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The Influence of High-Octane Fuel Blends on the Performance of a
Two-Stroke SI Engine with Knock-Limited-Compression Ratio

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ABSTRACT

The use of alcohol-gasoline blends enables the favorable features of alcohols to be utilized in spark ignition (SI) engines while avoiding the shortcomings of their application as straight fuels. Eucalyptus and orange oils possess high octane values and are also good potential alternative fuels for SI engines. The high octane value of these fuels can enhance the octane value of the fuel when it is blended with low-octane gasoline. In the present work, 20 percent by volume of orange oil, eucalyptus oil, methanol and ethanol were blended separately with gasoline, and the performance, combustion and exhaust emission characteristics were evaluated at two different compression ratios. The phase separation problems arising from the alcohol-gasoline blends were minimized by adding eucalyptus oil as a co-solvent. Test results indicate that the compression ratio can be raised from 7.4 to 9 without any detrimental effect, due to the higher octane rating of the fuel blends. Knock-limited maximum brake output also increases due to extension of the knock limit. The knock limit is extended by methanol-eucalyptus-ethanol-orange oil blends, in descending order.

Lean combustion in spark ignition engines has long been recognized as a means of both improving engine thermal efficiency and lowering exhaust emissions. Unfortunately, the conventional two-stroke SI engines as such cannot be used to operate on lean mixtures. Use of homogeneous charges of gasoline and air near the lean combustion limit in SI engines results in erratic combustion, poor driveability and a rapid increase in hydrocarbon emissions [1]. The presence of a large percentage of exhaust residuals in the combustion chamber leads to additional problems burning lean mixtures in two-stroke SI engines. Several approaches have been made to achieve lean combustion [2,3]. One method of meeting the requirements of lean combustion is increased compression ratio. The effect of increasing

compression ratio with lean mixtures permits a more effective utilization of available energy due to higher flame propagation speeds and higher expansion rates [4]. The increase in compression ratio is often limited by the extent of lean mixture operation, frictional and heat transfer losses and octane quality of the fuel. However, the problems associated with high compression ratios can be reduced to a certain extent with the help of high-octane fuels.

The commercially available gasoline fuel cannot, as such, be used to operate on lean mixtures and at high compression ratios in two-stroke engines, due to its low octane quality. In this regard, high-octane fuels such as methanol and ethanol fuels have been considered in several studies to operate at higher compression ratios [5,6,7]. However, many technical difficulties associated with the use of methanol and ethanol for commercial application in vehicles are yet to be overcome. Until then, the use of gasoline-methanol/ethanol blends is one alternative available for immediate use. Such blends have improved octane quality, lean limits, knock-limited compression ratio, thermal efficiency, power output and NO_x emissions. It was reported that an addition of 15 percent methanol to most motor gasolines would increase the research octane number (RON) significantly, with marginal gain in motor octane number (MON) [8,9]. With 15% methanol addition, typical gasoline having a RON of 93 and MON of 84 changed to RON and MON values of 97 and 85, respectively. The studies of Ingamells and Lindquist [10] and Menrad [11] suggest that the blend concentration having 15% methanol is the upper limit due to phase-separation difficulties. At higher concentrations of methanol/ethanol in gasoline blend, the major problems of concern are phase separation, vapor lock, driveability, cold starting and increased emissions of unburned methanol/ethanol and formaldehyde [12,13]. The occurrence of phase separation in a vehicular fuel system is intolerable because the alcohol-rich phase has a different calorific value and stoichiometric mixture requirement than the gasoline fuel.

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Besides methanol and ethanol, there are reports [14,15] suggesting that eucalyptus oil and orange oil possess high octane values and are also good potential alternative fuels for spark ignition engines. Their physical and chemical properties are similar to those of gasoline. They are easily miscible with gasoline. The high octane values of eucalyptus and orange oils increase the octane value of the blend when added to the low-octane gasoline. Also, eucalyptus oil is an effective co-solvent which protects the alcohol-gasoline blended fuel from phase-separation problems and is an attractive proposition in the current state of high-octane blend technology to resolve the phase separation difficulties arising with alcohol blends. The objective of the present work is to investigate the influence of these high-octane fuels with regard to engine performance, combustion, knock and exhaust emission characteristics viz., orange oil, eucalyptus oil, methanol and ethanol when blended with gasoline in a two-stroke SI engine at two different compression ratios. The proportion of orange oil, eucalyptus oil, methanol and ethanol fuels to be blended with gasoline is selected to allow the use of the maximum amount of these high-octane fuels compatible with unmodified engine requirements. It is believed that higher amounts of blended fuels would deteriorate the vaporization characteristics and demand major modifications on the engine, whereas too low amounts would provide small impact and marginal improvements in the knock-limited compression ratio compared to normal gasoline. In the present investigation, these high-octane fuels were blended with gasoline in the proportion of 20% by volume.

