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Full Length Article

The influence of n-pentanol blending with gasoline on performance, combustion, and emission behaviors of an SI engine

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ABSTRACT

This experimental research deals with the characteristic work on the performance, combustion, and exhaust pollutants for unleaded gasoline mixed with n-pentanol in the proportion of 5%, 10%, 15%, and 20% (by vol.) of the total quantity. The trials were performed on a 1-cylinder, 4-stroke, water-cooled, port-fuel injection (PFI) spark-ignition (SI) engine loading an AC active dynamometer so as to scrutinize the aforementioned behaviors of n-pentanol. The test fuels (unleaded gasoline, Pt5, Pt10, Pt15, and Pt20) were experimented with at various loads ranging from 1 kW to 5 kW with intervals of 1 kW under 1600 rpm fixed speed. The findings coming from the tests exhibited that the infusion of n-pentanol to gasoline has caused to reducing the HC, CO, CO_2, and NO emissions in contrast to the baseline gasoline however, O_2 levels were observed to be higher. At all of the engine loads, n-pentanol blends exhibited an improvement in BTE when compared with gasoline by reason of the inherent oxygen concentration of used alcohol. As hoped, the peak in-cylinder pressure and apparent heat release rate (HRR) values for the tested fuel blends were found to be higher than that of UG test fuel. It is to be noticed that the higher-order alcohol namely n-pentanol may be used as a partial replacement for gasoline fuel in the SI engine applications according to the experimental outcomes.

1. Introduction

Environmental pollution, especially atmospheric air pollution has been known as one of the most critical and vital issues that came across by humankind over the years worldwide and it still goes ahead to be [1]. The expectations of people concerning air pollution resulting from road transportation decrement have been augmenting day by day. Thus, the world has been eagerly focusing on the reduction of this pollution contributor, namely emissions, released from the vehicles by implementing strict emissions norms [2].

Turkey having a regional power in the Middle East is a candidate country for the European Union (EU) and is an associate member of major economies in G20 countries. According to the gross domestic product (GDP) at current prices in 2019, Turkey has the 20th largest economy all over the world meanwhile 8th largest economy in the EU [3]. In addition, Turkey possesses a resilient economy that substantiated its capacity worldwide economic crisis of 2008 and the following global financial recession [4]. Likewise, it is estimated that Turkey will reach the fastest expanding economy among the Organization for Economic Co-operation and Development (OECD) members throughout 2011–2017 along with the mean real GDP rowing rate of 6.7% [5]. In this regard, the growth of the economy has been followed by a rise in fuel consumption ensured in the transportation sector in recently developed and developing countries [6]. In this direction, the total vehicle number fueling with gasoline has been also increasing stepwise in Turkey over the years as in many countries. It is to be predicted that the entire number of vehicles powered by gasoline fuel reached 3.18 million by the end of November 2020 on account of an increase of approximately 1% each year while it was 2.86 million in 2014 [7]. While the production of gasoline fuel in Turkey was realized to be at 5.11 million tons in the year 2015, it was decreased to 4.65 million tons in the year 2018. However, the consumption of gasoline exhibits an upward inclination although not significantly. In 2018, the consumption of gasoline in Turkey was observed to be 2.33 million tons that was 1.16% higher than the past year [8]. Unfortunately, the price of gasoline in Turkey is reasonably high and also there are considerable taxes on gasoline fuel. What is more, Turkey has an elevated population having a straight influence on the consumption of gasoline [9]. In the points of EU directives, Energy Market Regulatory Authority (EMRA) goals, and Turkey's

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Nomenclature

SI	Spark-ignition
UG	Unleaded gasoline
PFI	Port-fuel injection
G100	100% gasoline
Pt5	5% n-pentanol/95% gasoline (by vol.)
Pt10	10% n-pentanol/90% gasoline (by vol.)
Pt15	15% n-pentanol/85% gasoline (by vol.)
Pt20	20% n-pentanol/80% gasoline (by vol.)
HC	Unburned hydrocarbon
CO	Carbon monoxide
CO_2	Carbon dioxide
NO	Nitrogen monoxide
NO_X	Nitrogen oxides
O_2	Oxygen
BTE	Brake thermal efficiency
HRR	The rate of heat release
IC	Internal combustion
CI	Compression-ignition
CR	Compression ratio
LHV	Latent heat of vaporization
CH_3CH_2OH	Ethyl alcohol
AFR	Air-fuel ratio
BSFC	Brake specific fuel consumption
EGR	Exhaust gas recirculation
ANN	Artificial neural network
RSM	Response surface methodology
R^2	Regression of coefficient
VCR	Variable compression ratio
MFB	Mass fraction burned
ECU	Electronic control unit
BDC	Bottom dead center
TDC	Top dead center
AC	Alternative current
SPD	Spark plug discharge
Cid	Combustion initial duration
CD	Combustion duration
EOC	End of the combustion
$w_1, w_2, \ldots, w_n$	Uncertainties of the independent variables
w_R	Uncertainty value of the result
$x_1, x_2, \ldots, x_n$	Independent variables
R	Dependent factor
EGT	Exhaust gas temperature
GDP	Gross domestic product
EU	European union
OECD	Organization for economic co-operation and development
EMRA	Energy market regulatory authority
CA,θ	Crank angle
k	Ratio of specific heat values
V	Cylinder volume
P	Cylinder pressure
Q	Net heat output
T_1	Inlet temperature of the engine cooling water
T_2	Outlet temperature of the engine cooling water
T_3	Inlet temperature of the exhaust calorimeter water
T_4	Outlet temperature of the exhaust calorimeter water
T_5	EGT arriving at the exhaust calorimeter
T_6	EGT leaving from the exhaust calorimeter

2023 vision targets, Melikoglu [6] recommended some models regarding the consumption of petroleum-based fuels in Turkey. In this context, the annual gasoline consumption in Turkey will reduce to 2.0 million m^3 in 2023 thanks to commencing the alternative fuel candidates.

In recent days, the regulations enacted by countries are noticed to be as rigid towards the use of petroleum-based fossil fuels because they damage the environment when burned in the internal combustion (IC) engines. The aforementioned reasons, therefore, have caused to explore the alternative, sustainable, renewable, and clean resources of energy by researchers in order to substitute for petroleum-based fuels [10]. In the last decades, the use of alternative fuel samples taking the place of traditional fossil-based fuels preferred in both compression-ignition (CI) engines and SI engines have been increasing even though there is plenty of recommended ways to solve air pollution issues [11–14]. As in many countries, the government of Turkey Republic handled this subject by taking initiatives in the year 2017 and regulated the mixing of ethanol obligation to the gasoline. According to the regulation, it is compulsory to add at least 3% by volume of ethanol produced from domestic agricultural raw materials into the gasoline in Turkey [15]. In other words, the above-mentioned obligation has directed to sell the mixture of 3% ethanol and 97% gasoline, leading an appropriate solution to drop the rate of dependency over crude oil.

Hence, it ensures decreasing the air pollution emitting from the SI engine at the point of a larger rate. It is to be noted that this program was active in all cities of Turkey until these days helping turn in low exhaust gas emissions like CO, HC, CO_2, etc. It has to be indicated that ethanol blending obligation was removed by the government since the demand for disinfectants and colognes is increasing around the world due to the epidemic disease (Covid-19).

The gasoline/alcohol blends have been used in the different types of SI engines for a long time. Furthermore, it can be stated that the interest in the use of alcohol with petroleum-based fuels commenced in the middle of the last century. This case is basically because of the grand requirement for hydrocarbons resulting in overuse of fossil-based energy sources all over the world. The tetraethyl lead has been added into the gasoline fuel as an additive to boost the octane rating of gasoline for long years but it has impaired health of people based on the accepted sight [2,16]. In the present perception, the pursue to establish a world which has energy-efficient, as well as pollution-free, has been swiftly continuing since the subjects and technologies about the alternating fuel are very well figured out in the laboratory conditions. In addition to this, the experiments were conducted on the blending of gasoline with aromatics like benzene, butadiene and few other compounds. By all means, a lot of additives used in the SI engines are known as carcinogens [11]. Moreover, these have led to generate smoke emissions from the exhaust during the combustion reaction inside the cylinder. It is worthwhile that the chances for evaluation of the optimization process to enhance the performance and emission patterns by altering the engine working conditions like spark timing, compression ratio (CR), etc. have been rapidly proceeding in the IC engine studies around the world and thereupon the developments concerning the aforementioned parameters are made [17,18]. Alcohols show similar physical and combustion characteristics to the gasoline. Alcohols have been thoroughly convenient fuel for the application of SI engine subrogating gasoline.

This is mainly due to the affirmative specifications such as latent heat of vaporization (LHV), flame speed, oxygen amount, and nearly complete combustion reaction inside the engine cylinder [19]. The engines fueled with alcohols permits of having higher CRs, and hence brake thermal efficiency (BTE) improves. This is accounted for their high octane rating and oxygen content and [13].

The prior works have investigated the influences of several alternative fuel mixtures upon the behaviors of the IC engines. The experimental outcomes of these papers have been presented drastic increments in the engine output power when operating the test blends while the substantial reductions in the exhaust gas emissions when the usage of particular concentrations of these blends. A number of previous examinations focusing on the blending of gasoline with alcohols like methanol (C_1), ethanol (C_2), propanol (C_3), and butanol (C_4) verified that there is an enhancement in the performance of the engine at large and significant mitigation in the exhaust emissions [20]. On the other hand, there are still shortcomings in blending gasoline with alcohol at lower temperatures because this causes to become a knocking occurrence and phase separation. Elfasakhany et al. [21], for instance, scrutinized the performance and emission levels for an SI engine operating with ternary fuel mixtures (ethanol/methanol/gasoline, n-butanol/*iso*-butanol/gasoline, and *iso*-butanol/ethanol/gasoline) and aimed to observe the favoring outcomes in volumetric efficiency and engine power. The researchers came across with disadvantageous results for the tested fuel blends. Although the infusion of stabilizers was executed for alcohol/gasoline blends, the concentration of alcohol was restricted with 10% under the low-temperature conditions.

The alcohol-based alternative fuels including ethanol are suggested as substantial energy resources for IC engine applications [22]. Ethanol or ethyl alcohol (CH_3CH_2OH) is sensed as a renewable and clean energy resource and it might be smoothly synthesized from agricultural feedstocks namely biomass like sugarcane and corn considering the low cost in the production [23–25]. Ethanol could be performed in the SI engine applications as a neat form or mixed with gasoline [26–28]. The physicochemical specifications of ethanol are close to those of pure gasoline [22]. Ethanol is extremely resistant to knock in the engine [24]. Although ethanol is a popular candidate for the gasoline owing to the less greenhouse gas impact, low harmful pollutants, the capability of blending homogenously with gasoline, high LHV, high oxygen content and octane rating, some of its challenges like lower heat capacity in compassion with gasoline, necessary modification on the engine before using in the engine as a fuel, and it is being produced from raw materials requiring wide yielding lands in terms of agricultural [30–32]. Ethanol has low molecular weight when compared with other alcohols except for methanol and it has generally replaced the other additives for using as an octane booster infused to the gasoline. Due to the inherent oxygen content in its chemical bonds, ethanol leads to contribute the better combustion process in the engine cylinder to get nearly complete combustion. Besides that, the absence of sulfur content in the ethanol would cause declining the air pollution problem [33–35]. There are many studies regarding the usage of short-chain alcohol like ethanol and methanol in SI engines. Some of them have summarized as follows: Al-Hasan [24], for example, pointed out the effects of the utilization of dissimilar UG/ethanol mixtures on the emission and performance features. The researcher observed that the equivalence air–fuel ratio (AFR) was declined together with the brake specific fuel consumption (BSFC). Yücesu et al. [36] performed a comparative analyses of SI engine performance in the points of experiments and mathematical outcomes fuelled the engine with ethanol/gasoline blends. Özsezen and Çanakçı [37] indicated that the corrosion characteristics are one of the most important parameter to observe that might be dropped a larger grade by applying advanced injection methods. Elfasakhany [38] researched the emissions and performance behaviors of gasoline/methanol hybrid blends in the SI engine. Turner et al. [39] examined the gasoline/ethanol blends in a SI engine and obtained that there was a remarkable decrement in the emissions of CO_2 and NO_X at all engine loading conditions. Doğan et al. [40] experimented the influence of gasoline/ethanol blends upon the performance and pollutant emissions of an SI engine via thermodynamic analysis. Kang et al. [41] highlighted that an augmentation of alcohol content in the dual-fuel mixture (ethanol/gasoline) caused to enhance the combustion process at which encourages the combustion reaction resulting in higher BTE.

