INTERNATIONAL JOURNAL OF AUTOMOTIVE AND MECHANICAL ENGINEERING (IJAME)
ISSN: 2229-8649 e-ISSN: 2180-1606
VOL. 18, ISSUE 1, 8612 – 8620
DOI: https://doi.org/10.15282/ijame.18.1.2021.20.0655

ORIGINAL ARTICLE

Utilisation of Chemical Waste Additives with Low Octane Commercial Gasoline Fuel to Enhance the Performance of SI Engines

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ABSTRACT – In this study, fusel oil additive from the waste product has been used as an octane number enhancer to improve gasoline engine performance. The fusel additive was added at 10%, 20% and 30% ratios to prepare the investigated fuel samples (M10, M20 and M30, respectively, in addition to pure gasoline M0). Engine tests were conducted at constant half engine load and increasing speed from 1500 rpm to 4500 rpm at 1000 rpm increments. Response surface methodology has been used as a statistical technique to describe the relationship between the investigated input variables with their responses to achieve the optimum operating conditions. Engine cyclic variations were analysed using wavelet analysis of in-cylinder pressure based on indicated mean effective pressure (IMEP) calculated for 100 consecutive cycles. The results showed that the higher brake power was obtained with blended fuel M20 during the engine operating speeds. The maximum increase of brake power found to be 23.6% with M20 compared to gasoline at 1500 rpm, which accompanied by a 7.3% increase in brake specific fuel consumption. On the other hand, the highest increase in brake thermal efficiency is found to be related to the engine speed and fusel additive ratio. Wavelet analysis shows that the engine cyclic variations decrease as the fusel additive introduce with gasoline. Moreover, fusel additive has a pronounced effect on decreasing the cycle to cycle variations of the IMEP time series with the lowest overall engine cyclic variations for M30. Accordingly, 20% fusel additive (M20) can be considered as a valuable octane enhancer for better engine performance.

ARTICLE HISTORY
Received: 20th Feb 2020
Revised: 29th Mar 2021
Accepted: 5th April 2021

KEYWORDS
SI engine;
Gasoline;
Fusel additive;
Engine performance;
Cyclic variations

INTRODUCTION

The growing energy demand due to the increasing population and modern live requirements represent a challenge that could restrict the development and lead to energy crises shortly. Though the researchers start to focus on utilising renewable energy resources, it still represents a limited share of the overall energy consumed compared to fossil fuel [1–4]. Among the different sectors, transportation and industry sectors represent the larger energy consumers. These sectors depend mostly on internal combustion engines, mainly designed to operate with fossil fuel [5]. Due to the high-speed characteristics of the SI engine, it is widely used in the transportation sector [6]. Gasoline fuel consumption is related to its properties, particularly octane number, that indicates the fuel conversion efficiency [7]. Additives with high octane number can be considered as an octane enhancer to improve engine performance.

Fusel oil additive is a by-product from the waste of alcohol production processes. These waste products are called molasses which considered a source of environmental pollution [8,9]. Due to the wide utilisation of alcohol in many fields, production factories available in many countries like Turkey and Brazil. These types of by-products can be considered viable cheap additives that can be used to improve fossil fuel quality and reduce the waste pollutant [10]. Many studies were conducted to improve engine performance using different additives [7,11–15]. However, the different compositions of fuel and additives limited the utilisation of these additives. Moreover, the low calorific value of additives restricts their utilisation at high ratios [16].

The high oxygen content of fusel oil is an important factor that may contribute to improving engine performance [17,18]. The fuel combustion process widely depends on the oxygen ratio in the fuel mixture that may lead to more efficient fuel combustion. The extremely high octane number and oxygen content can introduce fusel additives as a viable option with gasoline fuel [19]. Furthermore, many studies have been conducted successfully to enhance the fusel oil octane number through water extraction [20–22].

The objective of this study is to characterise engine performance using fusel oil additive as octane number enhancer with gasoline fuel. Response surface methodology has been used as a statistical technique to describe the relationship between the investigated input variables with their responses to achieve the optimum operating conditions. Engine cyclic variations were analysed using wavelet analysis of in-cylinder pressure based on indicated mean effective pressure calculated for 100 consecutive cycles. Fusel additive was added at 10%, 20% and 30% ratios and the prepared blended

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fuel samples denoted as M10, M20 and M30 in addition to pure gasoline M0. Engine tests were conducted at constant half engine load and increasing speed from 1500 rpm to 4500 rpm at 1000 rpm increments.

