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Investigation of Engine Performance Parameters and Emissions Upon Adding Solketal Admixture to Gasoline Fuel

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Abstract:

Purpose: *This research investigates the effects of adding solketal to gasoline on engine performance and environmental emissions. Solketal was mixed with gasoline to power a 150-cc motorcycle engine, tested under different loads (1.2 Nm, 6.2 Nm, and 11.2 Nm) at five RPMs (570, 850, 1044, 1269, and 1427).*

Design/Methodology/Approach: *We start by synthesizing glycerol as a byproduct of biodiesel production, and then we add solketal as an additive to gasoline. To examine the performance characteristics and combustion-generated emissions, we tested the physical and chemical properties of the blended fuel. Chemical and physical properties of the blended fuels were examined and measured, including density, heat value, flash point, and chemical exergy. Density was determined using an Anton DMA 35 device, while the heat value and flash point were assessed with a Labtron LBC-C22 oxygen bomb calorimeter and a PMA 5 tester, respectively.*

Findings: *Glycerin, a byproduct of biodiesel production, poses challenges for biodiesel manufacturing. Performance parameters like brake power (Pb), brake-specific fuel consumption (BSFC), brake thermal efficiency (BTE), and emissions (CO, CO2, O2, UHC) were assessed. Findings showed that a 15% solketal blend with gasoline re-sulted in optimal engine performance and decreased pollution emissions compared to other concentrations.*

Practical Implications: *This blend ratio notably reduced CO and UHC emissions. Moreover, incorporating the three compounds into gasoline improved brake power exergy due to their high density.*

Originality/Value: *Urban air pollution is mainly caused by gasoline-fueled internal combustion engine vehicles. Adding biofuel-based additives to gasoline presents a practical solution for decreasing emissions while improving engine performance.*

Keywords: *Glycerol derivatives, solketal, engine performance, environmental pollutants.*

JEL codes: *Q530, Q16.*

Paper type: *Research article.*

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1. Introduction

Presently, approximately 85% of the fuel consumed globally is derived from non-renewable fossil fuels (Ağbulut *et al.*, 2019). Studies have indicated that the transportation sector is the primary consumer of fossil fuels, leading to air pollution in both urban and rural areas (Tibaquirá *et al.*, 2018). The number of engine-powered vehicles is projected to reach 1.3 billion by 2030, with most of the increase expected in developing countries (Balat and Balat, 2009).

Due to the high cost and unsustainable nature of fuel sources, as well as the need to reduce emissions from fuels, there is a growing focus on improving the efficiency of internal combustion engines (ICEs) (Mohebbi *et al.*, 2018). Gasoline, a hydrocarbon mixture, is commonly used as fuel for ICEs. Refined from crude oil, gasoline is required to meet specific physical and chemical properties. Therefore, various standard codes govern the final gasoline product (Zhang and Batterman, 2010).

The air pollution resulting from the combustion of fossil fuels in the transportation sector comes in various forms, including suspended particulate matter (SPM), carbon monoxide (CO), unburned hydrocarbons (UHC), and nitrogen oxides (NOx), which have significant impacts on urban air quality (Liaquat *et al.*, 2010). Gasoline-fueled engines require a combustible mixture of air and gasoline, ignited by a spark from the spark plug. An internal combustion engine (ICE) is designed for a specific octane rating (OR).

Therefore, using gasoline with a lower OR than the design may cause knocking and ultimately damage the engine (Sharudin *et al.*, 2019). Conversely, the potential for reducing environmental emissions from fossil fuel combustion by altering fuel composition has led to extensive research on the use of renewable resources to achieve this goal (Elfasakhany, 2016). As a type of renewable resource, biomass fuels can be produced in various ways and then utilized as fuel or as an additive to a base fuel (Yusuf and Inambao, 2021).

To enhance its performance, different additives have been mixed with gasoline. The majority of relevant studies have focused on ethanol, oxygenated compounds, hydrogenated compounds, and alcoholic substances. Several research works have investigated oxygenated fuels such as glycerol derivatives, ethanol, or other alcoholic fuels in ICEs (Mukhopadhyay *et al.*, 2015; Liu *et al.*, 2015; Balki and Sayin, 2014; Alptekin *et al.*, 2015).

Ethanol and methanol, being cost-effective and demonstrating performance characteristics similar to gasoline, have shown the greatest potential for the transportation industry (Yusuf and Inambao, 2021; Balla *et al.*, 2013). However, pure ethanol cannot be directly used in premanufactured engines; instead, it should be blended with gasoline before being utilized in such engines (Sakthivel *et al.*, 2020).

The blending of gasoline and ethanol tends to boost the octane rating of the fuel. In fact, incorporating ethanol into gasoline at a 30% blending ratio has been observed to raise the octane rating from 92 to 100 (Sakthivel *et al.*, 2019). Regardless of the blending ratio, the addition of ethanol to gasoline improves the output torque while increasing the fuel consumption of the engine (Dorney *et al.*, 2001).