There is an evident shortcoming in the present literature where is emphasized concern with the intention of the exploration of the effects of higher-order alcohol-gasoline mixtures on the performance, harmful pollutants, and combustion behaviors of an SI engine. Besides that, methanol or ethanol-blended gasoline have been experimented with by the majority of the researchers, and thus, these studies have been presented in the above-mentioned literature survey. One of the most remarkable higher-order alcohols is pentanol in order to select in the SI engine application as an alternative fuel substitute. Pentanol is also called pentan-1-ol, n-amyl alcohol, or n-pentanol [42]. Pentanol is able to be synthesized from renewable and sustainable agricultural products by various techniques. Pentanol and its derivatives have long been recognized by the food industry as one of a lot of flavor compounds fabricated via fermentation processes. The researches have exhibited that pentanols together with their concerned acids, aldehydes, and esters to be the most dominant flavor and odor ingredients of fermented beverages [43]. In addition, pentanol is straight-chain alcohol that has been gaining attention these days on account of its benefits over other alcohols. Although it is longer-chain alcohol, pentanol is in want of low energy for its production in comparison with the other short-chain alcohols [44,45]. On the other hand, the utilization of higher-order alcohols was earlier dissuaded due to their high production cost, restricted production from non-petroleum sources, and productive utilization in the food industry [46,47]. The recent years have witnessed a renovated affinity in higher-order alcohols, as renewable and sustainable engine fuels, which have played a role in increasing the yield of these alcohols. In this regards, higher-order alcohol like butanol and pentanol can be produced from cellulose implementing contemporary fermentation techniques handling new strains of Clostridium species [48] and by biosynthesis from glucose utilizing genetically engineered micro-organisms such as Saccharomyces cerevisiae [49], Cyanobacteria [50], and Escherichia coli [51]. On top of that, there is also a different line where biomass might be gasified or steam-reformed or partially oxidized so as to generate synthesis gases such as CO_2, H_2, and CO that can be catalytically transformed to the higher-order alcohols via a process named higher alcohol synthesis [52]. Besides that, higher-order alcohols have been produced applying photosynthetic recycling of CO_2 or direct electro-microbial conversion pathway [53]. Essentially, this technique can assist to recycle CO_2, which is a greenhouse gas, into higher-order alcohols out of the requirement for deconstructing the biomass [54]. Moreover, biofuel producers with the aim of dropping the high costs are upgrading the registered biochemical routes for large-scale commercial production of higher-order alcohols [47]. Interestingly, it can be recommended in order to select pentanol in the esterification process throughout the production of biodiesel (which is an alternative fuel for diesel engines) because of its unsurpassed oil or fat solubility than methanol [43]. Furthermore, it is well-known that pentanol is a good corrosion inhibitor and it does not influence the fuel lines [55]. Unfortunately, the cost of pentanol is quite high when compared to lower-order alcohol these days because its production has been realized in limited amounts all over the world. When the utilization of this alcohol in the IC engines in the commercial points, the cost can be reduced.

Some of the considerable investigations regarding the long-chain alcohols will be addressed in the paragraph given underneath so as to consider better the effects of the test fuels on the engine behaviors because there are limited numbers of researches concerning the pentanol utilization on SI engine applications.

Yacoub et al. [56] aimed to investigate the performance and emission patterns of C1-C5 alcohols blending individually with gasoline, whose oxygen concentrations was the same, in a 1-cylinder gasoline engine. They concluded that higher alcohols of C4 and C5 exhibited the deteriorated knock resistance as contrary to UG. In general, entire tested fuel blends reduced CO emissions. Gautam et al. [57] explored the pollutant emission levels of a 1-cylinder Waukesha Cooperative Fuel Research engine running on the pentanol-gasoline blends at stoichiometric AFR and steady-state conditions. They determined that the cycle emissions (CO_2, CO, and organic matter hydrocarbon equivalent) of tested fuel blends were found to be very similar to those of gasoline while NO_X emissions were increased. Altun et al. [58] researched the influence of isopropanol-gasoline blends upon pollutant gases released from exhaust and engine performance behaviors. Experimental examination of this study performed on a 4-cylinder, 4-stroke SI engine operating with gasoline and its mixtures with isopropanol consisting of 5% and 10% alcohol (by vol.). Consequently, the utilization of isopropanol-gasoline blends caused to diminish the HC and CO emissions with ascending CO_2 emission. Togbé et al. [59] observed the speeds of the laminar flame of the 1-pentanol-air premixed laminar flame under diverse equivalence ratios (0.7–1.4) and at 423 K with 1 atm conditions. Gravalos et al. [60] experimentally examined the effects of lower-higher alcohol addition into gasoline on the emissions characteristics of an SI engine at different engine speed conditions. Consequently, they noted that HC and CO emissions in the exhaust gas were decreased with the working on alcohol blended fuel samples while NO emissions were obtained as higher than that of neat gasoline. The comprehensive experimental study was made by Gong et al. [61], who scrutinized the effect of various fuel blends having isopropanol (10%, 20%, 40% and 100%) and gasoline on the performance and harmful pollutant characteristics of a 3-cylinder, 4-stroke, PFI SI engine under the exhaust gas recirculation (EGR) rates of 0%, 5%, 10%, 15% and 20%, loads of 10%, 20%, and 40%, and fixed speed of 3000 rpm with the wide-open throttle. They concluded that EGR caused to decrease the NO_X emissions. CO and HC emissions showed vaguely variations at all loadings except for 10%. Lastly, particulate matter rates raised monotonically with the decline of EGR and an increase of load. Elfasakhany [62] studied the impacts of engine performance and exhaust emissions of an SI engine powered by three distinct fuel blends of gasoline contain of isobutanol (3%, 7%, and 10% by volume) at various engine speed operating conditions. He also recommended gasoline blended isobutanol up to 10% on a volume basis because of avoiding modifications on the engine. Experimental results revealed that CO and HC emissions were monitored to be at lesser in terms of fuel blends than that of gasoline at lower engine speed. Yusri et al. [63] worked the influence of binary blends with the volume rates of 5%, 10%, and 15% of 2-butanol and gasoline on the combustion, pollutant emissions and thermal balance specifications of a 4-cylinder, 4-stroke, naturally-aspirated SI engine under 50% throttle wide open and between 1000 rpm and 4000 rpm engine speed at 500 rpm intervals. They indicated that the exhaust emissions like CO, NO_X, and HC has diminished thanks to the increasing of 2-butanol fraction in the blend whereas CO_2 emission indistinctly rose. Additionally, the infusion of 2-butanol into the gasoline led to improve the coefficient of variation of indicated mean effective pressure. In other words, alcohol stabilized the combustion process. In their experimental study, Galloni et al. [64] tested gasoline and bio-butanol blends (20% and 40% butanol mass percentage) in a 4-cylinder, turbocharged, 16-valve SI engine having PFI system to evaluate the engine performance in the case of a partial load condition. The outcomes showed that BTE and engine torque was inconspicuous decreased when the alcohol concentration was increased while BSFC was somewhat increased. In addition, CO_2 and NO_X emissions augmented whereas HC and CO emissions dropped. Aiming at the performance behaviors of various alcohols (ethanol, propanol, butanol, and pentanol)-gasoline blends, containing alcohol at two ratios of 5% and 10%, in a 1-cylinder, 4-stroke, SI engine at different CR, Kothare et al. [65] found that the higher concentration of pentanol led to reducing the BSFC while improving in energy efficiency. Sivasubramanian et al. [66] explored the utilization of isopropanol-gasoline blends as alternative fuel blends for a medium-duty SI engine with multi-point fuel injection system. The binary blends composed of isopropanol with the rates of 10%, 20%, and 30% by volume in order to assess the influence of alcohol addition on the performance, combustion, and emissions. To conclude, a significant decrement in HC and CO emissions with increasing BTE and NO_X emissions and further, alcohol addition caused to affect negatively on the characteristics of engine performance. In addition, isopropanol infusion led to boosting the pressure in the cylinder and HRR. Dhamodaran et al. [67] examined the influence of the binary blends of n-butanol (up to 30 vol%)-UG blends on the engine characteristics of a 4-stroke, 4-cylinder, medium-duty SI engine at the range of 1400 rpm-2800 rpm engine speed and a fixed load (20 Nm). As a result, the engine released lesser CO and HC emissions with higher NO_X emissions when using fuel blends of n-butanol and gasoline. The BTE, peak in-cylinder pressure, HRR of the blends were also observed higher than that of pure gasoline. Geo et al. [2] studied the effect of ethanol and benzyl alcohols at ratios of 10% and 20% blending with gasoline on the combustion, emission and performance of a commercially available 2-cylinder SI engine having multi-point fuel injection system under the various loads from 20% to 100% with intervals of 20% and at stable speed of 2500 rpm. The BTE of the tested fuel mixtures increased in comparison with the neat gasoline while HC, NO_X, and CO emissions were reduced. According to the experimental results, higher-order alcohol namely benzyl alcohol was recommended for an alternative and optimum fuel additive to the gasoline. Uslu and Celik [68] scrutinized the influence of the infusion of the isoamyl alcohol (an isomer of the pentanol) which is generally known as fusel oil into the gasoline at various percentages (10%, 20%, and 30%) under different engine operating conditions such as compression ratios (8.0, 8.5, and 9.0) and engine speeds (2600, 2800, 3000, and 3200 rpm) with a full load. Fusel oil contains high percentages of isoamyl alcohol and it is acquired from sugar factories as a waste by-product. Based on the experimental studies, harmful pollutants released from the exhaust tailpipe turned in low with the usage of isoamyl alcohol in contrast to the baseline gasoline at all compression ratios conducted in the studies. When the utilization of 30% alcohol + 70% gasoline blend in the engine, CO, HC, and NO_X emissions reduced by approximately 12.2%, 6.45, and 35.6%, respectively in comparison with gasoline. The combustion analyses result exhibited that the in-cylinder gas pressure and heat release rates were generally jumped in high in all compression ratio conditions with using isoamyl alcohol. In other words, the highest in-cylinder gas pressure was recorded to be as 47.50 bar with 20% isoamyl alcohol addition into the gasoline at a compression ratio of 9.0 and engine speed of 2600 rpm. Additionally, the maximum heat release rate was computed to be at 8.64 J/deg when the engine was fuelled with 10% isoamyl alcohol blend under the aforementioned operating conditions. Interestingly, Uslu and Celik [69] also performed an artificial neural network (ANN) coupled response surface methodology (RSM) design optimization process for a SI engine running on the i-amyl alcohol/gasoline fuel blends with the intention of estimating the performance and pollutant emissions at various engine speeds and compression ratios. According to the optimization studies, the regression of coefficient (R^2) values for performance and emission parameters were calculated with the ANN model to be as 0.94 and 0.99, respectively. It means that the highest mean relative error was found to be lower than 7% in comparison with the outputs acquired from the tests. Furthermore, the optimum engine operating conditions and higher-order alcohol proportion in the gasoline was determined with implementing RSM design to be as the alcohol content of 15%, compression ratio of 8.31, and engine speed of 2957.58 rpm. As a result, the authors pointed out that the ANN model coupled with RSM design can be an influential technique so as to estimate and optimize the engine outcomes with the aim of minimizing the test numbers.