METHODOLOGY

In this study, fusel additive was provided by an alcohol production company in Turkey, and commercial gasoline fuel was supplied by a local gas station. Gasoline fuel and fusel additive properties are listed in Table 1 [6,7,21,23]. Gasoline fuel and fusel additive were mixed by volume and stirred for 20 minutes using an electrical magnetic stirrer at a stirring speed of 2000 rpm to ensure a homogenous mixture. Fusel oil is miscible with most solvents and can be used as a blended fuel with gasoline to operate SI engine [7]. The blended fuel sample was prepared by adding a fusel additive to gasoline fuel at ratios of 10%, 20%, 30% and denoted as M10, M20 and M30 in addition to pure gasoline M0 as listed in Table 2. The engine test was conducted using 4-cylinder Mitsubishi (4G93 SOHC) naturally aspirated spark ignition engine with specifications listed in Table 3. The engine has been connected to a water-cooled type eddy current dynamometer model ECB-200F from Dynatec Controls with 100 kW capacity, which utilised to load the SI engine. Figure 1 shows the gasoline engine test rig setup used in this study. The tests have been conducted at constant half engine load and increasing speed from 1500 rpm to 4500 rpm at 1000 rpm increment. Engine brake power (BP) has been determined based on the collected engine torque and speed, which in turn used together with the measured brake specific fuel consumption (BSFC) to calculate the engine brake thermal efficiency (BTE).

Table 1. Fuel and additive properties.

Property	Fusel additive	Gasoline
Heating value MJ/kg	29.93	43.5
Density kg/m^3	844	769
Kinematic viscosity mm^2/sec.	4.1	0.49
Oxygen content %	30.32	0
Octane number	106	95

Table 2. Tested fuel matrix

Fuel	Blending ratio (% by volume)
M0	100% gasoline
M10	90% gasoline + 10% fusel oil
M20	80% gasoline + 20% fusel oil
M30	70% gasoline + 30% fusel oil

Table 3. Engine specifications

Engine type	4-cylinder Mitsubishi
Bore	8.1 cm
Stroke	8.9 cm
Compression ratio	9.5:1
Injection type	ECI-Multi (electronically controlled multi-point fuel injection)
Max. torque	161 Nm @ 4500 rpm
Max. power	86 kW @ 5500 rpm

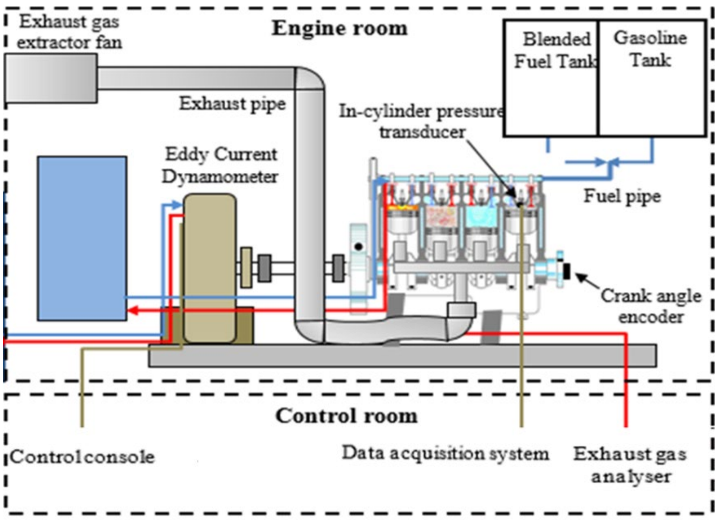

Figure 1. Gasoline engine test rig.

Response surface methodology (RSM) is common software used in various engineering applications as a statistical technique to describe the relationship between the input variables with its responses to achieve the optimum operation conditions [24]. It implies a set of statistical techniques in which the linear or polynomial functions are adopted. In this study, two influence variables, which are engine speed (rpm) and blend ratio (%) were considered. The responses determined during this investigation were the brake power (kW), brake specific fuel consumption (kg/kW.h) and brake thermal efficiency (%). All points from a specified candidate set are contained according to the implemented RSM (customer-defined designs).

Engine operation stability directly influences engine power and fuel consumption [25]. Engine cyclic variations were analysed based on collected in-cylinder pressure using the indicated mean effective pressure (IMEP) calculated for 100 consecutive cycles. The technique of signal processing is used to provide the ascertain simultaneous information ability about time and frequency to investigate the presence and persistence together. The time series of non-stationary power at a different frequency can be analysed using wavelet transform. Wavelet Power Spectrum (WPS) is represented by a surface and depends on both time and scale. The Global Wavelet Spectrum (GWS) is a useful quantity in this analysis that provides additional details about the time-series properties of spectral. Wavelet Power Spectrum (WPS) is the continuous wavelet transform square modulus plotted on a time-period plane [26–28]. It is dedicated in this study to describe the various periodicities of IMEP time series and their temporal variations. Global Wavelet Spectrum is useful to indicate the level of variation energy, which represents the WPS overall time average. The region under the U-shaped curve is called the Cone of Influence (COI) in which the edge effects should be considered, and the results inside this region may be inaccurate and unreliable [29].