This adjustment decreases the CO and UHC emissions of ICEs under various operating conditions (Iodice and Cardone, 2021). A common method of biodiesel synthesis is the transesterification process, which results in long-chain fatty acids along with short-chain alcohols such as methanol and ethanol (Hosseinpour *et al.*, 2016; Hajjari *et al.*, 2017).

Conversely, the transesterification process yields glycerol and methyl/ethyl ester (Aghbashlo *et al.*, 2017). Methyl/ethyl esters, accompanied by significant amounts of glycerol as a byproduct, are the primary products of the transesterification process. The growing demand for biodiesel has led to an increase in glycerol production worldwide, significantly impacting the supply-demand balance for this chemical product (Khalife *et al.*, 2018).

As a byproduct of biodiesel synthesis, glycerol accounts for approximately 10 wt.% of the total output products. The growing demand for biodiesel in recent years has led to a surplus of glycerol in the market, resulting in a decrease in its price and posing economic challenges for the biodiesel industry. This highlights the need to convert the abundant glycerol into a valuable resource through efficient, sustainable processes to support the biodiesel sector.

However, the low calorific value, inefficient combustion, and the production of acrolein, a highly toxic substance, when raw glycerol is burned, hinder its direct use as a fuel. To tackle these challenges, the glycerol obtained from biodiesel production is commonly transformed into an additive for oxygenated fuels.

This resulting additive not only recovers the energy content of glycerol but also decreases the emission of harmful gases due to the oxygen present in its molecular structure. Glycerol can be converted into an additive for oxygenated fuels through various methods, such as esterification, acetalization, sterilization, and catalysis.

Among the different glycerol-based additives, solketal (2,2-dimethyl-1,3-dioxolane-4-methanol) produced through catalysis can enhance fuel viscosity and combustion temperature (Aghbashlo *et al.*, 2018). In this research, the use of glycerol derivatives with the name Solketal will be considered, and in few researches, the effect of adding glycerol derivatives, especially Solketal, to gasoline has been investigated.

Therefore, this is a completely new issue that will be investigated experimentally and experimentally for the first time in this research. Therefore, the studies on the performance of the mixture of Solketal and gasoline are limited and are mostly about the production of Solketal and knowing its properties. In this research, the assumptions considered will be that the additives derived from glycerol will improve the performance (power, torque, fuel consumption) and the thermal efficiency of the engine) and reduce the emissions from the gasoline engine.

This type of fuel showed optimal behaviors in some percentages of its combination, which caused the best engine performance compared to other additive combinations and other percentages, resulting in a reduction in emissions. The use of oxygenated additives for fuel adjustment is considered an intriguing approach to reducing NOx formation (Aghbashlo *et al.,* 2019). Biodiesel fuels have drawbacks such as increased NOx emissions, poor atomization, and incomplete combustion. Admixtures and catalysts can help mitigate the negative impacts of biodiesel fuels.

Additionally, the use of metal oxides and metal nanoparticles is known to pose environmental risks. However, the use of biodegradable nanoparticles can significantly reduce these concerns (Aram Heidari-Maleni *et al.*, 2021). A study was conducted to investigate the effects of using a blend of diesel and biodiesel (derived from waste edible oil) at blending ratios of 5 and 10 vol.% on the combustion performance of a single-cylinder diesel engine running at a fixed rate of 1500 rpm.

The results indicated that, depending on the blending ratio, blending diesel with biodiesel can decrease thermal brake performance by 1.7 – 4.14% while increasing fuel consumption by 2.18 – 5.57% due to the higher viscosity and density of biodiesel, which hinders fuel atomization.

The use of the blended fuel also led to a reduction in the emission of CO, UHC, and CO_2, although it increased the emission of NOx (by 0.3 – 4.2%), primarily due to the higher cetane number of the blend compared to conventional diesel, which reduces the ignition delay of the internal combustion engine (Borugadda et al., 2018). The addition of solketal to the gasoline resulted in higher octane rating and density of the blend, along with a decrease in blend viscosity. The use of solketal led to a higher specific fuel consumption (SFC) compared to using pure gasoline.

Emission analysis results showed a reduction in CO and UHC emissions, accompanied by an increase in NOx and CO_2 production (Alptekin *et al.,* 2017). This study indicated that adding ethanol/methanol to gasoline can significantly reduce the emission of greenhouse gases (GHGs) while increasing engine efficiency, with the magnitudes of such effects varying with the blending ratio (Yusuf and Inambao, 2021).

Another study explored the conversion of glycerol (a byproduct of biodiesel synthesis) to triacetin and its application as a fuel admixture for ICEs. The tested fuels included different blends of gasoline with methanol and triacetin, compared against pure gasoline.

A response surface methodology (RSM)-based multi-objective optimization approach was used to optimize output parameters of the engine (e.g., NOx, HC, CO_2, CO, and BTE). Results showed that the tested engine produces a brake power of 1.17 kW with a fuel comprising gasoline (90.73 vol.%), methanol (4.94 vol.%), and triacetin (4.31 vol.%).

