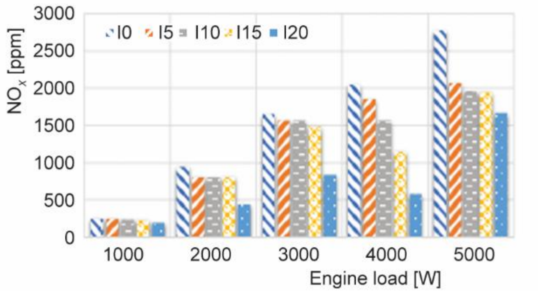

Figure 7. The NO$_x$ emisions

Conclusions

A gasoline engine fueled with isobutanol and gasoline mixtures was characterized at five engine loads (1-5 kW). Some results can be summarized as follows.

The LHV of isobutanol compared to gasoline caused an increase in the BSFC value for the same engine loads in all gasoline-isobutanol blends.

The addition of isobutanol reduced EGT at all engine loads. The I10 fuel with under all test conditions value was achieved the lowest EGT.

For all isobutanol-gasoline blends and at all engine loads, BTHE decreased compared to I0 fuel.

Due to the high O content of isobutanol, CO emissions have been significantly reduced for I5, I10, I15 and I20 fuels compared to I0 fuel.

The HC emissions decreased at all engine loads. At low engine loads, isobutanol accumulation was more effective in reducing HC emissions.

The NO$_x$ emissions increased as engine load increased. Compared to gasoline, NO$_x$ values decreased in all fuel blends.

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Nomenclature

BP – brake power
BSFC – brake specific fuel consumption
BTE – brake thermal efficiency
CO – carbon monoxide (emissions)
EGT – exhaust gas temperature
HC – hydrocarbon
I0 – pure gasoline
I5 – blend containing 5 vol% of isobutanol in gasoline
I10 – blend containing 10 vol% of isobutanol in gasoline
I15 – blend containing 15 vol% of isobutanol in gasoline
I20 – blend containing 20 vol% of isobutanol in gasoline
iBu – isobutanol
LHV – lower heating value
nBu – n-butanol, 1-butanol
NO – nitrogen monoxide or nitric oxide
SI – spark ignition (engine)
sBu – sec-butanol
tBu – tert-butanol

References

[1] Lee, Sunggyu., *et al.*, *Handbook of Alternative Fuel Technologies*, CRC Press, Boka Raton, Fla, USA, 2007