RESULTS AND DISCUSSION

The engine test was conducted in this study to reveal the influence of adding fusel additive with gasoline fuel at increasing ratios on engine performance enhancement. The tests have been conducted at increasing engine speed from 1500 rpm to 4500 rpm and constant half engine load (50% throttle position). The additive was adopted at an increasing ratio from 0% to 30% at 10% increment ratio (M0, M10, M20, M30) to assess the optimum value of additive for better engine performance. Figure 2 shows the effect of fusel additive blend ratio with gasoline on engine brake power at increasing engine speed from 1500 rpm to 4500 rpm. Different trends have been indicated by each blend with increasing engine speed, brake power affected by increasing fusel additive ratio in all the speeds. In this case, two conflicting factors indicate the produced brake power, fuel heating value and octane number. For gasoline, it has a higher heating value than the fusel additive, which in turn has a higher octane number than gasoline fuel, as listed in Table 1. In general, blended fuel M20 reveals the higher brake power among the other fuel sample during the whole engine operating speeds, which may be due to the dominant octane number enhancement effect over the heating value in this case. However, increasing fusel additive blend ratio to 30% leads to a noticeable reduction in the engine brake power, which may be due to the dominant heating value deterioration effect over the octane number in this cause [7].

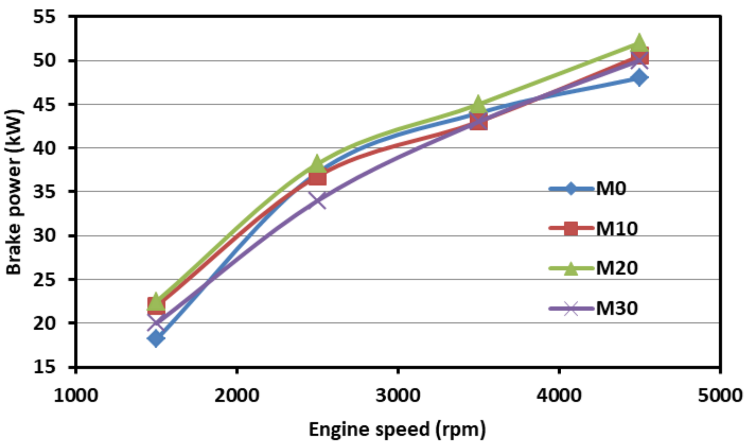

Figure 2. Effect of blend ratio on engine brake power.

Figure 3 shows a 3D surface plot of brake power against engine speed and fusel additive blend ratio with gasoline. The relation between input variables (engine speed and fusel additive ratio) and response (brake power) has been plotted to understand the interaction between them. It can be seen that engine speed has more effect on brake power than fusel additive ratio. Accordingly, the higher brake power obtained at the maximum engine speed for the whole fuel samples. Figure 4 depicts the counter surface plot of the high brake power obtained within the engine speed range of 1500-4500 rpm and fusel additive ratio of 0% - 30% with gasoline. It can be seen that the highest increase in brake power is related to the engine speed and fusel additive ratio, with a maximum value of 23.6% obtained at 20% fusel additive ratio and 1500 rpm engine speed. Accordingly, the highest increase in brake power linked statistically with the engine load and speed and the fusel oil additive have an insignificant impact on the engine brake power.

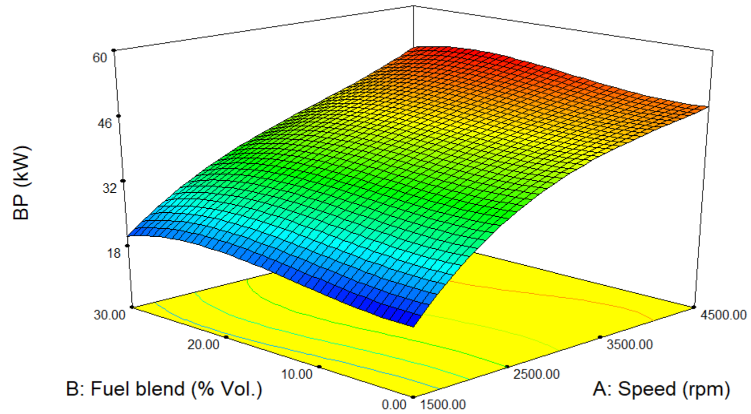

Figure 3. 3D surface plot of brake power against engine speed and fuel blend ratio.