Investigation of the impact of using a blend of ethanol and glycerol to power a reciprocating ICE revealed that the suggested fuel (ethanol and glycerol at a blending ratio of 3:1, i.e., 75% ethanol and 25% glycerol) was entirely renewable. The analysis of the combustion of the ethanol-glycerol fuel in the examined engine focused on combustion thermodynamics and exhaust emissions. The findings were compared to those of gasoline and ethanol as reference fuels. The results indicated that the levels of NOx, CO, and UHCs emissions were not significantly different from those observed with gasoline. The engine performance, as represented by indicated mean effective pressure (IMEP), decreased by less than 3%, while the thermal efficiency was approximately 4% lower compared to using ethanol as fuel.

Further research revealed that the emission levels were quite similar to those of gasoline, except for CO, which was notably lower with the proposed fuel blend (Szwaja *et al.*, 2022). Despite the widespread investigations performed on the use of alcohols to enhance motor performance while reducing combustion-related emissions, it is clear that the disadvantages of alcohols tend to outweigh the benefits of introducing additives to the fuel. Therefore, in the current study, solketal was utilized as an additive to gasoline fuel, and the impact on engine performance parameters and combustion emissions was examined.

2. Materials and Methods

In this experiment, you used a 150 cc single cylinder engine and we transferred the necessary force from the output shaft of the gearbox using the horizontal axis to a gearbox with a ratio of 5.7 to 1, then using a dynamometer that was designed and used by ourselves. We checked and reported the necessary parameters. The method of fuel consumption is based on the volume rate of fuel.

Analyzing exhaust gases by spx device, which we measured the analysis of 4 gases carbon monoxide, carbon dioxide, oxygen and unburned hydrocarbons. The compression ratio is 8:1 based on the characteristic curve of the tested engine. The type of fuel injection into the engine is based on the carburetor system. In this system, we did not use the catalyst because it was not installed on the system.

2.1 Fuel Properties

Chemical and physical properties of the blended fuels were examined and measured, including density, heat value, flash point, and chemical exergy. Density was determined using an Anton DMA 35 device, while the heat value and flash point were assessed with a Labtron LBC-C22 oxygen bomb calorimeter and a PMA 5 tester, respectively. The physical characteristics of the blend used are detailed in Table 1.

Table 1. *Physical properties of the used fuels.*

FUEL	Abbreviation	Low heat value (kJ/kg)	Chemical exergy (kJ/kg)	Density (kg/L)	Flash point
Gasoline	G	43400	46556	0.737	- 43
Gasoline + Admixture Solketal at 5%	G+A5%	38688	42452	0.775	- 26.3
Gasoline + Admixture Solketal at 10%	G+A10%	38003	41732	0.785	- 23.5
Gasoline + Admixture Solketal at 15%	G+A15%	37318	41010	0.795	- 20.7

Source: *Own calculations.*

2.2 Test Procedure

According to the characteristics of this substance that has been the attention of researchers, we also studied by combining this substance in different percentages with gasoline fuel according to the desired conditions.

The engine test took place at an ambient temperature of 32 degrees and an altitude of 1320 meters above sea level. Effects of admixtures at various blending ratios on performance parameters of a 150-cc four-stroke engine were examined at different levels of applied load (1.2, 6.2, and 11.2 Nm) with a constant engine rotational speed of 2500 rpm and five gearbox output rotational speeds (570, 850, 1044, 1269, and 1427 rpm).

2.3 Analysis

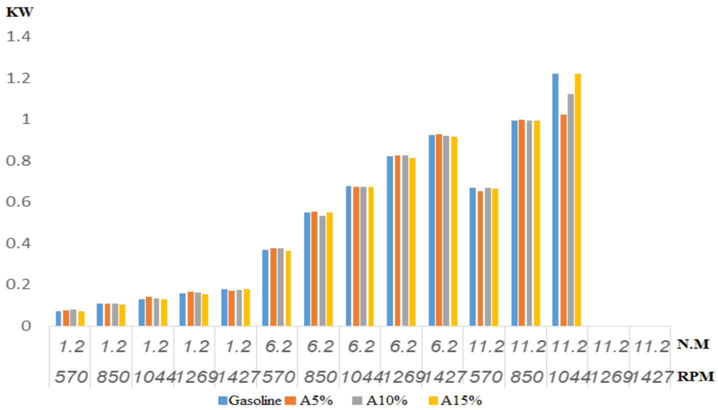
Each engine test was conducted in quadruplicate. The performance parameters and combustion-generated emissions were calculated and analyzed. RSM was utilized for the design of experiments in this study. The data analysis and graphical presentation of the resulting diagrams were carried out in Design Expert ver. 13.0.5.

3. Results and Discussion on Engine Performance Parameters

3.1 Brake Power (Pb)

Figure 1 illustrates the changes in brake power concerning the engine load and gearbox output speed for the examined blended fuels (solketal mixed with gasoline). However, with an increase in the engine load to 6.2 and then 11.2 Nm, the brake power surged significantly. The addition of solketal to gasoline up to 15% resulted in a slight boost in brake power, likely due to the oxygen present in the molecular structure of the blended fuel; this contributes to the oxygen content of the mixture, promoting combustion completion. The higher density of the blend raises the oxygen content per unit volume of the injected fuel, enhancing the engine's brake power. Referring to Figure 1, fuel blends with 5% and 10% solketal exhibited slightly lower performance compared to the blend with 15% solketal across all engine operating conditions. As depicted in Figure 1, nearly identical brake powers were achieved at an engine load of 11.2 Nm and gearbox output speeds of 850 and 1044 rpm.