PROPERTIES OF HIGH OCTANE FUELS

In this study, four fuel blends are considered for testing, where the base fuel is commercial gasoline. The blend components are orange oil, eucalyptus oil, methanol and ethanol fuels. The combined proportions (by volume) of all the four fuel blends tested are as follows:

1. 20% Orange oil + 80% Gasoline + 3.5% SAE30
2. 20% Eucalyptus oil + 80% Gasoline + 3.5% SAE30
3. 20% Methanol + 75% Gasoline + 5% Eucalyptus oil + 2.8% SAE30 + 0.7% Castor oil
4. 20% Ethanol + 20% Eucalyptus oil + 60% Gasoline + 2.8% SAE30 + 0.7% Castor oil.

The properties of fuel components and blend fuels are summarized in Table 1. Castor oil was used as a lubricant in the case of methanol/ethanol blends, and standard SAE 30 oil was employed in the case of eucalyptus oil and orange oil blends. The eucalyptus oil was added with gasoline-methanol/ethanol blends to overcome the phase separation problems. The details of the phase separation of the alcohol fuel blends are discussed in the following section.

The distillation characteristics of the above four fuel blends were evaluated based on the ASTM D86 [16] method and are shown in Fig. 1. It can be seen from this figure that the distillation characteristics of 20% orange oil blend and eucalyptus oil blend fuels indicate them to be nearly equal to that of test gasoline. Hence, addition of orange oil and eucalyptus oil up to 20% in gasoline is expected to give good startability and acceleration,

Table 1. Properties of High-Octane Fuels and their Blends with Test Gasoline

Properties	Gasoline	Methanol	Ethanol	Orange Oil	Eucalyptus Oil	80G+20Or	80G+20Eu	75G+20M+ 5Eu	60G+20E + 20Eu
Chemical Formula	-	CH ₃ OH	C ₂ H ₅ OH	C ₁₀ H ₁₆	C ₁₀ H ₁₈ O	-	-	-	-
Specific Gravity (kg/m ³) @28°C	708	795	790	840	897	735	746	734	762
Lower C.V. (kJ/kg)	43115	19674	26790	45267	39264	43610	41289	37808	38825
Heat of Vaporization (kJ/kg)	330	1104	842	-	-	-	-	-	-
Stoichiometric Air- Fuel Ratio	15.0	6.46	9.0	14.21	12.55	14.58	14.18	12.77	13.01
Viscosity (Centi- poise) @28°C	0.42	0.6	1.2	0.95	2.05	-	-	-	-
Boiling Point (°C)	30-225	65	78	150	167	44.5	41	42	41
Octane number									
RON	94	109.6	100.0	106.0	100.2	-	-	-	-
MON	80	87.4	89.0	-	-	-	-	-	-

Fig.1 Distillation characteristics with different fuel blends

without any vapor lock problem. Methanol blend fuel has relatively lower distillation temperatures compared to test gasoline. The vapor pressure of the methanol blended fuel is also expected to be higher. These characteristics might cause some vapor lock problems in the fuel line system. Ethanol-gasoline blends distillation characteristics also usually exhibit similar to the methanol-gasoline blends. However, the presence of eucalyptus oil in the ethanol-eucalyptus-gasoline blend fuel makes the distillation characteristics similar to the test gasoline fuel and hence will not cause any vapor lock problem. The theoretical air-fuel ratio requirements of the four fuel blends were computed on a volume basis assuming that the blended fuels are mixed physically without any chemical reaction at the room temperature (28-35°C). The computed stoichiometric air-fuel ratios for the four fuel blends are given in Table 1. The lower calorific values of the fuel blends are also different from its fuel components, as expected, and are listed in Table 1. The theoretical air requirement and lower calorific value of the fuel blends is in the following descending order: orange oil blend-eucalyptus oil blend-ethanol blend-methanol blend. The specific gravity of all the four fuel blends (Table 1) indicates them to be denser than the test gasoline fuel by about 3.6 to 7.6 percent. This might pose fuel vaporization problems, in particular during starting and part-load operating conditions.

The properties of the fuel components in the blends are briefly discussed below:

ORANGE OIL - Orange oil can be extracted from the peel of orange fruits. The main ingredient of orange oil is d-limonene ($C_{10}H_{16}$). The specific gravity is 20% denser than gasoline. The lower calorific value is about 5% higher than the value for gasoline. The cold starting would be difficult if orange oil is used as a sole fuel in the engine due to its high initial distillation temperature (Table 1). It has been reported that orange oil has a higher flame propagation velocity than gasoline [15]. To evaluate the theoretical air-fuel ratio requirement for orange oil, the

standard SAEJ1829 recommended practice [17] for hydrocarbon fuels was employed, based on the principal constituent fuel molecule. Hence, the following relationship is applicable for orange oil:

$$(A/F)_s = \frac{4.321 * 15.99[2 + (0.5)(H/C)]}{[(12.001 * 1) + (1.0079)(H/C)]} \quad (1)$$

The cost of the orange oil is nearly two times higher than for commercial gasoline. The present production of orange oil is very limited to meet the needs of the food (flavors) and soft drink industries and hence the high cost. However, the price of orange oil can be brought down to a level comparable with gasoline in the future by increasing the cultivation of orange plantations. India has a very good potential with a strong agricultural base to develop these fields if they are found to be suitable as an alternative fuel/additive for gasoline engines.