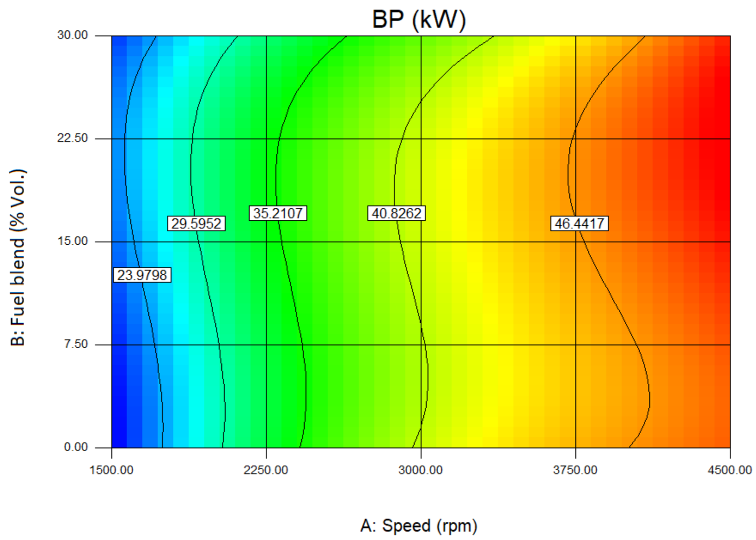

Figure 4. Counter surface plot of brake power against engine speed and fuel blend ratio.

Figure 5 shows the effect of fusel additive blend ratio with gasoline on engine brake specific fuel consumption at increasing engine speed from 1500 rpm to 4500 rpm. The same trend of increase for BSFC with increasing fusel additive ratio has been indicated within all the speeds. In this case, the fuel heating value is the dominant factor that affects the BSFC. For gasoline, it has a higher heating value than the fusel additive, as listed in Table 1, which in turn leads to lower BSFC compared to other fuel samples. In general, increasing the percentage of fusel additive in the blend leads to a slight increase in the BSFC. This increase can be due to the heating value deterioration effect, which requires more fuel consumption for the same power [21].

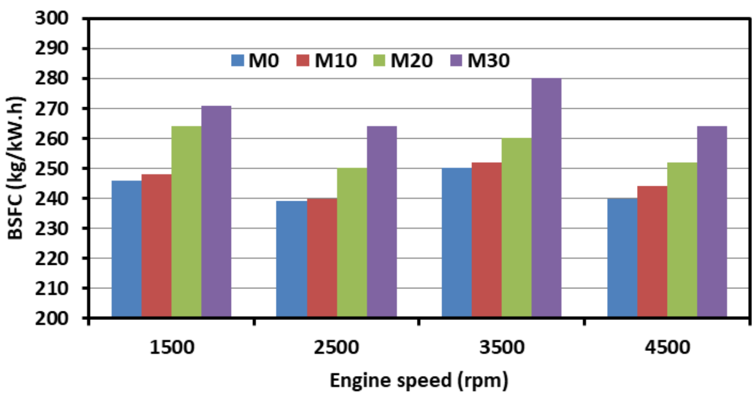

Figure 5. Effect of blend ratio on engine BSFC.

Figure 6 shows the 3D surface plot of BSFC against engine speed and fusel additive blend ratio with gasoline. The relation between input variables (engine speed and fusel additive ratio) and response (BSFC) has been plotted to understand the interaction between them. It can be seen that engine speed has a significant effect on BSFC in addition to fusel additive ratio. Accordingly, the lower BSFC obtained with gasoline (M0) at different engine speeds. Figure 7 depicts the counter surface plot of the lower BSFC obtained within the engine speed range of 1500-4500 rpm and fusel additive ratio of 0% - 30% with gasoline. It can be seen that the decrease in BSFC is related to the engine speed and fusel additive ratio. The lowest BSFC found to be 240 kg/kW.h for gasoline (M0) at 1828 rpm. Accordingly, the highest increase in brake specific fuel consumption linked statistically with the engine load and speed and the fusel oil additive has a significant impact on the engine brake specific fuel consumption.