As observed in the literature, the influence of the different types of alcohol fuels on the performance and exhaust harmful pollutants has been reported for a long time. Alcohols possessing a relatively higher octane number as compared to gasoline supply lesser pollution levels when used as fuel in the IC engines. Although most of the literature works tested short-chain alcohols and butanol mixed with gasoline in the SI engine application, trials concerning the use of n-pentanol or n-amyl alcohol are limited in the literature. Furthermore, n-pentanol can be synthesized from renewable and sustainable raw materials by applying various techniques. In this context, n-pentanol has to be evaluated as an alternative fuel for IC engine applications. In addition, it was concluded from the comprehensive literature survey that the combustion characteristics such as HRR, rate of pressure rise, and in-cylinder pressure of an SI engine have not been sufficiently studied when the engine was fueled with n-pentanol/gasoline fuel mixtures. For that reason, this present paper deal with the effect of n-pentanol supplementation into the UG at different concentrations (5%, 10%, 15%, and 20% by vol.) on the performance (BTE and EGT), exhaust emissions patterns (HC, CO, CO_2, O_2, and NO), and combustion behaviors (in-cylinder gas pressure, HRR, and rate of pressure rise) at various engine loads (1–5 kW) with a constant engine speed of 1600 rpm and compared them with those of UG. The objective of choosing diversified blend concentrations within a particular range is to detect the best mixture ratio in view of environmentally friendly as well as providing suitable engine outcomes.

2. Test fuels

In the current study, commercially existent UG having an octane rating of 95 was chosen as a reference fuel (G100) and it was purchased from a local gasoline firm located in Kirikkale, Turkey. The higher-order alcohol of n-pentanol (99% extra pure) was supplied from Acros Organics, USA. The blends comprising 5%, 10%, 15%, and 20% at a volumetric ratio of n-pentanol in the gasoline were individually prepared in the laboratory conditions and are hereby labelled to as P5, P10, P15, and P20, respectively. In other words, for instance, P10 contains 10% n-pentanol and 90% gasoline fuel on a volume basis. In the experiments, the higher-order alcohol concentration in the gasoline was limited (up to 20% by volume) in order not to implement a modification on the engine.

The reason for selecting maximum n-pentanol concentration by 20% (v/v) in baseline gasoline is to avoid from the knocking. By the way, a 25% n-pentanol + 75% gasoline fuel blend (by volume) was also tested in the research engine under the predetermined engine operating conditions, as mentioned above. However, the knocking was heard by authors, and the real-time combustion analyzer presented a knocking behavior because of the lower octane number of the n-pentanol which was shown in Table 1. For that reason, 25% (by volume) n-pentanol proportion in gasoline was not thoroughly experimented with at the highest compression ratio due to the above-mentioned reason. It should be tested reasonably lesser compression ratio, however, it can lead to reducing the thermal efficiency generated from the engine. As a result, this fuel blend was not placed and discussed in this paper at the following sections.

The aforementioned test fuels were prepared just prior to beginning the engine experiments in order to prevent the phase separation in the fuel mixture, i.e. to secure the homogeneity of fuel blends. Meanwhile a gravitational observation has been conducted for monitoring the stability of the prepared test fuel samples. The fuel blends have been stored in the glass bottles for two weeks at the ambient temperature of 25 °C and in a dark medium. During the stability test, all of the test fuels clearly demonstrated a single phase. The fuel specifications of gasoline and 1-pentanol are tabulated in Table 1.

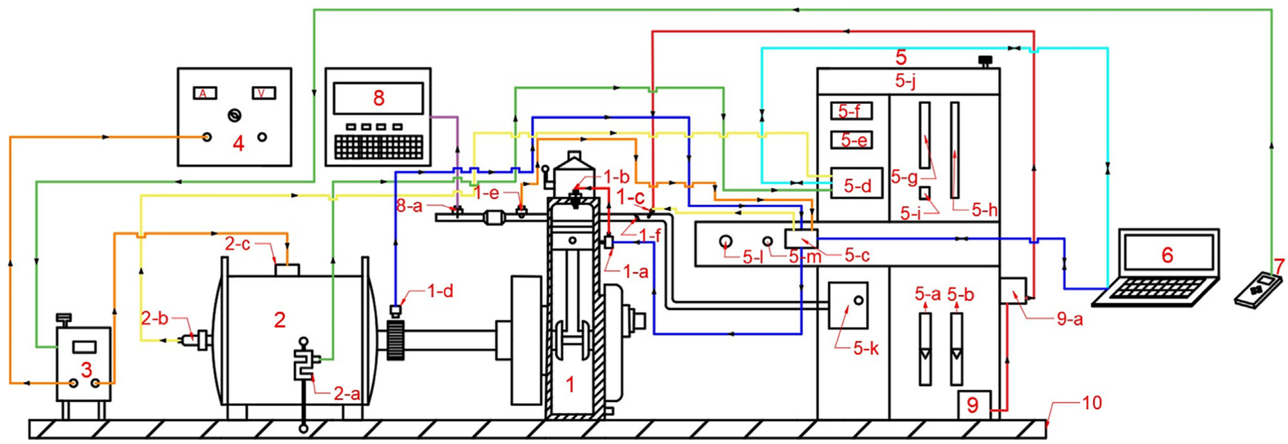
3. Experimental setup and test procedure

In the present research, the trials were carried out on a 1-cylinder, 4-stroke gasoline engine. The schematic and pictorial views of the experimental test rig were plotted in Fig. 1. The tested engine has the PFI system ability to inject the fuel and electronic ignition facilitated. The technical properties of this SI engine were comprehensively tabulated in Table 2.

The test engine has an electronic controlled fuel injection system admitted of and it can control by a closed-loop system with a lambda sensor on the exhaust gas. The engine has been loaded thanks to an AC active dynamometer (Galen-Tech 11 kW) with Siemens controller which is mounted on the engine shaft and it has an ability to load this engine. In addition, the experimental test rig involves high-speed data acquisition (NI USB-6210 Bus Powered

Table 1
The fuel specifications of the test fuel samples [2,47,68–71].

No	Properties	Unit	Gasoline	Pentanol
1	Chemical formula	–	C_4–C_{12}	C_5H_{11}–OH
2	Oxygen content	wt. %	0	18.15
3	Lower heating value	MJ/kg	44.0	34.65
4	Density	kg/m^3	720–775	814.8
5	Viscosity at 25 °C	mm^2/s	0.5–0.6	2.89 (at 40 °C)
6	Auto-ignition temperature at 1.013 bar	°C	420	300
7	Molecular weight	g/mol	95.2–105	88.15
8	Motor octane number	–	82–92	–
9	Research octane number		91–100	80
10	Boiling point	°C	210	137.5
11	LHV	kJ/kg	223.2	308.05
12	Stoichiometric AFR	–	14.2–15.1	11.73
13	Vapor pressure at 20 °C	kPa	–	6



1 variable compression ratio (VCR) engine, 1-a ignition coil, 1-b spark plug, 1-c gasoline injector, 1-d hall effect sensor, 1-e O_2 sensor, 1-f throttle valve
2 AC dynamometer, 2-a Load-cell, 2-b encoder, 2-c dynamometer and speed control connection
3 dynamometer speed control unit 11 kW
4 AC dynamometer 380 V board
5 measuring component stand, 5-a engine cooling rotameter, 5-b exhaust calorimeter rotameter, 5-c gasoline engine ECU, 5-d data acquisition device, 5-e load indicator, 5-f rpm indicator, 5-g manometer, 5-h fuel measuring burette, 5-i fuel cock, 5-j fuel tank, 5-k engine intake air measurement system, 5-l throttle position control system, 5-m system switch
6 computer interface
7 load and speed control interface device
8 gas analyzer device
9 gasoline injection pump, 9-a gasoline filter

Fig. 1. Schematic layout of the experimental rig.

Table 2
Technical properties of the used SI engine.

No	Item	Specification
1	Brand	Kirloskar VCR Engine
2	Model	TV 1
3	Cylinder number	One
4	Stroke type	Four
5	Compression ratio	6–10
6	Maximum load condition	5 kW at 1600 rpm
7	Engine speed (Maximum)	1850 rpm
8	Stroke length	110 mm
9	Cylinder bore	87.5 mm
10	Connecting rod length	230 mm
11	Swept volume	661.5 cc
12	Cooling type	Water-cooled
13	Spark timing	26° before TDC
14	Idling speed	750 rpm
15	Inlet valve closing	35.5° after BDC
16	Inlet valve opening	4.5° before TDC
17	Exhaust valve closing	4.5° after TDC
18	Exhaust valve opening	35.5° before BDC
19	Load capacity	0 to 50 kg

M Series Multifunction DAQ Device, NI DAQmx driver Software, 16-bit, 250 kS/s) and recording system to get engine characteristic data. The fundamental sensor data gathered were as follows: in-cylinder pressure sensor for determining the gas pressure revealed in the cylinder during each cycle and encoder for detecting the crank position. The thermocouples were placed to the suitable position to measure the engine temperatures. Furthermore, the details of the engine instrumentations which were used in the present work were presented in the Supplementary data file section A as a Table 1. During the tests, the mass flow rates of the water circulating in the engine and exhaust calorimeter device were kept constant by 250 L/h and 100 L/h, respectively for each fuel types.

The exhaust gas emissions were observed with the help of Bosch brand BEA 350 model exhaust gas analyzer. This device has used the non-dispersive infrared and electro-chemical transmitter technique to measure the emissions released from the engine. Five gas pollutants namely CO, CO_2, HC, O_2, and NO were mainly taken into account. Accordingly, the measurement range of the exhaust gas analyzer device was tabulated in Table 3.

The test setup has been applied to collect entire the experimental data for 50 consecutive engine cycles. The measured data were associated and filtered so as to eliminate the errors coming from the experimentations by using suitable software. Therefore, a square root method that has been represented by Holman [72] was applied to the engine experiments for computing the uncertainties. The equation was given in the form of:

$$w_R = \left[\left(\frac{\partial R}{\partial x_1} w_1 \right)^2 + \left(\frac{\partial R}{\partial x_2} w_2 \right)^2 + \cdots + \left(\frac{\partial R}{\partial x_n} w_n \right)^2 \right]^{1/2} \quad (1)$$

where,

- $w_1, w_2, \ldots, w_n$: Uncertainties of the independent variables,
- w_R: Results' uncertainty values,
- $x_1, x_2, \ldots, x_n$: Independent variables,
- R: Dependent factor and it is a function of independent variables.

Table 4 shows the uncertainty values for the equipments and calculated parameters.

Table 3
The technical properties for the exhaust gas analyzer device.

No	Item	Unit	Measurement range
1	CO	vol. %	0–10 vol%
2	CO_2	vol. %	0–18 vol%
3	HC	ppm	0–9999 ppm
4	O_2	vol. %	0–22 vol%
5	NO	ppm	0–5000 ppm
6	λ	–	0.500–9.999
7	K-type thermocouple	°C	0–1200

Table 4
Uncertainty of equipments and calculated parameters.

No	Measurement	Uncertainty (%)
1	Engine power	±0.92
2	Engine speed	±0.79
3	Engine load	±0.06
4	Fuel flow rate	±0.92
5	EGT	±1.00
6	Burette fuel measurement	±1.00
7	Air flow rate	±0.75
8	Time	±0.20
9	BTE	±1.48
10	CO	±0.95
11	CO_2	±0.83
12	HC	±1.18
13	O_2	±0.75
14	NO	±0.75

Prior to the engine tests, the compression ratio was adjusted to 10:1 which is the maximum parameter for the tested engine and kept constant for all types of fuel samples even though the engine provides a wide range of compression ratio, as observed in Table 1. The engine tests for all the tested fuels were performed by limiting the engine at a fixed speed (1600 rpm) because the engine has run at this speed with a maximum efficiency. Afterward, the engine was loaded from 1 kW to 5 kW to observe the engine behaviors and emission patterns. The tests were achieved under a steady-state status for all the tested fuels out of any modification on the tested engine. Before the main testing, the engine ran with neat gasoline for 20 min to warm up the engine and hence readings were to be noticed for the trial numbers in order to responsibility of the condition.