Figure 1. *Variations of brake power with applied load when solketal is admixed with gasoline at 3 different blending ratios.*



Source: *Own study.*

3.2 Brake-Specific Fuel Consumption (BSFC)

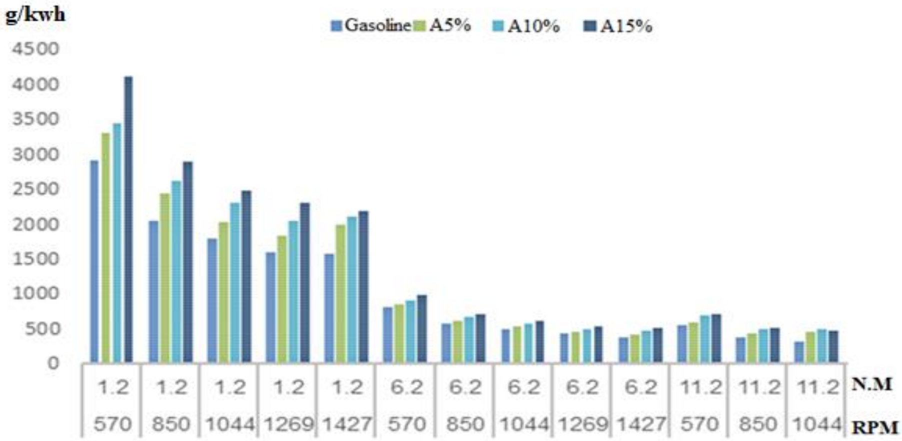
According to Figure 2, BSFC was highest at an applied load of 1.2 Nm and a gearbox output speed of 570 rpm, compared to other levels. BSFC shows a decreasing trend as the applied load and gearbox output speed increase beyond these levels. In general, admixtures displayed higher BSFCs than the base fuel (i.e., gasoline), consistent with the findings of (Alptekin and Canakci et al., 2017) from their investigation of the engine under various operating conditions with different fuels. BSFC decreases with an increase in either the applied load or the gearbox output speed.

3.3 Brake Thermal Efficiency (BTE)

Figure 3 illustrates variations of BTE with the applied load to the engine for different gasoline-based fuels. According to this figure, the BTE increases with the applied load and gearbox output speed. This increase is noticeable at applied loads of 6.2 and 11.2 Nm.

Based on Figure 3, when the applied load was fixed at 1.2 Nm, the BTE was measured at 41.9, 39, and 36.3 for the solketal dosages of 5, 10, and 15%, respectively, indicating a decreasing trend.

Figure 2. *Variations of BSFC with applied load when solketal is admixed with gasoline at 3 different blending ratios.*

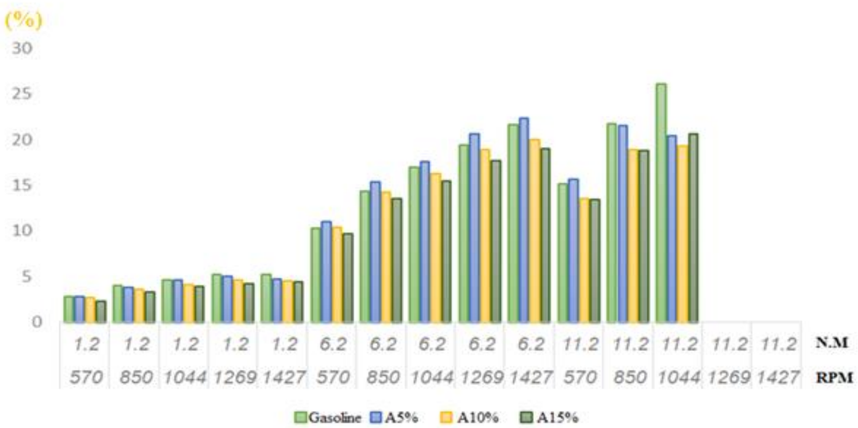


Source: *Own study.*

When the applied load was fixed at 6.2 Nm, the BTE was measured at 174, 159.8, and 151 for the solketal dosages of 5, 10, and 15%, respectively. When the applied load was maximized at 11.2 Nm, the BTE was measured at 192.3, 172.6, and 176.3 for the solketal dosages of 5, 10, and 15%, respectively.

Consequently, the results showed that, on average, the BTE increases with the dosage of admixture, thereby reducing the brake thermal value. With the solketal, average BTE for the admixture dosages of 5, 10, and 15% was measured at 3.4, 73.127, and 112.116, respectively, with an average total BTE of 118.81. Indeed, the solketal admixture provided for 8.6 lower BTE than the base fuel.