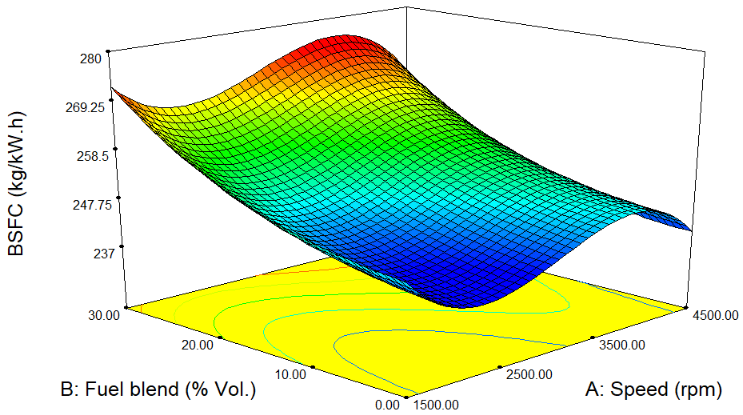

Figure 6. 3D surface plot of BSFC against engine speed and fuel blend ratio.

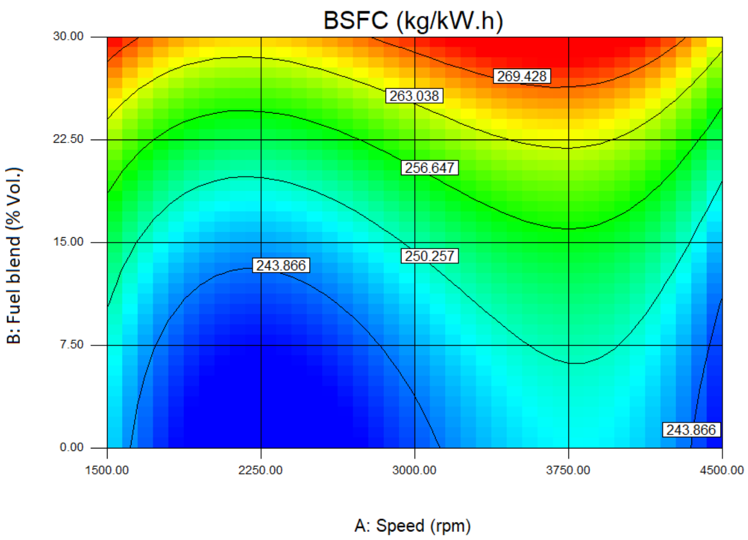

Figure 7. Counter surface plot of BSFC against engine speed and fuel blend ratio.

Figure 8 shows the effect of fusel additive blend ratio with gasoline on engine brake thermal efficiency at increasing engine speed from 1500 rpm to 4500 rpm. The same trend of increase for BTP with increasing fusel additive ratio has been indicated within all the speeds. In this case, the fuel octane number and oxygen content is the dominant factor that affects the BTE. For the gasoline, it has a lower octane number than the fusel additive, as listed in Table 1, which in turn leads to lower BTE compared to other fuel samples. In general, increasing the percentage of fusel additive in the blend leads to a noticeable increase in the BTE. This increase can be due to the increase in blended fuel octane number and oxygen content effect, which enhanced the fuel conversion efficiency [11].

Figure 9 shows the 3D surface plot of BTE against engine speed and fusel additive blend ratio with gasoline. The relation between input variables (engine speed and fusel additive ratio) and response (BTE) has been plotted to understand the interaction between them. It can be seen that engine speed has a significant effect on brake thermal efficiency in addition to fusel additive ratio. Accordingly, the highest BTE obtained with 30% fusel additive (M30) at maximum engine speeds. Figure 10 depicts the counter surface plate of the higher BTE obtained within engine speed range of 1500 rpm – 4500 rpm and fusel additive ratio of 0% - 30% with gasoline. It can be seen that the highest increase in BTE related to the engine speed and fusel additive ratio. Accordingly, the highest increase in brake thermal efficiency linked statistically with the engine load and speed and the fusel oil additive have a slight impact on the engine brake thermal efficiency.

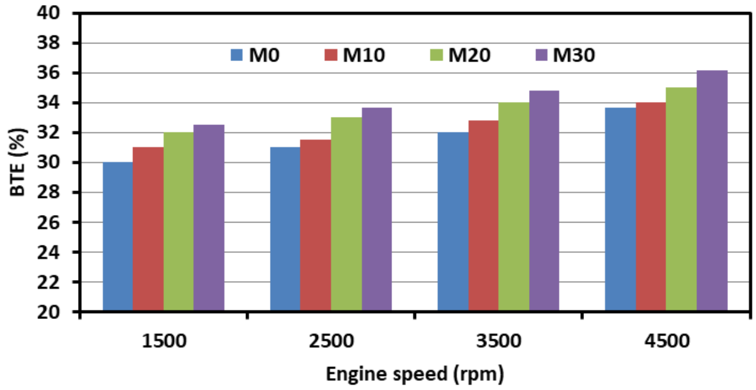

Figure 8. Effect of blend ratio on engine brake thermal efficiency.