In accordance with the work aimed before the experiment, optimum λ = 1 condition was ensured in every case in line with the appropriate air–fuel ratio studies for each cycle and load conditions. The operating condition of the SI engine was provided by a fully electronic open-access technology PE3-SP000 series ECU during the tests. The interface image given in the Supplementary data file (as mentioned underneath) is realized by determining and recording the spraying time in milliseconds (ms) of the injection system injector at continuous pressure of 3 bar under fully open-access conditions with the ECU and Dynamometer control unit USB connection, which will provide the λ = 1 condition suitable for each desired load and revolution. Generally, after providing λ = 1 for each coordinated situation with the exhaust emission device calibrated for the fuel to be researched for optimum engine working conditions, the test file has been uploaded to the ECU from the computer and the experiments have been carried out in the optimum working condition until the end of the experiment with this regulated program. In addition, the amount of fuel can be increased and decreased by changing the instantaneous fuel injection time during the experiments. Furthermore, the fuel injection time can be adjusted at the appropriate crankshaft angle (CA) intervals at the time of fuel intake. On the other hand, the O_2 lambda sensor mounted at a suitable distance on the engine exhaust pipe of the test system, after selecting the closed loop in the connection and control software made to the ECU, the sensor voltage values for known fuels are entered into the system memory via the interface control computer and the desired lambda values are continuously supported and hence final experiments have been performed under the desired operating conditions. Additionally, Bosch brand 11 mm iridium spark plug was utilized in the test system. The spark timing can be also controlled using the ECU, as mentioned above. In the present experiments, the spark timing was adjusted to be as 26°CA before TDC for each fuel type. The SI engine computer fuel injection interface (Fig. 1), the O_2 sensor interface (Fig. 2), and the spark timing adjustment system computer interface screen according to engine speed and throttle position were presented in Supplementary data file section B.

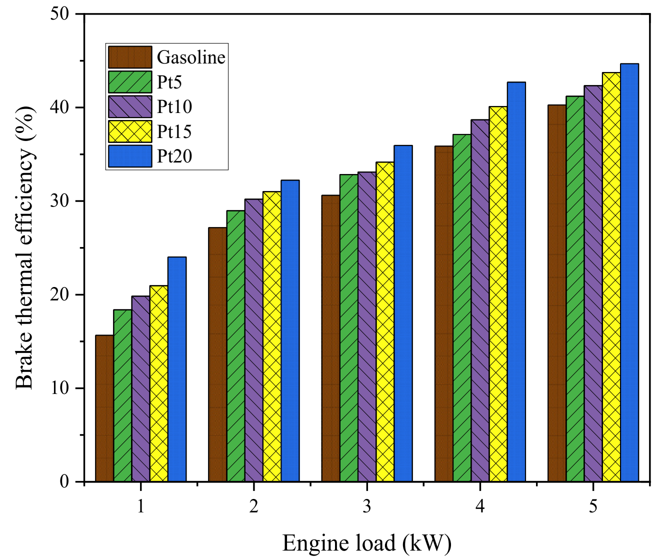


Fig. 2. The change in BTE at different loads.

In this study, the usability of the target n-pentanol alcohol based fuel by mixing it with the gasoline fuel of a current system was investigated without making any changes in the engine and fuel system. In this context, experimental studies have been made by creating conditions where λ = 1 condition was fulfilled in each cycle and load conditions of the engine and the engine can operate without knocking behavior. For that reason, the λ = 1 conditions for Pt5, Pt10, Pt15, and Pt20 fuels and the case under which the engine can operate at the appropriate ignition advance were loaded into the ECU after the appropriate work program was set with the test system's main computer interface, and the engine was tested and analyzed without knocking. When the n-pentanol concentration in the blends increased, the knocking has occurred from the software, therefore, the engine was stopped and the experiments were not continued higher than 20% (v/v) proportion. The conditions under which it can operate without knocking were primarily made by means of the PE3-SP000 series ECU and the open-access program (version: 3.06.01), which is used as open access. Experimental studies have been carried out by providing the conditions under which the cylinder pressure change due to the change to CA works without knocking with the other combustion analysis-performance analysis program (ICEengineSoft_9.0) working simultaneously on the main computer of the advance adjustment test system where the engine will run without knocking. The previously mentioned program was monitored instantly on the screen image of the test computer interface and the experimental working conditions were recorded when the pressure change without knocking was achieved. The combustion analysis program was set during the test.

4. Results and discussion

The following sections exhibit the findings along with the discussions according to the up-to-date literature upon the performance, combustion, and emission characteristics for the binary blends of n-pentanol/gasoline under different loads such as 1 kW, 2 kW, 3 kW, 4 kW, and 5 kW with a stable speed of 1600 rpm.

4.1. Brake thermal efficiency

The thermal efficiency points out the capability of the combustion system to acknowledge the tested fuel and ensures comparable opinions of evaluating how effective the energy in the fuel is transformed into the mechanical outlet [73]. Fig. 2 presented the BTE results for all the tested fuels in contrast to the neat gasoline at dissimilar loading conditions. As seen, considerable augmentations in BTE figures were noticed for entire the tested fuel specimens when the engine loading increased from 1 kW to 5 kW. At the highest engine load, the maximum BTE for gasoline, Pt5, Pt10, Pt15, and Pt20 were occurred to be as 40.27%, 41.20%, 42.34%, 43.74%, and 44.68%, respectively. The indicated thermal efficiency results were also acquired from the engine trials for all the test fuels. In this context, the indicated thermal efficiency at the maximum engine loading condition for gasoline, Pt5, Pt10, Pt15, and Pt20 were found to be at 44.08%, 44.32%, 44.79%, 45.45%, and 46.99%, respectively. In addition, when the friction loss, as a type of mechanical loss, was examined for each fuel, it was to be noted that the increase in the engine load caused to increase the friction loss. In the test system, friction and pumping lost were evaluated together. In this regard, the lost values for friction, pumping, etc. at the highest engine load were obtained to be at 1.18 kW, 1.12 kW, 1.02 kW, 0.93 kW, and 0.88 kW, respectively. Getting more than 40% efficiency from the engine may sound challenging. In the present experimental research, the test system and selected SI engine were commissioned for the first time, and the measurements were made with an AC active generator based dynamometer system working with high efficiency. In addition to these situations, it is thought that providing optimum operating conditions with open access new technology ECU of the SI engine is effective in the high efficiency of the engine and the use of a correct measurement method to increase the engine efficiency above 40%. Furthermore, the fact that the test engine is new has been a factor in low friction losses. The absence of accessory systems such as the alternator, water pump, and cooler compressor powered by an engine, enabled the engine to get more power that is effective. It was to be noted that the infusion of higher-order alcohol to pure gasoline caused to improve the BTE values remarkably at all engine loading conditions. Furthermore, it could be clearly stated that the BTE values increased with the rising of the proportion of the n-pentanol in the fuel blends. The basic parameters towards the enhancement in the BTE figures were as follows: appropriate atomization characteristics and acceleration in the mixing process. Besides, it also well-known that alcohol-based fuel sources have higher octane number as well as higher laminar flame speed than those of baseline gasoline fuel. Therefore, in the case of utilizing alcoholic fuels in the SI engines, they can lead to being decreased combustion duration. As can be confirmed from Fig. 7 which would be explained in detail, the combustion duration of the n-pentanol/gasoline blends were formed to be shortened in comparison with the conventional gasoline. Moreover, alcohol-based fuels possess larger LHV characteristics than that of gasoline. For those reasons, when the higher-order alcohol was added into the gasoline, the BTE values were increasing [29]. In other words, due to the higher LHV features of alcohol-based fuels than gasoline, n-pentanol absorbs more heat from the engine cylinder contents throughout the vaporization process in the compression stroke. As a result, this cools the intake charge remarkably, hence rising the charge intensity, which in turn increases the volumetric efficiency of the engine for alcohol/gasoline blends. Furthermore, it leads to reduce the work needed for compressing the charge, therefore enhancing the total BTE at all engine loads. It can be thought that the BTE should decrease after a certain percentage depending on the increase in the alcohol content in the mixture. However, the present study showed that up to 20% n-pentanol addition into the gasoline caused to increase in the BTE gradually. By all means, it will not be difficult to say that there are the reasons mentioned above in the occurrence of this situation. The authors do agree that alcohol addition higher than 20% (by volume) can reduce thermal efficiency owing to the lesser energy content. This idea can be confirmed by looking into the paper published by Uslu and Celik [68]. The researchers investigated various isoamyl alcohol (one of the isomers of the pentanol) infusion to the gasoline caused to increase in the BTE at all engine operating conditions; meanwhile, the maximum results were observed when the engine operated with a 20% higher alcohol blend. The produced vapor's quality along with the existence of the native oxygen molecules in the binary blends resulted in the improvement of the combustion reaction taking place inside the cylinder. n-pentanol has much more oxygen molecules in its chemical structure. This causes an improvement in the quality of the combustion process thereby enhancing the BTE. A relationship can be made between BTE and combustion characteristics. Notwithstanding, this topic will be discussed comprehensively in the next sections. However, a brief explanation was needed here as well. As will be mentioned in subsection 4.4, in-cylinder gas pressure figures of n-pentanol/gasoline blends were monitored to be higher than that of conventional gasoline fuel because alcohol-based fuel has higher laminar flame speed and higher oxygen content than those of gasoline. This case can effectuate a more convenient area in the SI engines for combustion reaction and this route along with in-cylinder gas pressure, the work done in the piston enhances more than gasoline [68]. In addition, preferring a higher compression ratio in the tested engine the highest in-cylinder gas pressure for all kinds of test fuel close to the TDC since the adiabatic flame temperatures of alcohol-based fuels are lesser than gasoline and hence, it causes a reduction in the heat losses from the combustion chamber resulting in higher in-cylinder gas pressure as well as BTE. When the literature is examined, it is seen that there is an increase in the effective brake efficiency in alcohol fuel additions that contain oxygen due to its chemical structure up to a certain amount.

Similar results and their reasons were also presented by various researchers available in the published papers. Geo et al. [2], for instance, tested the influence of higher-order and lower order alcohols mixing with gasoline of the engine characteristics of an SI engine. The authors highlighted that higher-order alcohol blend demonstrated an enhancement in BTE by 10.18% and 11.52% for 10% and 20% benzyl alcohol in the gasoline as compared to pure gasoline at full load. Meanwhile, lower-order alcohol also showed a small improvement by 2.15% in 10% ethanol and 3.51% in 20% ethanol concentration in the gasoline in comparison with the reference fuel. The infusion of the alcohols into the gasoline increased the BTE remarkably at all operating conditions. Obviously, the researchers found that the improvement in the BTE with using both higher-order and lower-order alcohols in the gasoline because of the fact that the basic reasons behind the BTE increments were accelerated mixing and proper atomization. Likewise, the available oxygen molecules in the combustion chamber coming from the alcohols contributed to the combustion process inside the cylinder. Godwin et al. [74] tested dual fuels including 10% n-butanol, *iso*-butanol, n-pentanol, and benzyl alcohol in an SI engine under different engine loads (from 20 to 100%). The addition of n-pentanol into the gasoline by 10% (by volume) contributed to the improvement of the BTE by 7.38% when compared to the gasoline at 100% load. From different perspective, Masum et al. [75] prepared optimum C2-C6 alcohols/gasoline blends in order to achieve better characteristics than E15. In this regard, three optimum fuel blends were constituted based on the aspects of maximum energy content, research octane number, and petroleum displacement. When the SI engine was powered by the aforementioned fuel blends at different engine speeds, BTE was increased in contrast to the baseline gasoline in the range of 2.49–4.00% at 5000 rpm. The alcohol/gasoline blends exhibited higher BTE than gasoline due to the fact that alcohols have oxygen molecules in their chemical structures whereas gasoline has no oxygen. This led to increasing the BTE thanks to the more complete combustion process.

4.2. Exhaust gas temperature

The exhaust gas temperature (EGT) pointed out the comprehension of the combustion process or otherwise called the in-cylinder temperature by detecting the temperature of the burned gas after it left the engine. The alteration of EGT for gasoline and n-pentanol/gasoline blends at various engine loads were displayed in Fig. 3. It can be noticed that the EGT measurement for all the test fuel specimens demonstrated an increasing inclination with the rise in the engine loading. The EGT values for gasoline, Pt5, Pt10, Pt15, and Pt20 at the highest engine load situation were recorded to be as 481.96 °C, 472.66 °C, 461.24 °C, 446.08 °C, and 435.69 °C, respectively. It can be concluded that the infusion of n-pentanol into the neat gasoline fuel has caused to descend in the EGT values because of the enhancement of the combustion reaction and substantial with the ascending in the concentration of alcohol in the binary blend. Moreover, it is to be clearly indicated that the higher LHV feature of the n-pentanol resulted in declining the temperature in the combustion chamber for the tested gasoline engine principally throughout the ending of the induction stage. To conclude, the aforementioned reason can remarkably influence the temperature inside the cylinder during the compression's final stage resulting in a significant dropping in the EGT. Although alcohol-based fuel candidates exhibit a substantial delay in the ignition, n-pentanol having native oxygen atoms in its molecular structure leading to advance the physicochemical features resulting in a much reduction combustion states than that of traditional gasoline fuel. Hence, the usage of higher-order alcohol/gasoline blends in the tested SI engine could decline the waste heat in the exhaust from an efficient point of view than that of neat gasoline. From the graph, it was observed that the measurement results of the EGT highlighted a drastic decrement of 1.8% to 9.6% with the binary blends of n-pentanol/gasoline in contrast to the conventional gasoline at the highest engine load. Moreover, it was evident from the apparent HRR graph that the combustion process for n-pentanol/gasoline blends commenced early as compared to gasoline. This case caused a descending in the combustion stage and from behind dropping the quantity of wasted energy via exhaust gases. It can be indicated as concerning the aforementioned reason that the BTE figures were also improved. In addition, it could be noticed that there is an impairment in the period of the combustion taking place inside the cylinder assignable to the higher and accelerated laminar flame speed, and thereby, the EGT values decreased [2].