[2] Awad, O. I., *et al.*, Using Fusel Oil as a Blend in Gasoline to Improve SI Engine Efficiencies: A Comprehensive Review, *Renewable and Sustainable Energy Reviews*, *69* (2017), Oct., pp. 1232-1242
[3] Sun, S., *et al.*, Vehicle Emissions in a Middle-Sized City of China: Current Status and Future Trends, *Environ Int, 137* (2020), 105514
[4] Celik, M. B., Performance Improvement and Emission Reduction in Small Engine with Low Efficiency, *Journal of the Energy Institute, 80* (2007), 3, pp. 175-180
[5] Celik, M. B., Experimental Determination of Suitable Ethanol-Gasoline Blend Rate at High Compression Ratio for Gasoline Engine, *Appl. Therm. Eng., 28* (2008), 5-6, pp. 396-404
[6] Bayrakceken, H., Kus, R., Alternative Fuels Used in Vehicle, *J. of Science, 6* (2006), 1, pp. 125-144
[7] Brownstein, A. M., *Renewable Motor Fuels: The Past, the Present, and the Uncertain Future*, Butterworth-Heinemann, Oxford, UK, 2015
[8] Avci, A., Donmez, S., Butanol as Biofuel and Fermentation Production, *Electronic Journal of Microbiology TR, 2* (2011), pp. 1-12
[9] Rosenblatt, D., *et al.*, Particulate Measurements: Ethanol and Isobutanol in Direct Injection Spark Ignited Engines, Report, The International Energy Agency Advanced Motor Fuels, IEA, Annex 35-2, pp. 24-27
[10] Uslu, S., Investigation of Using Amyl Alcohol on Spark Ignition Engine with Experimental and Artificial Neural Networks, Ph. D. thesis, Karabuk University, Karabuk, Turkey, 2018
[11] Irimescu, A., Study of Cold Start Air-Fuel Mixture Parameters for Spark Ignition Engines Fueled with Gasoline-Isobutanol Blends, *International Communications in Heat and Mass Transfer, 37* (2010), 9, pp. 1203-1207
[12] Schifter, I., *et al.*, Performance and Emissions of Gasoline-Dual Alcohol Blends in Spark-Ignited Single Cylinder Engine, *International Journal of Engine Research, 18* (2017), 9, pp. 941-950
[13] Kilicaslan, K., The Effect of Engine Performance and Exhaust Emissions of Isobutanol-Diesel Blends, Ph. D. thesis, Marmaru University, Istanbul, Turkey, 2010
[14] Elfasakhany, A., *Investigations on Performance and Pollutant Emissions of Spark-Ignition Engines Fueled with n-Butanol-, Isobutanol-, Ethanol-, Methanol-, and Acetone–Gasoline Blends: A Comparative Study*, Elsevier Ltd., Amsterdam, The Netherlands
[15] Zaharin, M. S. M., *et al.*, Evaluation on Physicochemical Properties of Iso-Butanol Additives in Ethanol-Gasoline Blend on Performance and Emission Characteristics of a Spark-Ignition Engine, *Appl. Therm. Eng., 144* (2018), Nov., pp. 960-971
[16] Garayev, A., *et al.*, Performance and Emission Characteristics of Pyridine and Isobutanol Added Gasoline-Ethanol-Water Blends in a Single Cylinder SI Gasoline Engine, *Journal of Thermal Science and Technology, 41* (2021), 1, pp. 11-21
[17] Shang, W., *et al.*, An Experimental Study on Combustion and Cycle-By-Cycle Variations of An N-Butanol Engine with Hydrogen Direct Injection under Lean Burn Conditions, *Sensors*, *22* (2022), 3
[18] Michelbach, C., Tomlin, A., An Experimental and Kinetic Modeling Study of the Ignition Delay and Heat Release Characteristics of a Five Component Gasoline Surrogate and Its Blends with Iso-Butanol within a Rapid Compression Machine, *Int. J. Chem. Kinet., 53* (2021), 6, pp. 787-808
[19] Regalbuto, C., *et al.*, Experimental Investigation of Butanol Isomer Combustion in Spark Ignition Engines, *Proceedings*, SAE Technical Papers, 2021-01-1271, 2012
[20] Alasfour, F. N., Effect of Using 30% Iso-Butanol-Gasoline Blend on Hydrocarbon Emissions from a Spark-Ignition Engine, *Energy Sources, 21* (1999), 5, pp. 379-394
[21] Alasfour, F. N., NOx Emission from a Spark Ignition Engine Using 30% Iso-Butanol-Gasoline Blend: Part 1 Preheating Inlet Air, *Applied Ther. Engin., 18* (1998), 5, pp. 249-256
[22] Alasfour, F. N., Butanol - a Single Cylinder Engine Study: Engine Performance, *Int. J. Energy Res., 21* (1997), 1, pp. 21-30
[23] Elfasakhany, A., Experimental Investigation on SI Engine Using Gasoline and a Hybrid Iso-Butanol/Gasoline Fuel, *Energy Convers. Manag., 95* (2015), May, pp. 398-405
[24] Irimescu, A., Fuel Conversion Efficiency of a Port Injection Engine Fueled with Gasoline-Isobutanol Blends, *Energy, 36* (2011), 5, pp. 3030-3035
[25] Yusoff, M. N. A. M., *et al.*, Performance and Emission Characteristics of a Spark Ignition Engine Fuelled with Butanol Isomer-Gasoline Blends, *Transp. Res. D. Transp. Environ., 57* (2017), Dec., pp. 23-38
[26] Rice, R. W., *et al.*, Exhaust Gas Emissions of Butanol, Ethanol, and Methanol-Gasoline Blends, *J. of Engin. for Gas Turbines and Power, 113* (1991), 3, pp. 377-381
[27] Alasfour, F. N., A Single-Cylinder Engine Study: Availability Analysis, *Applied Thermal Engineering, 17* (1997), 6, pp. 537-549

[28] Saraswat, M., *et al.*, Performance and Emission evaluation of Butanol blends in SI Engine, *Proceedings*, 2nd Int. Con. on Compu. and Expe. Methods in Mech. Engi., Greater Noida, India
[29] Wojcieszyk, M., *et al.*, Performance of Anisole and Isobutanol as Gasoline Bio-Blendstocks for Spark Ignition Engines, *Sustainability (Switzerland), 13* (2021), 16
[30] Varol, Y., *et al.*, Comparison of Methanol, Ethanol, or N-Butanol Blending with Unleaded Gasoline on Exhaust Emissions of an SI Engine, *Energy Sources, Part A: Recovery, Utilization and Environmental Effects, 36* (2014), 9, pp. 938-948
[31] Rodríguez-Antón, L. M., *et al.*, Physical Properties of Gasoline, Isobutanol and ETBE Binary Blends in Comparison with Gasoline Ethanol Blends, *Fuel, 166* (2016), Feb., pp. 73-78
[32] Awad, O. I., *et al.*, *Overview of the Oxygenated Fuels in Spark Ignition Engine: Environmental and Performance,* Elsevier Ltd., Amsterdam, The Netherlands
[33] Olson, A. L., *et al.*, A Review of Isobutanol as a Fuel for Internal Combustion Engines, Multidisciplinary Digital Publishing Institute (MDPI), *Energys, 16* (2023), 22, 7470
[34] Xiao, H., *et al.*, Combustion Performance and Emission Characteristics of Diesel Engine Fueled with Iso-Butanol/Biodiesel Blends, *Fuel, 268* (2020), 117387

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