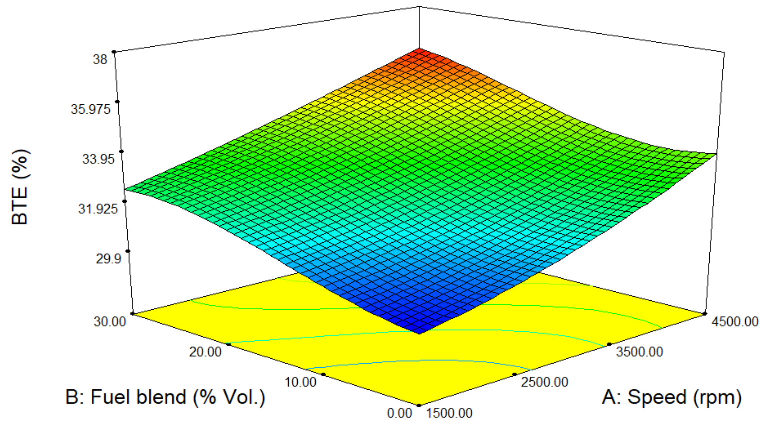

Figure 9. 3D surface plot of brake thermal efficiency against engine speed and fuel blend ratio.

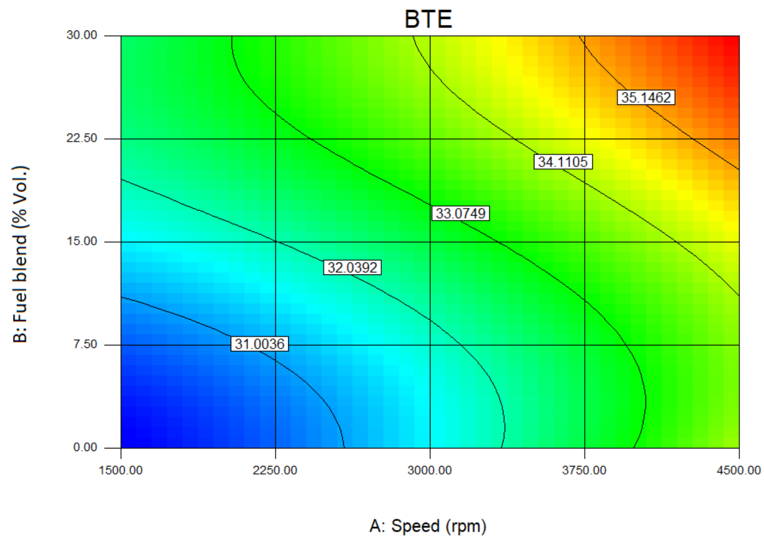

Figure 10. Counter surface plot of brake thermal efficiency against engine speed and fuel blend ratio.

Engine operation stability is a major issue that should be considered when dealing with fuel additives that influence fuel property and in turn, affect the combustion process. Analysis of in-cylinder pressure for 100 consecutive cycles was conducted and dedicated to evaluating engine cycle to cycle variations. For this purpose, IMEP was considered in this analysis as the investigated parameter to obtain more accurate and reliable results. Wavelet Power Spectrum (WPS) and Global wavelet spectrum (GWS) were used in this study to indicate the engine cyclic variations at a constant engine speed of 2500 rpm and half engine load. The red noise background spectrum in the WPS depicted by the enclosed contour lines regions represent a higher than 95% confidence level [29]. The Cone of Influence (COI) is represented by the area under the U-shape curve. The edge effects in this region become significant which may lead to unreliable results and limits their adoption [29].

Figure 11 depicts the IMEP results of WPS and GWS for 100 consecutive cycles with pure gasoline. Based on the IMEP time series for 100 consecutive length recorded engine cycles, periodicities of less than 64 cycle have been considered in this study. From the WPS and GWS depicted in Figure 11, the cyclic variations appear at multiply time scales with pure gasoline fuel. However, for blended fuel M10, the cyclic variations show intermittent fluctuations with low frequency as obvious in Figure 12.