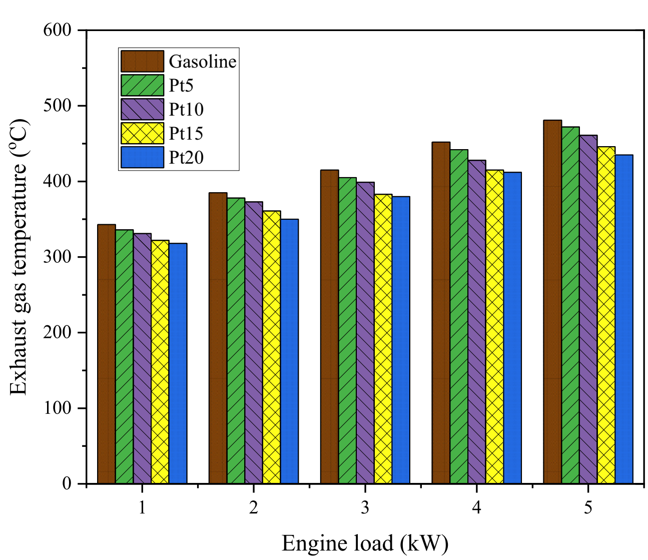


Fig. 3. The change in EGT at different loads.

Similar findings were observed by various researchers. Topgül et al. [76], for instance, investigated the impact of the ethanol concentration in the gasoline on the engine performance and harmful pollutants in an SI engine at varying compression ratio (8:1, 9:1, and 10:1) and ignition timing (from 10^{O} to 36° before TDC) at a stable engine speed of 2000 rpm with wide-open throttle position. The researchers observed that the EGT values were reduced when the ignition timing increased because higher ignition timing led to the occurring combustion process earlier in the cylinder and dropped the temperature. In addition, the EGT values were declined depending upon the proportion of the alcohol in the blends. Masum et al. [75] reported that the addition of different alcohol at various percentages into the gasoline caused to decrease in the EGT in the range of 1.9–4.3% in overall engine speeds owing to the lesser energy content of the alcohols. The researchers also indicated that the EGTs boosted with speed since the consumed fuel amount in the cylinder increased at high speed. On the other hand, low EGT was an advantage of a fuel sample for performing in an engine on account of reducing the manifold cost. Godwin et al. [74] measured the EGTs by 654 °C for gasoline while 616 °C for 10% n-pentanol/90% gasoline blend. It could be attributed to the higher LHV of alcohol as compared to gasoline resulting in decreasing temperature inside the cylinder at the end of the induction process that decreases the in-cylinder temperature as well as EGT. Sharudin et al. [77] studied the effect of higher-order alcohol (*iso*-butanol) blend with methanol/gasoline mixture on the performance and emissions of an SI engine at dissimilar speeds. The researchers appeared that the addition of alcohols decreased the EGTs between 1.3% and 4.5% in contrary to the gasoline in overall engine speeds because of the lower energy content of the alcohols. This reason was also pointed out by Stein et al. [12] and Agarwal et al. [78]. Eyidogan et al. [79] examined the influence of the methanol and ethanol addition into the gasoline at 5% and 10% (by volume) proportions on the performance and combustion characteristics of a vehicle powered by an SI engine at various speeds and wheel powers. The infusion of alcohol into the gasoline resulted in lower EGT values in the range of 0.2–1.6% at 80 km/h and 0.3–1.4% at 100 km/h when compared to pure gasoline. Although the researchers also indicated the similar reasons explained by various authors as mentioned above, they highlighted that the extra air was absorbed into the cylinder so as to achieve the similar wheel power outlet that fractionally diminished the EGT because BSFC of the dual blends was higher than that of gasoline fuel.

4.3. Engine temperatures

In the present experimental research, plenty of temperatures from various points of the engine test set-up running on the gasoline and its blends with n-pentanol higher alcohol were measured and recorded under different engine load conditions. Table 5 exhibits the measured temperatures comprehensively. In general, the temperatures of the points were declined when the engine was powered by n-pentanol blends due to the lesser energy content and higher LHV characteristics of n-pentanol, as mentioned above.

4.4. In-cylinder pressure

Fig. 4 depicts the influence of n-pentanol addition into the gasoline upon the in-cylinder pressure with regards to the crank angle for the test fuels under the maximum load of 5 kW. As can be seen in Fig. 4, the maximum in-cylinder pressures for the binary blends were appeared to be higher in comparison with the neat gasoline. The highest in-cylinder pressure values were measured to be as 37.11 bar for Pt20, 36.43 bar for Pt15, 36.37 bar for Pt10, 36.30 bar for Pt5, and 36.16 bar for gasoline fuel at the crank angle

Table 5
The measured temperatures from various points of the engine set-up.

Engine load (kW)	Fuel type	Temperature (°C)					
		T_1	T_2	T_3	T_4	T_5	T_6
1	Gasoline	40.00	54.02	40.00	52.38	343.60	180.51
	Pt5	30.12	45.06	30.13	43.38	336.98	181.10
	Pt10	33.69	48.40	33.70	46.51	331.36	185.80
	Pt15	37.63	51.24	37.63	49.29	322.85	179.88
	Pt20	39.80	53.64	39.78	50.44	318.34	178.89
2	Gasoline	37.17	53.11	37.17	53.05	385.83	217.06
	Pt5	28.76	46.25	28.76	45.14	378.90	217.73
	Pt10	32.78	49.93	32.79	48.97	373.21	224.19
	Pt15	35.96	52.16	35.95	51.63	361.00	223.39
	Pt20	40.31	55.32	40.28	53.91	350.01	209.05
3	Gasoline	34.80	53.21	34.79	53.84	415.11	249.80
	Pt5	27.96	47.49	27.95	47.36	405.18	246.88
	Pt10	32.27	51.61	32.27	51.83	399.58	251.68
	Pt15	35.37	53.19	35.36	53.74	383.13	248.11
	Pt20	40.62	57.31	40.62	56.53	380.82	235.37
4	Gasoline	32.35	52.75	32.36	55.15	452.10	279.18
	Pt5	26.47	47.97	26.47	48.83	442.89	270.90
	Pt10	30.98	50.40	30.98	49.69	428.67	249.13
	Pt15	34.77	54.64	34.76	55.68	415.89	268.54
	Pt20	40.98	59.52	40.95	59.20	410.92	262.83
5	Gasoline	27.71	52.24	27.71	55.95	481.96	297.58
	Pt5	24.79	48.13	24.79	49.19	472.66	290.20
	Pt10	31.38	52.78	31.37	53.29	461.24	282.48
	Pt15	34.04	54.69	34.02	54.72	446.08	273.70
	Pt20	41.70	62.83	41.69	65.14	435.69	293.54

T_1: Inlet temperature of the engine cooling water.
T_2: Outlet temperature of the engine cooling water.
T_3: Inlet temperature of the exhaust calorimeter water.
T_4: Outlet temperature of the exhaust calorimeter water.
T_5: EGT arriving at the exhaust calorimeter.
T_6: EGT leaving from the exhaust calorimeter.

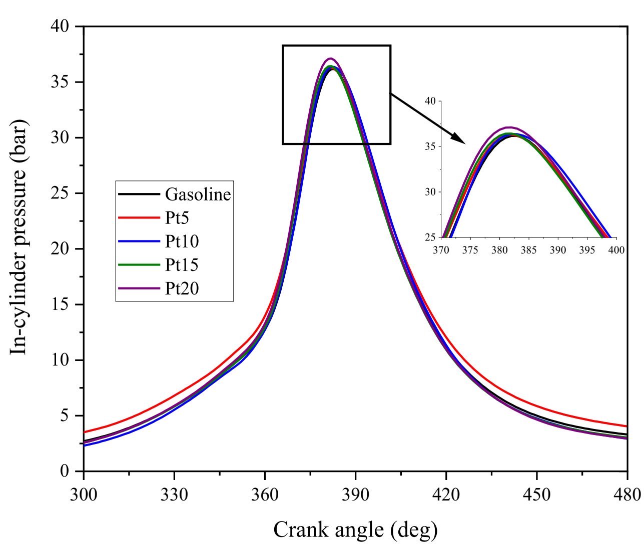


Fig. 4. The effect of n-pentanol infusion into the gasoline on the in-cylinder pressure.

of 382 deg. Besides that, the in-cylinder gas pressure boosted with the rising engine load. This case can be attributed to the increasing amount of fuel, injected into the combustion chamber, and volumetric efficiency [79]. As observed, the peak in-cylinder pressure for Pt20 revealed the highest amongst the test fuel samples. This can be explained as the existence of the native oxygen molecules found in the alcohol's chemical bonds leading to improve combustion reaction when the radicals have been generated throughout the combustion process. In other words, the existence of the oxygen molecule expedites the combustion process thanks to the improvement of the reaction [74,80]. Another reason is the higher flame speed characteristic of the pentanol than that of gasoline, resulting in higher in-cylinder pressure. This case constitutes a more convenient region in SI engines to form the combustion process and in this route along with in-cylinder gas pressure, the work done in the piston enhances more than gasoline [81]. Geo et al. [2] observed that the peak in-cylinder pressure occurred with using 20% (v/v) higher-order alcohol (benzyl alcohol) in the gasoline at the maximum engine loading condition as compared to both gasoline and ethanol/gasoline blend. The researchers pointed out that the existence of the surplus amount of oxygen molecules accelerated the combustion by assisting the enhanced combustion process. Uslu and Celik [68] tested one of the isomers of the pentanol which was isoamyl alcohol in the gasoline up to 20% concentration (by volume) in an SI engine at various engine operating conditions. The researchers found that the highest in-cylinder pressure was measured to be at 47.50 bar with 20% isoamyl alcohol/80% gasoline blend at a compression ratio of 9:1 and speed of 2600 rpm.

4.5. Heat release rate

The influence of n-pentanol infusion into the gasoline on the apparent HRR values with regards to the crank angle at the maximum engine load portrayed in Fig. 5. The calculation of the HRR is an approach with the intention of acquiring some knowledge regarding the combustion process in the IC engines. The HRR is performed in engine performance effects in different working conditions and identical engine performances at equal operations. Furthermore, it is well known that the physicochemical characteristics of the tested fuel samples used in IC engines are one of the key fac-

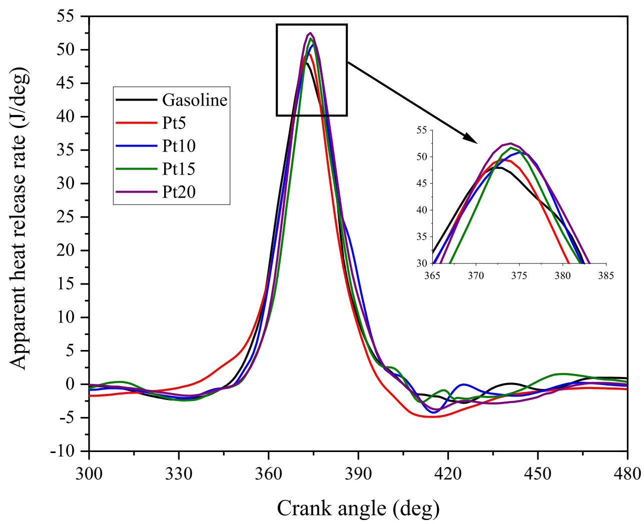


Fig. 5. The effect of n-pentanol addition into the gasoline on the apparent HRR.

tors that influence the HRR [79]. Moreover, HRR of an SI engine is known to depend upon the plenty of factors like air–fuel mixing rate, auto-ignition temperature, LHV of the fuel, and calorific value [66]. The HRR was computed for each fuel operation based on the first law of thermodynamics from the related in-cylinder pressure measurements. In other words, a standard single-zone model according to the first law of thermodynamics has been implemented for calculating apparent HRR. The CA dependent HRR was found with Equation (2), as given below [79].

$$\frac{dQ}{d\theta} = \frac{k}{k-1}P\frac{dV}{d\theta} + \frac{1}{k-1}V\frac{dP}{d\theta} \tag{2}$$

where,

- Q: Net heat input,
- P: Cylinder pressure,
- V: Cylinder volume,
- θ: Crank angle (or CA somewhere),
- k: Ratio of specific heat values and it accepted to be as 1.35.