Figure 3. *Variations of BTE with applied load when solketal is admixed with gasoline at 3 different blending ratios.*



Source: *Own study.*

3.4 Combustion-Generated Emissions

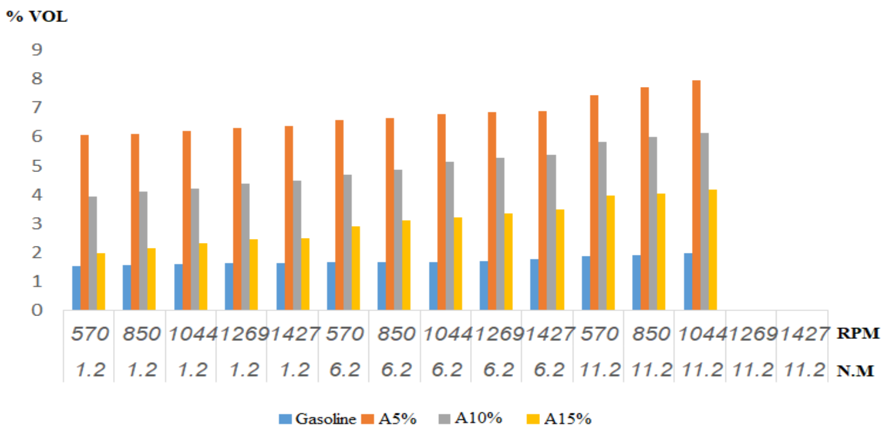
This section examines the combustion-generated emissions of the tested engine, such as carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), and unburned hydrocarbons (UHCs). The engine is fueled by a blend of gasoline and solketal at varying dosages (5, 10, and 15%) and operates at a constant rotational speed of 2500 rpm under different applied loads (1.2, 6.2, and 11.2 Nm) and various gearbox output speeds (570, 850, 1044, 1269, and 1427 rpm).

3.4.1. Carbon monoxide (CO)

CO is a toxic and odorless gas produced in an engine operating at rich equivalence ratios (Yakın and Behçet, 2021). When there is insufficient oxygen to convert all carbon in the fuel to CO_2, incomplete combustion results in CO formation. Figure 4 illustrates CO emissions during gasoline combustion with a heat value of 43400 kJ/kg. The figure indicates that CO emission rises from 1.53 vol.% to 1.98 vol.% as the applied load and gearbox output speed increase to 11.2 Nm and 1269 rpm, respectively.

Incomplete combustion leading to CO formation in the combustion chamber is caused by low oxygen levels and/or high equivalence ratios (Yusuf et al., 2021). CO emissions were present in all operational conditions. The impact of adding solketal to conventional gasoline is clearly shown in the comparative bar chart of CO emissions in Figure 4. The chart demonstrates that CO emission decreases as the admixture dosage increases. A more pronounced decrease was observed when the fuel blend with a 5% admixture was tested under loads ranging from 1.2 to 11.2 Nm at any of the five gearbox output speeds.

Figure 4. *Variations of CO emissions with applied load when solketal is admixed with gasoline at 3 different blending ratios.*



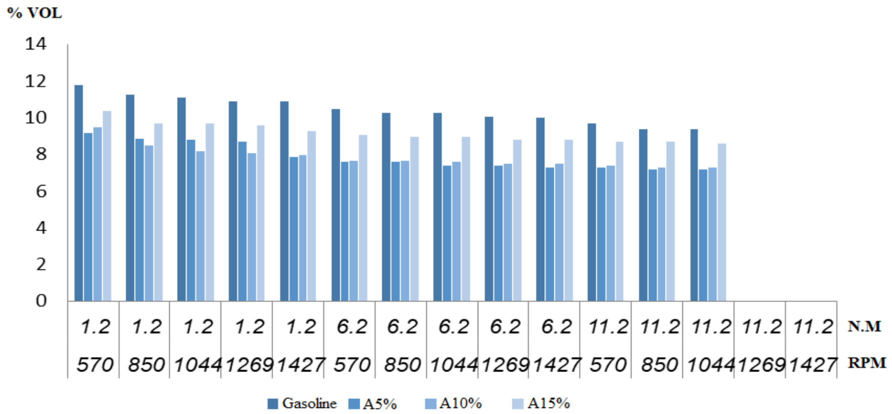
Source: *Own study.*

3.4.2. Carbon dioxide (CO_2)

Figure 5 illustrates CO_2 emissions for various fuel blends. As per the data, the highest CO_2 emission recorded was 11.4 vol.% when the load and gearbox speed were set at 1.2 Nm and 570 rpm, respectively. This can be attributed to the fact that combustion is nearly complete at lower speeds and loads, but becomes incomplete as both the load and speed increase, resulting in decreased CO_2 emissions (and increased CO emissions).

At a load of 11.2 Nm and gearbox speeds of 850 and 1044 rpm, the CO_2 emission was approximately 9.4 vol.%. Introducing solketal at 5% at gearbox speeds of 570, 850, and 1044 rpm resulted in a decrease in CO_2 emissions to 7.3 vol.% compared to 9.4 vol.% for gasoline, indicating a 30% reduction.
For solketal dosages of 5% and 10%, similar CO_2 emission levels were observed across all load and speed variations. However, with a dosage of 15%, at a load of 1.2 Nm, the CO_2 emission rose to the level of pure gasoline, with the difference in CO_2 emission becoming significant again as the load increased to either 6.2 or 11.2 Nm.