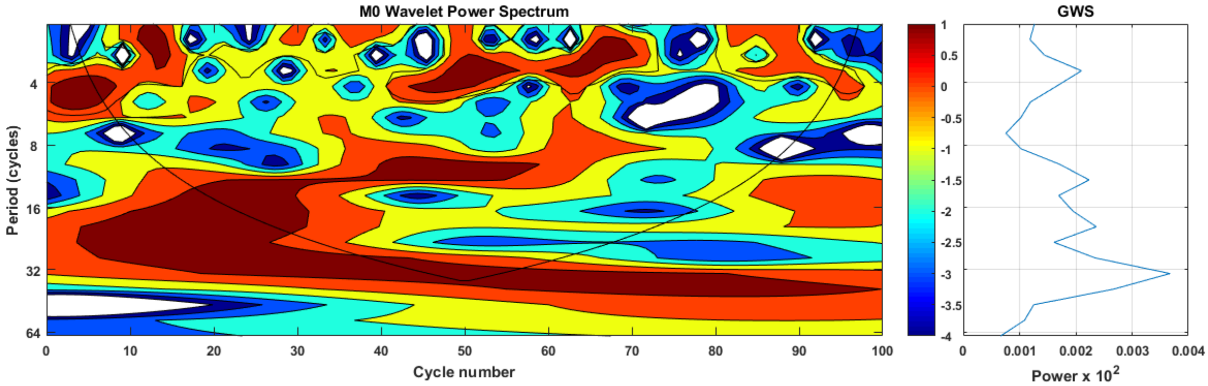

Figure 11. Wavelet analysis of IMEP with pure gasoline at 2500 rpm engine speed.

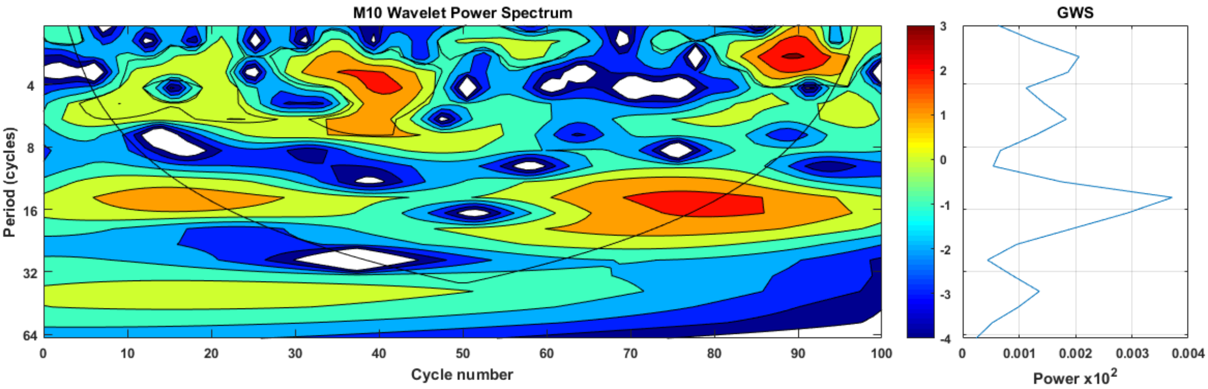

Figure 12. Wavelet analysis of IMEP with blended fuel M10 at 2500 rpm engine speed.

Figures 13 and 14 show noticeable development of low-frequency persistent oscillations in the engine cyclic variations with increasing additive ratio. For gasoline, the persistent oscillation occurs around an 8-cycle period and between 8 cycles and 16 cycle period lasting over almost 35 engine cycles. Increasing the fusel additive in the blend to 30% leads to the appearance of persistent oscillation occurs around the 4-cycle period and around the 8-cycle period, as well as between 4-cycle and 8-cycle period and between 8-cycle and 16-cycle period lasting over almost 15 engine cycles. Moreover, the GWS plots for tested fuel samples reveal a significant decrease in the spectral power with an increasing additive ratio in the blend. Accordingly, the lowest overall spectral power observed for blended fuel M30 with the highest for pure gasoline indicates a noticeable effect of additive ratio on overall engine cyclic variations.