The stoichiometric air/fuel ratio of n-pentanol is 11.73 and gasoline is 15.05 while the energy content of gasoline is 44.00 MJ/kg and methanol is 34.65 MJ/kg. This can be one of the reasonable grounds for the considerable differences in the trends of combustion behaviors [35]. The apparent HRR values for test fuels were computed according to the first law of thermodynamics using the corresponding pressure values occurred in the cylinder, as given in Fig. 4. The peak apparent heat release values were obtained to be as 47.95 J/deg for gasoline at 372 deg, 49.52 J/deg for Pt5 at 373 deg, 50.85 J/deg for Pt10 at 375 deg, 51.69 J/deg for Pt15 at 374 deg, and 52.51 J/deg for Pt20 at 374 deg. The abstraction rate for the hydrogen and formation of radical throughout the combustion phasing as affected by the activation energy needed in order to fracture the bond. In the point of the above mentioned reason, n-pentanol needs fewer activation energy to break the chain. Furthermore, the enhanced abstraction rate for hydrogen along with the being of the surplus oxygen molecules result in much more fuel occurring in the combustion reaction and hence, a higher apparent HRR figures revealed with n-pentanol addition into the gasoline as compared to reference gasoline [2,79].

The comprehensive literature survey showed that similar findings and their reasons were explained by various researchers. Godwin et al. [74], for instance, measured the HRRs by 23.7 J/deg and 24.2 J/deg for gasoline and Pt10, respectively. The researchers explained the reason as the enhanced hydrogen abstraction rate and formation of radical resulted in more complete combustion process. Uslu and Celik [68] calculated the highest HRR values using isoamyl alcohol blends because of the combustion that occurred earlier than the highest heat point achieved by gasoline operating. In this context, the maximum HRR values were obtained to be 8.64 J/deg for 10% isoamyl addition into the gasoline while 8.5 J/deg for gasoline operation. Geo et al. [2] highlighted that the maximum apparent HRR was found with using higher-order alcohol blend as compared to both lower-order alcohol blend and gasoline operations. In this regard, the HRR values for gasoline and benzyl alcohol/gasoline blend were calculated to be as 23.7 J/deg and 26.4 J/deg, respectively. This case might be explained that the presence of oxygen molecules together with the enhanced hydrogen abstraction rate results in more fuel falling within the combustion process causing higher HRR with higher-order alcohol blend in contrary to the gasoline. Sivasubramanian et al. [66] investigated the effects of isopropyl alcohol concentration on the combustion behaviors of an SI engine under various engine operating conditions. The researchers found that the apparent HRR values for 10%, 20%, and 30% isopropanol addition into the gasoline were calculated to be as 54 J/deg, 56 J/deg, and 58 J/deg, respectively whereas gasoline had 52 J/deg. This case could be clarified that the higher laminar flame speed, apart from the oxygen concentration, of isopropyl alcohol would cause shortening the duration of the combustion leading in increase the HRR. Likewise, a higher LHV behavior of isopropyl alcohol and auto-ignition temperature than gasoline led to reducing the intake air temperature and made it colder, and because of which a much more quantity of fuel was injected into the cylinder. The above-stated researchers also obviously indicated that the colder air possesses a greater amount of oxygen molecules due to its higher density. For that reason, the higher amount of intake fuel would lead to a more complete combustion process inside the cylinder and hence the apparent HRR was increased.

4.6. The rate of the pressure rise

The rate of the pressure rise is found as the variation of in-cylinder gas pressure appertaining to the CA the first derivative. It is to be reported that the rate of the pressure rise above 10 bar/deg CA means the knocking in the IC engines [82].

Fig. 6 illustrates the rate of the pressure rise for test fuel specimens at the maximum load condition. It is to be noticed that an increase in the engine load led to increasing the rate of the pressure rise. Shrivastava et al. [83] inferred that the rate of the pressure rise jumped with the ascending of the CR as well as the load. It can be clearly stated that the rate of the pressure rise is a mandatory parameter to observe the knocking formation in an engine. It can be concluded that the highest rates of the pressure rise for gasoline, Pt5, Pt10, Pt15, and Pt20 were observed to as 1.69 bar/deg, 1.68 bar/deg, 1.61 bar/deg, 1.61 bar/deg, and 1.52 bar/deg, respectively. It can be inferred that there is no pronounced alteration in the maximum rates of the pressure rise with the infusion of n-pentanol to neat gasoline.

4.7. Mass fraction burned

The mass fraction burned (MFB) is descriptive of several phases of the combustion process takes place in an SI engine with regard to CA duration. In other words, the MFB can be defined as the accumulative emitted heat in consecutive CAs ranging from the beginning to the end of the combustion process by total heat emitted in the overall combustion period [84]. As indicated by Heywood [84], the functional equation made use of presenting the MFB com-

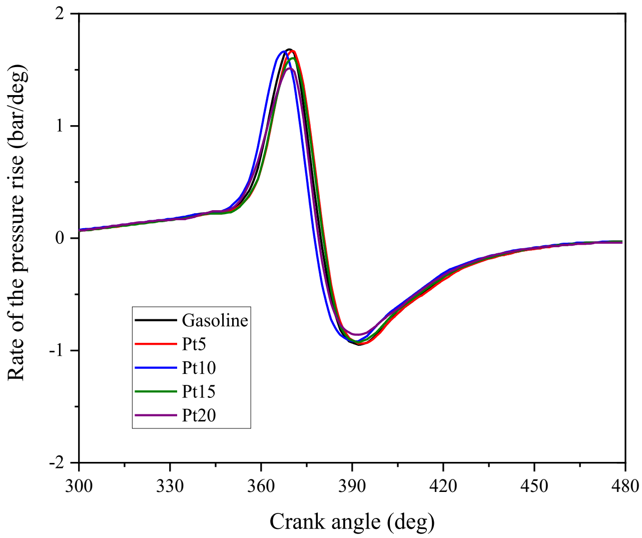


Fig. 6. The influence of n-pentanol addition into the gasoline on the rate of the pressure rise.

busted against CA curve is the Wiebe function, as shown in underneath.

$$MFB = 1 - exp\left[-a\left(\frac{\theta - \theta_0}{\Delta\theta}\right)^{m+1}\right] \quad (3)$$

where,

- θ: Crank angle,
- θ_0: Start of the combustion,
- $\Delta\theta$: Total duration of the combustion,
- a and m: Adjustable parameters (In this study, the widespread values for SI engine were taken into account to be as 5 and 2 for a and 2 m parameters, respectively [84]).

Fig. 7 portrays the combustion characteristics of the tested SI engine running on the gasoline fuel and its different blends with n-pentanol (Pt5, Pt10, Pt15, and Pt20) at the highest engine loading condition. The spark plug discharge (SPD) is the instant happening of the spark in plug, and it adjusted to be at 26°CA before TDC for each fuel type. The combustion initial duration (Cid) was identified as the CA range between SPD and 5% MFB [85]. Among the characteristics plotted in Fig. 7, two parameters are known as significant. 0–10% MFB combustion duration is described as the CA range between the start of the spark discharge and 10% mass burned and the 10–90% MFB combustion duration is characterized as the CA intervals between 10% and 90% mass burned in the cylinder [86]. The combustion duration (CD) was described as the 10–90% MFB interval in CA degree [85]. 90% MFB designates the end of the combustion (EOC) in the engine [78,86] even though some researchers have indicated actual points of EOC [87]. The faster burning rate of the oxygenated hydrocarbons has previously pointed out by many researchers [85,88]. In this context, this case can also be reported to express why n-pentanol added alternating fuel samples have a shorter CD in comparison with the gasoline which has no oxygen molecule in its chemical composition [85].

4.8. Nitrogen monoxide

Fig. 8 displays the change in nitrogen monoxide (NO) emission for gasoline and the binary blends of gasoline/n-pentanol across the various engine loading conditions. From the graph, it was noticed that the NO emission has progressively enhanced with regards to the engine loading increment for all test fuels. This is due to the higher temperature that occurred in the cylinder. In other words, NO emission forms when the nitrogen in the intake air is reacted with oxygen atoms at elevated in-cylinder temperatures above 1600 °C [68]. The EGT can reflect the in-cylinder temperature. As seen in Fig. 3, the maximum EGT values were measured with the use of gasoline while the least value was found with Pt20. A similar trend was obtained in NO_X emission. The generation of NO emissions is mostly influenced by the temperature revealed in the cylinder and the excess amount of oxygen concentration. The nitrogen chains disintegrate at the condition of high temperature. Afterward, these nitrogen bonds integrate with the oxygen molecules in the monotonic form being inside the cylinder. Additionally, the formation of NO emissions is principally affected by the rates of the reaction of nitrogen molecules throughout the connecting stage at higher temperatures. At lower temperatures, nitrogen shows inert gas characteristics and existences N_2 form, i.e., in a diatonic form. At the highest engine load, the NO emissions for gasoline, Pt5, Pt10, Pt15, and Pt20 were recorded to be as 1255 ppm, 1233 ppm, 1162 ppm, 1102 ppm, and 1082 ppm,

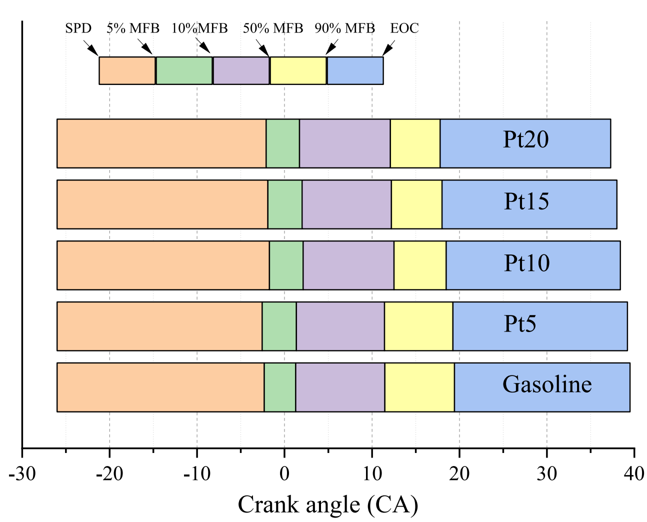


Fig. 7. The combustion behaviors of the tested SI engine operating with gasoline and its blends with n-pentanol at the highest engine loading condition.

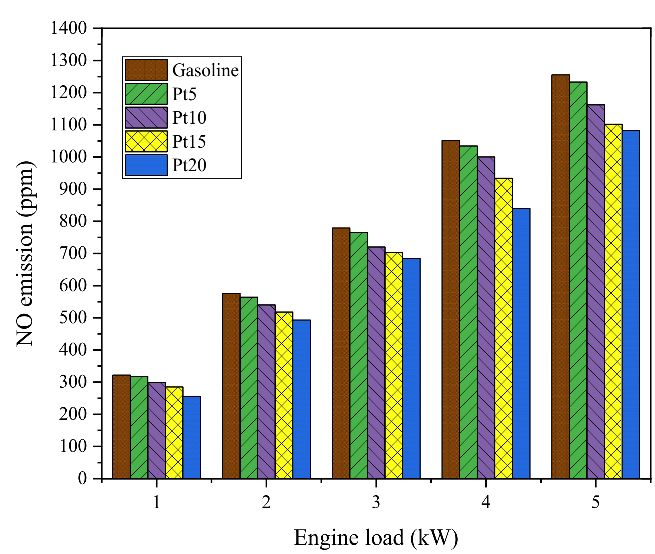


Fig. 8. The change in NO emission at different loads.

respectively. As observed, the maximum NO emission values were measured with gasoline at all engine loading conditions amongst the test fuels while the minimum figures were obtained with the Pt20 fuel blend.