Figure 5. *Variations of CO_2 emissions with applied load when solketal is admixed with gasoline at 3 different blending ratios.*



Source: *Own study.*

3.4.3. Oxygen (O_2)

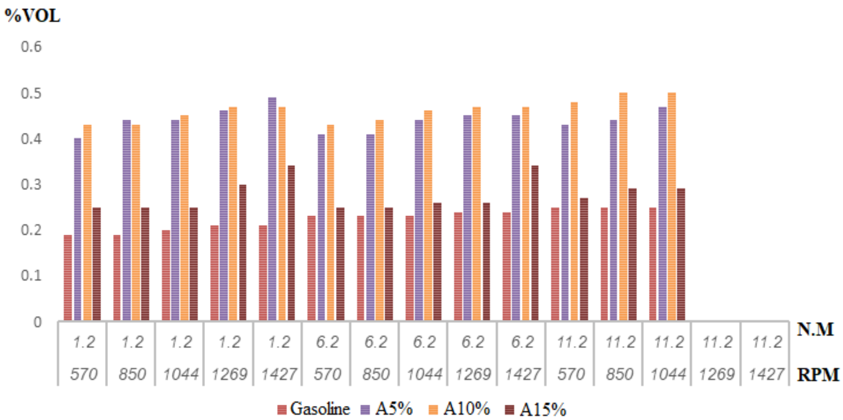
According to Figure 6, illustrating oxygen emission levels for various fuels, it is clear that for gasoline, at an applied load of 1.2 Nm, O_2 emissions ranged from 0.19% to 0.21% for all gearbox output speeds. The range shifted to 0.23% to 0.24% with an applied load of 6.2 Nm. At 11.2 Nm load and gearbox speeds between 570 to 1044 rpm, O_2 emissions remained relatively stable.

The results indicated that at this load and various other levels, combustion was thorough and efficient due to optimal engine parameter adjustments. O_2 emission serves as an indicator of oxidation, where higher O_2 levels signify improved oxidation and thus better combustion.

The addition of solketal to gasoline mitigates the gasoline's impact on combustion quality while boosting O_2 emissions regardless of blending ratio, load, or gearbox speed.

However, the increase in O_2 emission was most noticeable at 5% and 10% solketal concentrations. At higher gearbox speeds, the influence of solketal on O_2 emission was less pronounced, yet the blend of base gasoline and solketal yielded higher O_2 emissions than gasoline alone.

When solketal dosage reached 15%, O_2 emission closely matched pure gasoline at lower speeds but diverged significantly as gearbox speed rose to 1260 or 1427 rpm, likely due to excessive speed and complete fuel combustion.
Figure 6. *Variations of O2 emissions with applied load when solketal is admixed with gasoline at 3 different blending ratios.*



Source: *Own study.*

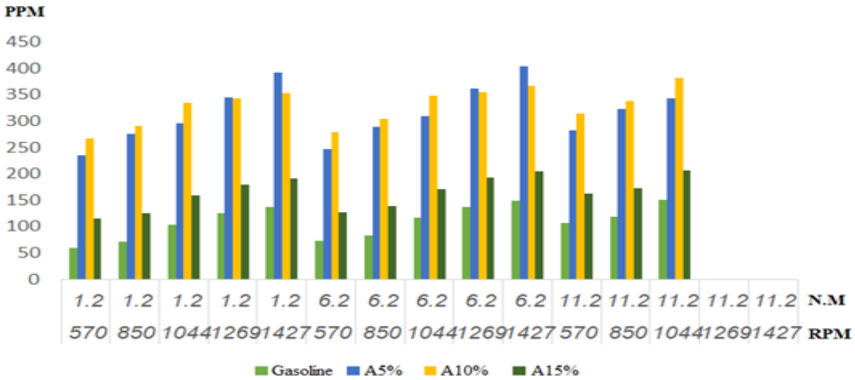
3.4.4. Unburned hydrocarbons (UHCs)
Considering Figure 7, UHC emissions decreased at lower applied loads and gearbox output speeds but followed an increasing trend at higher loads and speeds. The variations of UHC emissions with applied load (1.2, 6.2, and 11.2 Nm) and gearbox output speed (570, 850, 1044, 1269, and 1427 rpm) are shown in Figure 7 when solketal is mixed with gasoline at different levels. UHC emissions result from incomplete combustion in the combustion chamber.

The highest UHC emission levels with gasoline as fuel were observed at a gearbox output speed of 1044 and an applied load of 11.2 Nm. Mixing solketal with gasoline at 5% increased UHC emissions by 311%, 287%, and 252% at applied loads of 1.2, 6.2, and 11.2 Nm, respectively, compared to using pure gasoline. At higher gearbox output speeds (e.g., 1044 rpm), UHC emissions for fuels with solketal at 5%, 10%, and 15% were measured at 310 ppm, 348 ppm, and 172 ppm, respectively, with an applied load of 6.2 Nm.