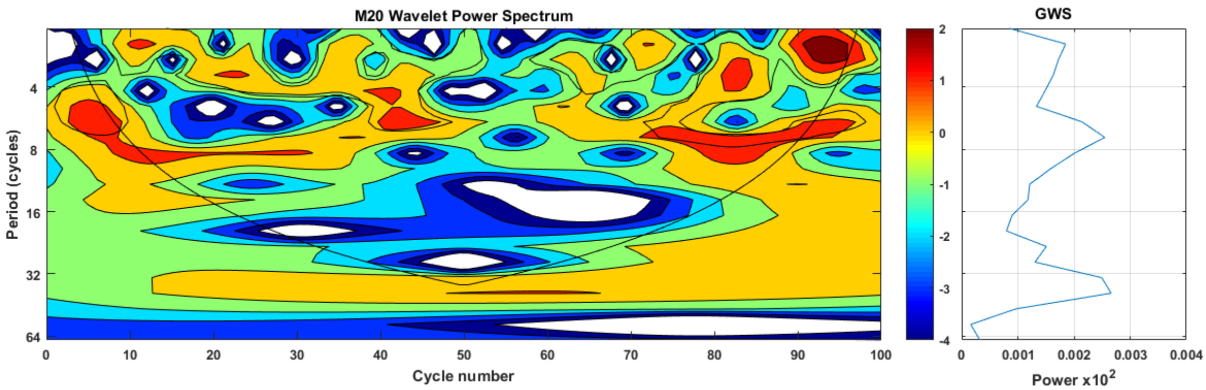

Figure 13. Wavelet analysis of IMEP with blended fuel M20 at 2500 rpm engine speed.

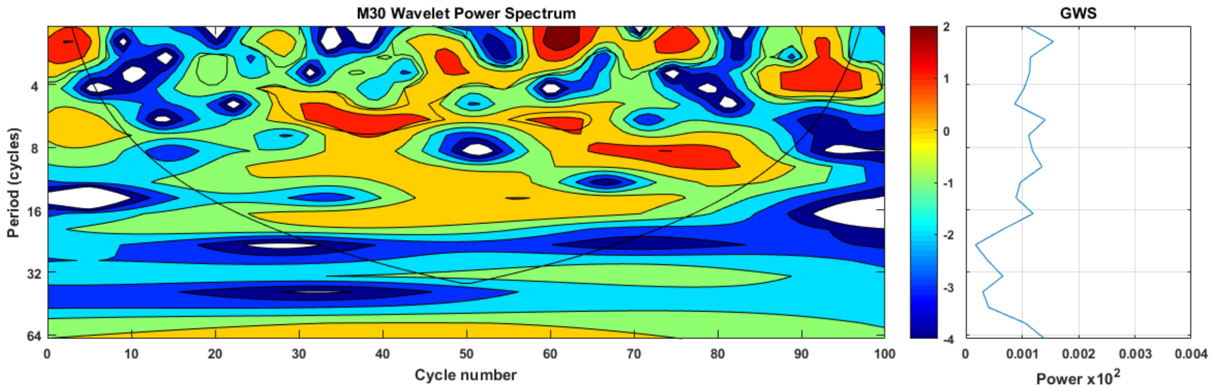

Figure 14. Wavelet analysis of IMEP with blended fuel M30 at 2500 rpm engine speed.

CONCLUSION

Fusel additive from the waste products has been used as an octane number enhancer to improve gasoline engine performance in this study. Engine tests were conducted at variable speeds and constant half engine load to evaluate the prepared fuel. Response surface methodology is used to describe the relationship between the investigated input variables (engine speed and fusel fuel ratio) with its responses (brake power, brake specific fuel consumption and brake thermal efficiency) to achieve the optimum operating conditions. Engine cyclic variations were analysed using wavelet analysis of in-cylinder pressure based on indicated mean effective pressure. The main finding of this study can be listed as follows:

i. The highest increase in brake power is related to the engine speed and fusel additive ratio.
ii. Blended fuel M20 reveals the higher brake power among the other fuel sample during the engine operating speeds.
iii. Engine speed has a significant effect on BSFC in addition to fusel additive ratio. Increasing the percentage of fusel additive in the blend leads to a slight increase in the BSFC. The lowest BSFC found to be 240 kg/kW.h for gasoline (M0) at 1828 rpm.
iv. The maximum increase of brake power with M20 compared to gasoline found to be 23.6% at 1500 rpm, which accompanied by 7.3% increase in brake specific fuel consumption.
v. Engine speed has a significant effect on brake thermal efficiency in addition to fusel additive ratio. The highest increase in BTE is related to the engine speed and fusel additive ratio. Increasing the percentage of fusel additive in the blend leads to a noticeable increase in the BTE.
vi. From the wavelet analysis of IMEP for different fuels, it is found that the spectral power decreases as the fusel additive introduces with gasoline, indicating that fusel additive has a pronounced effect on decreasing the engine cycle to cycle variations.
vii. A comparison of the GWS for the tested fuel reveals that the blended fuel M30 has the lowest overall spectral power, while the pure gasoline fuel M0 has the higher overall spectral power.
viii. Finally, the best engine performance at lower cyclic variations was obtained at 20% fusel additive (M20). Therefore, fusel additive can be considered at a certain ratio as a valuable octane enhancer for better engine performance.

ACKNOWLEDGEMENT

The author would like to thank the technicians staff of Renewable Energy Research Unit for the technical support.

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