This clearly shows that NO emission is influenced by the type of fuel. Masum et al. [11] discussed some parameters (dissimilar fuel composition, engine modification, and engine operating conditions) that affect the NO_X formation in the SI engines. n-pentanol has a higher LHV and lower adiabatic flame temperature than those of gasoline. This feature leads to a decrease in the in-cylinder temperature due to the cooling effect resulting in the withdrawing of the heat from the combustion chamber. In other words, the higher LHV of n-pentanol causes to mask the generation of NO emissions in spite of the presence of the excess amount of oxygen molecule in the fuel's molecular structure. In addition, the presence of oxygen and the large flame propagation speed of alcohol-based fuels lead to a reduction in NO emission. Furthermore, the increase in the fraction of the alcohol in the blend resulted in the reduction of NO emissions. By the way, the formation of NO emission in the tested engine is related to the combustion reaction phasing. NO emissions reduced with the increase of n-pentanol concentration in the mixture because of decreasing the peak in-cylinder temperature resulting from the retardation of the combustion. In other words, the later combustion phasing results in less NO emission. As stated in Table 5, the infusion of higher-order alcohol into the conventional gasoline diminished the EGT which is the indicator of the in-cylinder temperature due to the higher LHV resulting in a cooling effect in the cylinder. When the MFB characteristics of the tested fuel presented in Fig. 7 were evaluated together with the generation of NO emission, it can be obviously seen that the addition of alternative alcoholic fuel into the gasoline caused to decrease in the overall combustion duration. Especially, later combustion phasing of n-pentanol blended tested fuel have shorter combustion duration and hence lower amount of NO gas was formed during this phase. As a result, n-pentanol addition into the baseline gasoline leads to less formation of NO. Uslu and Celik [68] observed that the addition of pentanol isomer (isoamyl alcohol) into the gasoline at various percentages (10–30% by volume) led to decrease the NO_X emissions and the lowest NO_X emission measured to be as 780 ppm with the 30% isoamyl alcohol blend at a compression ratio of 8:1 with a speed of 2600 rpm. The researchers reported that isoamyl alcohol that has higher volumetric efficiency might compose of a more convenient condition for the combustion process in the SI engines, and hence the work in the piston turned in high as compared to gasoline along with the in-cylinder gas pressure. In addition, some of the fuel specifications of isoamyl alcohol such as higher LHV and lesser adiabatic flame temperature than those of gasoline led to diminishing in the peak temperature in the cylinder. Furthermore, a high flame propagation speed and the existence of oxygen of alcohol-based fuels bring about a reduction in the NO_X emissions [89]. Qian et al. [70] pointed out that the generation of NO_X could be basically controlled by local oxygen proportion as well as the temperature inside the cylinder. As opposed view, some studies indicated higher NO or NO_X emissions for alcohol/gasoline fuel blends in comparison with gasoline [60,90] meanwhile some of them reported fluctuating results [91,92]. Yacoub et al. [56], for instance, demonstrated the NO_X emissions of higher-order alcohols/gasoline blends compared with short-chain alcohol/gasoline blends and reference gasoline fuel. As a result, all fuel blends with same oxygen mass content of 5.0% presented advancing raise in the NO_X emissions from short- to higher-order alcohol mixtures when then engine operated with optimized conditions. The researchers explained the reason for this increments in the NO_X emissions that high flame temperature, low enthalpy of vaporization, and comparatively advanced timing at low compression ratio.

4.9. Carbon dioxide

The carbon dioxide (CO_2) pertains to the complete combustion process of the test fuel in the IC engines and further it is a product of the end-combustion of fuel which involve carbon in its chemical bond. It happens owing to the higher post-combustion temperature, as stated above. The availability of a satisfactory quantity of oxygen atoms in the combustion chamber to achieve a complete combustion also boosts the concentration of CO_2 emission. By reason of sufficient participation of oxygen molecule, the hydroxyl radical OH which is knowns as one of the main oxidizing determinant converts CO to the CO_2 [93]. The CO_2 emission is taken into consideration a considerable greenhouse gas, and for this reason, it has to be maintained at admissible grades all over the world. As known, CO_2 is formed inherently in the atmosphere and is a typical end-product of the combustion process. By all means, the ideal combustion of hydrocarbon fuels at the stoichiometric air–fuel ratio or lightly lean mixture situations generate only water and CO_2 [94]. Fig. 9 portrays the change in CO_2 emission for gasoline and other tested fuel blends at different loads. It can be inferred from the graph that the increasing inclination was appeared in CO_2 emission figures for all tested fuels. At the maximum engine load, the CO_2 emissions were measured to be as 16.10%, 15.85%, 15.76%,15.66%, and 15.48% for gasoline, Pt5, Pt10, Pt15, and Pt20, respectively. As is well known that the formation of the CO_2 emission among the exhaust gases is affected by the consumption of fuel as well as the carbon content of the tested fuel [95]. For this reason, maximum CO_2 emissions at all engine loads were formed with conventional gasoline while the minimum results were obtained with the utilization of the Pt20 fuel blend. When the SI engine powered by Pt20, there is approximately between 0.97% and 3.85% decrease in the CO_2 emissions. Moreover, the less amount of carbon content along with the lower amount of fuel consumption in the used higher order-alcohol leads to drop the CO_2 emissions in comparison with the gasoline [2]. In addition, CO_2 emission is clearly concerned about the efficiency of the engine combustion process [96]. Mohan et al. [97] stated that the lower CO_2 emissions, the higher efficiency of the combustion process in the engine. On the other hand, Feng et al. [96] monitored opposite characteristic, that was more CO_2 emission would release when the combustion process was more efficient. Geo et al. [2] observed that the addition of ethanol and benzyl alcohol into the

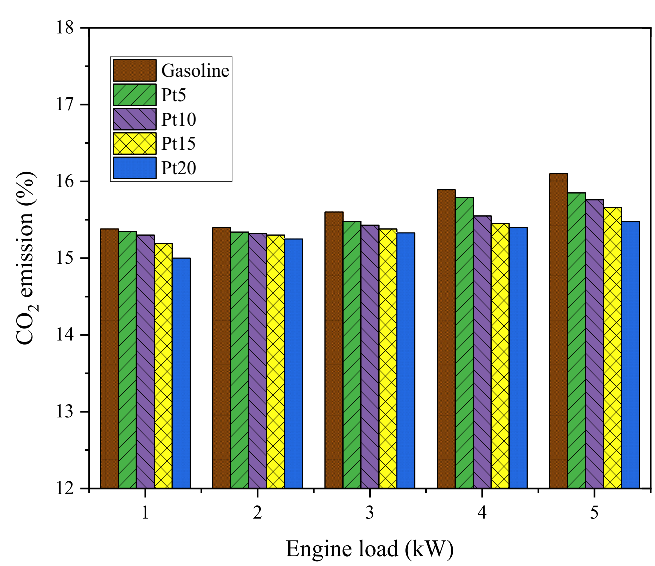


Fig. 9. The change in CO_2 emission at different loads.

gasoline at different ratios caused to decrease the CO_2 emissions at all engine loading conditions because of diminishing the carbon content along with the lesser fuel consumptions as compared to the gasoline. Gautam et al. [57] determined to be lower brake specific emissions of CO_2 and CO when the engine fueled with higher-order alcohol/gasoline blends by 16–23% than gasoline fuel. Elfasakhany et al. [98] mentioned that CO_2 emission generally depended upon the amount of CO and unburned HC emissions as well as air–fuel ratio. The researchers also pointed out that the alcohols have lesser energy content and higher LHV than those of gasoline and thus, the combustion products' temperature was observed to be lower, which was also validated by the EGT and in-cylinder gas pressure of dual alcohols, and that retarded the formation of the CO and HC conversion to the CO_2 emission or even slowed down the reaction. It could be concluded that the amount of the CO_2 decreased while CO and HC emissions increased.

4.10. Unburned hydrocarbon

The unburned hydrocarbon (HC) emissions are composed of the uncompleted combustion process inside the cylinder by the reason any motive [99]. The parameters such as the inhomogeneity behavior of the air–fuel mixture inside the combustion chamber, colder cylinder walls, becoming less end-of-compression temperature, enhanced surface/volume ratio in the combustion chamber, and inadequate oxygen concentration lead to occurring HC emissions [68]. The change in HC emissions for all of the tested fuel samples with respect to the progressive engine load from 1 kW to 5 kW was displayed in Fig. 10. When the graph was examined, the highest HC emissions for test fuels were measured at the lowest engine load. Namely, the highest HC emission for gasoline, Pt5, Pt10, Pt15, and Pt20 were measured to be as 220 ppm, 200 ppm, 191 ppm, 184 ppm, and 178 ppm, respectively while the lowest values at 5 kW load were 150 ppm, 145 ppm, 134 ppm, 128 ppm, and 121 ppm, respectively. This can be explained as the concentration of the input air/fuel mixture along with the premixing procedure for the tested fuel samples at the low-temperature condition. As observed, the n-pentanol/gasoline alternative fuels emitted fewer HC emissions at lower loads than that of reference gasoline fuel. This is due to the improved combustion reaction resulting from the excess amount of oxygen content in the alcohol and thereby, it oxidizes unburned HC emissions. It is to be noted that the oxygen proportion in the blends boosts the rates of the combustion resulting in a lesser amount of HC emissions in the exhaust gases than that of pure gasoline fuel. From this perspective, the fraction of the inlet air/fuel mixture at the highest engine loads declines the HC emissions and hence ascends the temperature of the combustion chamber at the maximum load. The dropping ratios for the HC emission of Pt5, Pt10, Pt15, and Pt20 at the maximum load was calculated to be as 3.33%, 10.67%, 14.67%, and 19.33%, respectively. It was clearly stated from the aforementioned results that the n-pentanol blends demonstrated favorable results owing to its better fuel characteristics, i.e. LHV and rate of the combustion in comparison with the gasoline test fuel [2]. According to Uslu and Celik [68], the HC emissions of an SI engine were decreased when the isoamyl concentration of blend was increased. Elfasakhany et al. [98] reported that the increasing of the blend ratios of the fuel samples, leaning condition, and excess air ratio caused to increase the HC and CO emissions but increase CO_2. Elfasakhany [62] declared that unburned HC emissions produced from the SI engine running on the *iso*-butanol/gasoline blends were measured to be lower than that of gasoline fuel at lower than or equal to 2900 rpm engine speed. Elfasakhany [100] examined, in one more work, the influence of n-butanol/bio-ethanol/gasoline and *iso*-butanol/bio-methanol/gasoline blends in and SI engine under various engine speeds. Based on the emissions measurements, all of the fuel blends presented lesser CO_2, HC, and CO emissions than those of pure gasoline fuel. Moreover, the highest HC and CO emissions of tested fuel blends were eventuated at a moderate engine speed (3000 rpm). Besides that, the maximum concentration of mixed fuel samples could ensure the least HC and CO emissions.

4.11. Oxygen

Fig. 11 illustrates the change in O_2 emission at different loads for the tested fuel specimens. As seen, the increasing engine load leads to descend of the O_2 emission for all test fuels because the combustion process has been enhanced at the higher engine load condition [101]. The maximum O_2 emission figures for gasoline, Pt5, Pt10, Pt15, and Pt20 were found to be at 0.66%, 0.72%, 0.76%, 0.82%, and 0.99%, respectively. It can be inferred that the infusion of alcohol into the gasoline caused to increase the oxygen emission. This due to the inherent oxygen concentration of the alcohol. Moreover, the increase in the alcohol blend ratio in the blend leads to increase the oxygen emission due to the above-mentioned reason. Unfortunately, there is a lack of research in the present literature concerning the O_2 emissions of alcohol/gasoline blends.