These values indicate an increase in UHC emissions when the solketal dosage was raised from 5% to 10%. However, further increasing the solketal dosage to 15% reduced UHC emissions by -180% and -202% compared to dosages of 5% and 10%, respectively. This can be partly attributed to the reduction in the time for heat transfer from the engine.

As the combustion wall temperature increases, the flash off time is constrained, causing the flash points to potentially remain in the middle of the combustion chamber instead of shifting to the wall edges. The oxygen content of the fuel enhances the combustion process while decreasing the UHC emissions. The addition of solketal to gasoline fuel results in higher UHC emissions, which can be clarified by the lower heat value of the fuel blend compared to pure gasoline.
This, in turn, leads to the release of lower amounts of thermal energy, consequently lowering the combustion chamber temperature.

Figure 7. *Variations of UHC emissions with applied load when solketal is admixed with gasoline at 3 different blending ratios.*



Source: *Own study.*

3.5 Results of Simulating the Emissions with the Help of Software

Analysis of variance (ANOVA) was conducted to assess the impact of solketal dosage, gearbox output speed, and applied load on combustion-generation emissions as independent parameters.

Using the polynomial model for the ANOVA, the following general model was developed for predicting the CO emission:

$$
\begin{aligned}
\mathrm{CO} = {} & +3.05735 + 0.316644p - 0.018596t - 0.000185s + 0.13564p * t \\
& + 0.000052p * s + 0.000012t * s - 0.026474p^2 + 0.004018t^2 \\
& + 1.12626E - 07s^2
\end{aligned}
$$

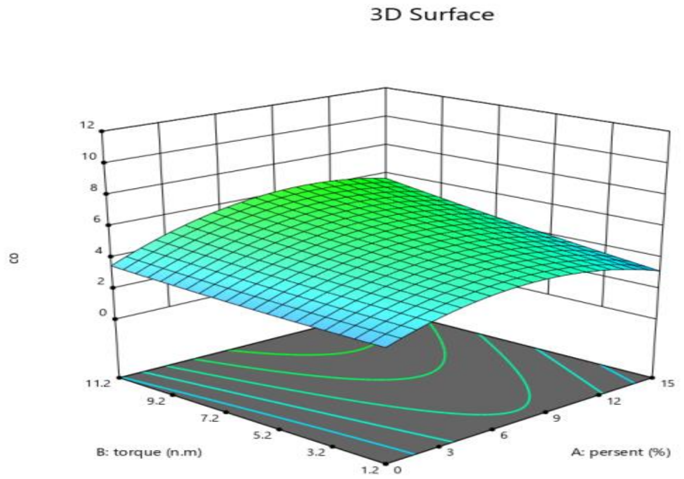
where: p: percentage, t: applied load, and s: speed

Figure 8 presents significant mutual effects on the CO emission. The mutual effect of admixture dosage-applied load was found to be significant for both independent variables. Using the polynomial model for the ANOVA, the following general model was developed for predicting the CO_2 emission:

$$CO_2^{0.5} = +3.52200 - 0.073075p - 0.046105t - 0.000211s + 0.000901p * t + 2.81062E - 06p * s + 7.16808E - 06t * s + 0.003579p^2 + 0.000616t^2 + 1.45312E - 08s^2$$

where: *p:* percentage, *t*: applied load, and *s*: speed

Figure 8. *3D diagram of the effects of admixture dosage and applied load on the CO emission.*



Source: *Own study.*

Figure 9 presents significant mutual effects of applied load-admixture dosage on the CO_2 emission, which were found to be significant.

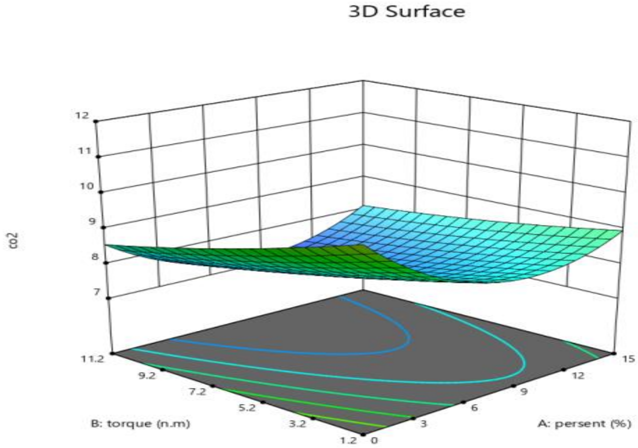
Using the polynomial model for the ANOVA, the following general model was developed for predicting the O_2 emission:

$$O_2 = +0.244903 + 0.035449p - 0.000415t - 0.000031s - 0.000137p * t + 2.35035E - 06p * s + 9.09380E - 08t * s - 0.002231p^2 + 0.000410t^2 + 3.60223E - 08s^2$$

where: *p:* percentage, *t*: applied load, and *s*: speed

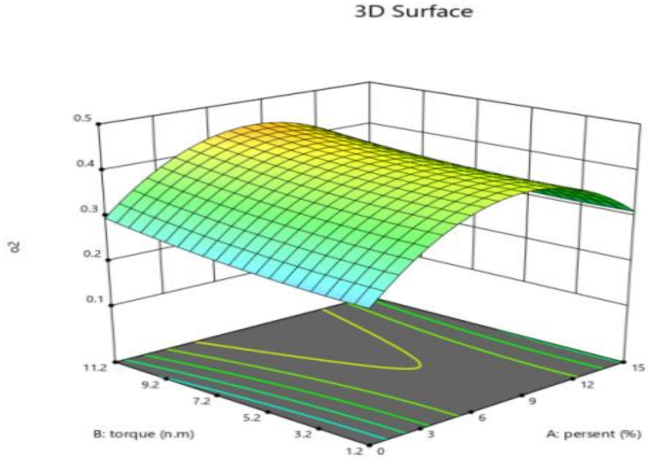
Figure 10 presents significant mutual effects of applied load-admixture dosage on the O_2 emission through exhaust gases, which were found to be significant.

Figure 9. *3D diagram of the effects of admixture dosage and applied load on the CO_2 emission.*



Source: *Own study.*

Figure 10. *3D diagram of the effects of admixture dosage and applied load on the O_2 emission.*



Source: *Own study.*

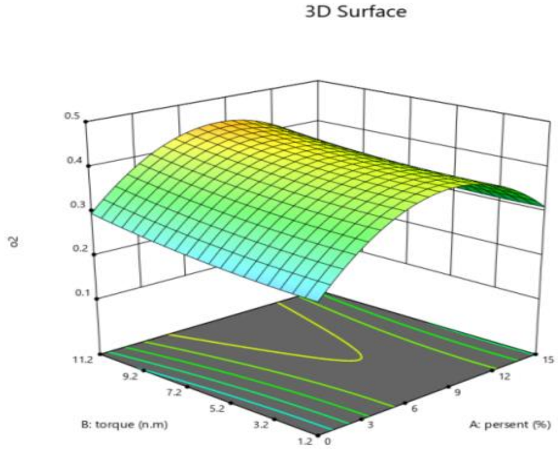
Using the polynomial model for the ANOVA, the following general model was developed for predicting the UHC emission:

$$\begin{aligned} UHC = {} & +23.80918 + 41.89484p - 1.48154t + 0.075550s \\ & + 0.004268p * t - 0.001828p * s + 0.000624t * s - 2.43718p^2 \\ & + 0.455041t^2 + 0.000028s^2 \end{aligned}$$

where: *p:* percentage, *t*: applied load, and *s*: speed

Figure 11 presents significant mutual effects of admixture dosage and applied load on the UHC.

Figure 11. *3D diagram of the effects of admixture dosage and applied load on the UHC emission.*



Source: *Own study.*

4. Conclusion

With the pure gasoline as the base fuel, the brake power exhibited a slighter increasing trend at an applied load of 6.2 or 11.2 Nm rather than 1.2 Nm. For all operating conditions, the blend fuels containing the solketal at 5 and 10% exhibited slightly lower performance than the one with 15% solketal.

Specific fuel consumption decreased with increasing the applied load due to the resultant improvement in the fuel-related power generation. With gasoline as fuel, BSFC was higher at an applied load of 1.2 Nm and a gearbox output speed of 570 rpm, as compared to other levels of applied load and gearbox output speed.

With increasing the applied load and gearbox output speed, the BSFC followed a decreasing trend. Results showed that, on average, the BTE increases with the dosage of admixture, thereby reducing the brake thermal value. With the solketal, average BTE for the admixture dosages of 5, 10, and 15% was measured at 3.4, 73.127, and 112.116, respectively, with an average total BTE of 118.81.

Indeed, the solketal admixture provided for 8.6 lower BTE than the base fuel. Investigations showed that CO emissions decrease upon adding the solketal to the gasoline. However, a sharper trend was seen when the fuel blend containing the admixture at 5%, rather than other dosages, was subjected to loads of 1.2, 6.2. and 11.2 Nm at gearbox output speeds of 570, 850, 1044, 1269, and 1427 rpm.

When the solketal was admixed with the gasoline at either of 5% and 10%, regardless of the applied load and gearbox output speed, CO_2 emission remained almost the same. For all blend fuels, introduction of solketal limited the impact of gasoline on the combustion while increasing the O_2 emission.

The improvement in O2 emission was, however, more remarkable when the solketal dosage was either 5 or 10%. When the solketal dosage was 15%, O_2 emission was close to that of pure gasoline at lower gearbox speeds, but then significantly deviated from the gasoline as the gearbox speed increased to 1260 or 1427 rpm, which could be attributed to too high gearbox output speed and complete combustion of the fuel.

Our results showed that UHC emissions were ideal for the gasoline, as compared to the solketal-added blend fuels. Admixing the solketal with the gasoline at 5% increased the UHC emission by 311, 287, and 252% when the applied load was set to 1.2, 6.2, and 11.2 Nm, respectively, as compared to the case with pure gasoline as fuel.

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