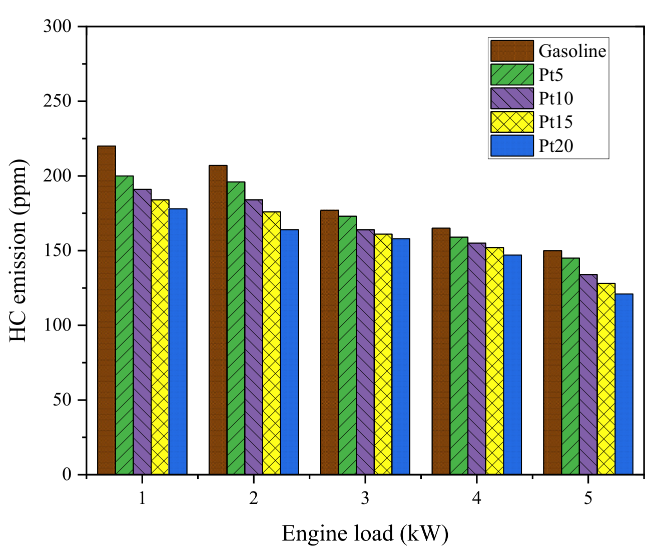


Fig. 10. The change in HC emission at different loads.

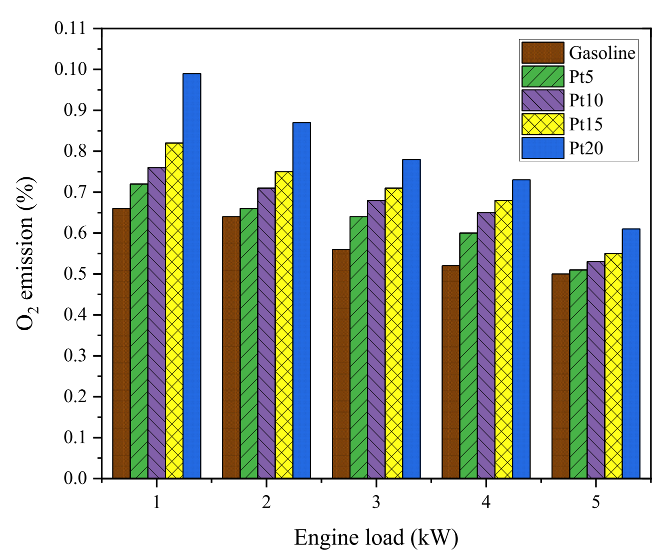


Fig. 11. The change in O_2 emission at different loads.

Some of them were summarized in order to confirm the present experimental study. Özçelik et al. [102], for instance, investigated the influences of different bioethanol/gasoline blends on the vehicle emission parameters. The researchers found that the addition of bioethanol into the gasoline caused to increase the O_2 emissions at all studied engine speeds due to the fact that the bioethanol contains oxygen in its chemical composition. Srinivasan and Saravanan [103] scrutinized the effects of ethanol and oxygenated additives (cycloheptanol and cyclooctanol) infusion into the gasoline fuel on the engine characteristics. As a result, the O_2 emission was observed to be higher than that of gasoline operation because of the increase in the percentages of oxygenated additives and ethanol in the blend. Srinivasan and Saravanan [104] also tested ethanol and unleaded gasoline fuel with isoheptanol blends in an SI engine. Similar to their first explained study, higher O_2 emissions were monitored when the engine was operated with the test fuel having ethanol and oxygenated additive.

4.12. Carbon monoxide

Carbon monoxide (CO) is a gas that possesses not odor and color. The density of the CO is slightly higher than that of atmospheric air and also it has exceptionally toxic characteristics for humans [105]. The CO emission is a consequence of meager oxygen concentration inside the cylinder where leads the generating of unburned HC emissions. The CO emission is also directly bounded up with the number of carbon atoms placed in the chemical structure of the fuel [84]. In other words, a fuel having a low C/H ratio generates lesser emissions since the carbon atom is major element for forming CO and smoke [68]. Fig. 12 shows the alteration of the CO emission for neat gasoline and the binary blends of n-pentanol/gasoline according to the engine loads. It can be noticed that the CO emission results has progressively descended when the engine was loaded for entire the test fuels. As alcohol-based alternative fuels have a fewer number of carbon atoms in their chemical composition, a diminishment in the generation of CO emissions was monitored with the infusion of n-pentanol into the neat gasoline fuel [68]. The minimum measurements were occurred at the highest engine load. The least CO emissions for gasoline, Pt5, Pt10, Pt15, and Pt20 were recorded to be as 0.416%, 0.347%, 0.331%, 0.296%, and 0.269%, respectively. As is well known, at the low loading conditions, the combustion temperature would be less. This can be also validated with observing the EGT results. To conclude, low combustion temperature leads to decrease the generation of CO emission. On the other hand, in the case of higher loading conditions, the fuel consumption was increased and low residence duration results in higher formation of CO emission [2]. The incomplete combustion process, local rich regions, and worse mixing situations are also reasons for CO emissions [74]. When the related graph was evaluated, it can be seen a remarkable reduction in CO emission figure of the binary blends of Pt5, Pt10, Pt15, and Pt20. In the literature, there is a limited number of studies regarding the pentanol or its isomers using as an engine fuel. For that reason, some higher-order alcohols/gasoline fuel blends results were explained for supporting this study. Uslu and Celik [68], for instance, observed the minimum CO emission by 0.74% in an SI engine with utilizing 30% isoamyl alcohol/70% gasoline blend at 3200 rpm and the compression ratio of 9:1 whereas the maximum CO emission was found to be at 1.35% with neat gasoline at a compression ratio of 8:1 and speed of 2600 rpm. Gu et al. [106] investigated n-butanol and its blends (10%, 30%, and 40%) with gasoline in an SI engine; the findings exhibited that the usage of pure alcohol caused to increase HC and CO emissions while reduced the NO_X emissions; but, the NO_X, CO, and HC emissions of n-butanol blend fuel were obtained to be lower than those of neat gasoline. Gravalos et al. [60] presented a comparative observations of CO_2, HC, CO, and NO harmful pollutants between lower molecular mass alcohol/gasoline and higher-lower molecular mass alcohol gasoline blends and the results showed that the treatment of lower molecular mass alcohol/gasoline with higher molecular mass alcohols caused to decrease CO emissions. Yacaoub et al. [56] mentioned that higher-order alcohols (such as propanol, butanol, and pentanol) blends with gasoline led to a considerable decrement in the CO emissions as compared to the lower-order alcohols (such as methanol and ethanol) blends with gasoline as well as pure gasoline. Godwin et al. [74] explained that the alcohol/gasoline fuel blends had sufficient duration for appropriate mixing process when the load was low on account of acquiring more complete combustion process; however, when the engine load was increased, diminishing the duration existing for mixing and deficient combustion happened resulting in increasing concentration of CO emission. The researchers concluded that the benzyl alcohol/gasoline blend produced the least CO emission by 0.62% since it had the highest oxygen content and thereupon the reduction occurred in the CO emission emitted from the exhaust. Masum et al [75] indicated that when the engine powered by alcohol/gasoline blends, the level of the CO emissions was decreased with respect to the neat gasoline fuel at high engine speed because the engine had a limited duration so as to finalize the combustion process; therefore, a higher flame speed specification of alcohol helped completing the combustion.

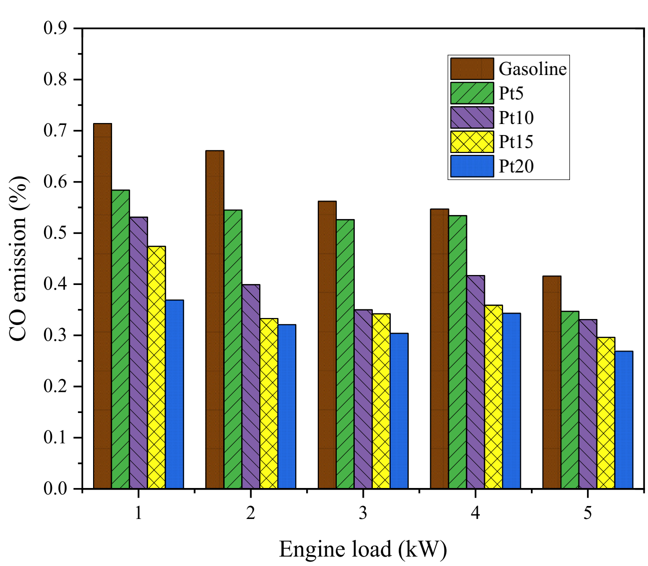


Fig. 12. The change in CO emission at different loads.

5. Conclusions

This experimental study principally deals with the influence of the infusion of higher-order alcohol to neat gasoline test fuel up to 20% by volume in a single-cylinder, four-stroke, research engine. In other words, n-pentanol were mixed in 5%, 10%, 15%, and 20% by volume with gasoline in order to recognize the effect on the performance, combustion, and emission characteristics. From the study, the following substantial conclusions were drawn:

1. All of the tested fuel samples having n-pentanol exhibited favorable engine performance behaviors across the pure gasoline test fuel.
2. At the highest loading condition, BTE for Pt20 was obtained to be the maximum followed by Pt15, Pt10, Pt5, and UG test fuel. In addition, the BTE of Pt20 was measured to be higher by 10.95% than that of gasoline under 100% load.

3. The EGT figures for the higher-order alcohol/gasoline blends were measured to be lesser than that of neat gasoline. This is on account of the early start of combustion along with the less duration in the combustion stage.
4. The emission measurements for gasoline and other test fuel samples showed that the higher-order alcohol infusion to the gasoline led to diminish the most of the exhaust emissions in contrast to the neat gasoline. It could be noted that the presence of the inherent oxygen molecules in the molecular structure of the n-pentanol enabled less amount of emission ratios than that of gasoline.
5. The formation of NO emission were also recorded to be low for n-pentanol treated gasoline by reason of the high LHV of n-pentanol leading the reduction in NO emissions. Pt20 blend exhibited the least NO emissions amongst the other test fuels at all engine load conditions.
6. When the combustion characteristics were examined, the in-cylinder pressure and apparent HRR values for higher-order alcohol/gasoline mixtures were appeared to be superior as compared to neat gasoline.

In conclusion, the obtained results through the experimental research presented that n-pentanol infusion to gasoline fuel up to 20% by volume out of any modification on the tested engine has improved the combustion, performance, and exhaust emission features. On top of that, experimental outcomes expressly demonstrated that n-pentanol could be an effective, powerful, and promising oxygenated additive on account of having many considerable advantageous for use in SI engines as mentioned above. On the other hand, the high production cost and the selling price of the n-pentanol, which can be produced from renewable feedstocks, is the prominent issue under today's conditions and for that reason, this subject should be figured out by researchers in order to use this alcohol in the IC engines and its price should be decreased below the cost of gasoline. In this way, countries will achieve an alternative fuel additive instead of pure gasoline and can economically drop their foreign dependence. In further studies, the isomers of the pentanol and other long-chain alcohols (hexanol, heptanol, octanol, decanol, etc.) can be tested in gasoline engines as fuel additives. Notably, binary blends of n-pentanol and baseline gasoline fuel can be assessed with the object of declining harmful pollutants. However, these test fuel samples have to be investigated in further studies at multifarious engine working conditions as well as long-term experiments with the aim of indicating their impacts on the engine performance environmental pollutions, and combustion characteristics. In addition, similar experiments can be performed in dissimilar test engines and vehicles with the purpose of generalizing the findings. Moreover, the engine working situations such as engine speed, compression ratio, injection timing, injection pressure, etc. can be optimized by implementing different optimization techniques like RSM, Taguchi, and ANN. As a result, the outcomes were compared with gasoline, and hence, the most suitable operating conditions are determined for the aforementioned alternative fuel blends. Besides that, an SI engine running on the prepared tested fuel specimens should be experimented in the points of the energy, exergy, exergoeconomic, enviroeconomic, sustainability, exergoenviroeconomic, etc. so as to acquire complete analyses.

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CRediT authorship contribution statement

Hayri Yaman: Project administration, Funding acquisition, Methodology, Writing - review & editing. **Murat Kadir Yesilyurt:** Conceptualization, Investigation, Methodology, Validation, Visualization, Writing - original draft, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jestch.2021.03.009.

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