EUCALYPTUS OIL - Eucalyptus oil is steam-extracted from eucalyptus leaves. The main ingredient is 1.8 cineol ($C_{10}H_{18}O$). The leaves of eucalyptus consist of 6.6-8.7% liquid and semi-solid types of hydrocarbons. The specific gravity is about 30% denser than gasoline. The lower calorific value is about 5 to 10% less than the value for gasoline. It has been reported in the literature that the flame propagation velocity of eucalyptus oil is higher than that of gasoline [14]. Further, the flame propagation velocity increases with an increasing ratio of eucalyptus oil under stoichiometric mixture operating conditions. To evaluate the theoretical air-fuel ratio requirement for eucalyptus oil, the standard SAEJ1829 recommended practice [17] for oxygenated fuels was employed, based on the principal constituent fuel molecule. Hence, the following relationship is applicable for eucalyptus oil:

$$(A/F)_s = \frac{4.321 * 15.999[2 + (0.5)(H/C) - (O/C)]}{[(12.001 * 1) + (1.0079)(H/C) + (15.999)(O/C)]} \quad (2)$$

At present the cost of eucalyptus oil is about one and a half times higher than for commercial gasoline. This is partly because the current production of eucalyptus oil is very limited to meet the needs of the pharmaceutical industries. In India, eucalyptus trees are grown extensively due to their potential use in paper and construction industries; it is quite possible in the future that the cost of eucalyptus oil will be comparable to commercial gasoline fuel.

The orange oil and eucalyptus oil employed in the present investigations were obtained from the distillation process. These fuels are clear from any foreign particles. In the present study no attempt has been made to chemically analyze these fuels for possible extraneous materials. A detailed chemical analysis of orange oil and eucalyptus oil is reported elsewhere [14,15].

METHANOL - For its relatively good lean combustion characteristics, methanol has been found to be a more suitable fuel compared to gasoline and other hydrocarbon fuels. There has been sufficient evidence

[18-21] to show that methanol has wider flammability limits and higher flame speeds under lean conditions than gasoline. Methanol can be produced from natural gas, coal, municipal solid wastes, waste biomass and specially grown biomass. Methanol's most desirable feature is its high octane quality. Methanol rates 106-115 octane number by the research method and 88-92 octane number by the motor octane method [22]. Because of these characteristics, methanol is considered to be one of the most likely alternative automotive fuels for SI engines in the foreseeable future [23]. Methanol has a heat of combustion half that of gasoline, but its latent heat of evaporation is nearly four times that of gasoline. Using pure methanol as a sole fuel requires major modifications to the vehicles due to its shortcomings, such as low volumetric density, high aldehyde emissions, cold starting, corrosion and chemical degradation of materials. But adding up to 20% methanol to gasoline would not require any major modifications on the engine. It also enables all the positive properties of methanol to be utilized while avoiding the shortcomings of its application as a straight fuel. Methanol as sole fuel will not cause any vapor lock, but low concentrations of methanol in gasoline-methanol blend have drastic effects on front-end gasoline volatility. The vapor pressure of the blend is higher than either component. Another problem with the use of methanol in motor gasoline is associated with its tendency to undergo phase separation in the presence of very small concentrations of water. 15% methanol by volume should result in no solubility problems if anhydrous conditions are maintained. However, for typical gasolines phase separation occurs in the presence of less than 1% water.

ETHANOL - Ethanol can be produced from any feed stock containing carbohydrates by using well-developed, commercial processes. Suitable feed stocks include corn, wheat, sorghum, sugar beet, sugar cane, potatoes and other grains [24]. Ethanol can either be blended with gasoline or used alone. Pure ethanol is being used as a SI engine fuel in Brazil and is being considered for use in the U.S and elsewhere. However, vehicle modifications are required for pure ethanol fueling because its properties are different from those of gasoline (Table 1). Ethanol has a much lower calorific value than gasoline. Ethanol's low stoichiometric air-fuel ratio and high heat of vaporization require carburetor recalibration and increased heating of the air-fuel mixture to provide satisfactory driveability. The major disadvantages of ethanol fuel are the decrease in power output and the increase in specific fuel consumption. These disadvantages can be offset by using higher compression ratios made possible by ethanol's higher octane rating. Blends of ethanol in gasoline are commonly used in vehicles designed to operate on gasoline. Vehicle studies [12] with ethanol-gasoline blends showed that addition of ethanol to gasoline without carburetor modifications results in lower CO emissions, volume-based fuel economy, driveability and performance. Because of the sensitivity to phase separation at low water concentrations, special fuel handling techniques would have to be used with ethanol-gasoline mixtures.

CONTROL OF PHASE SEPARATION WITH ALCOHOL-GASOLINE BLENDS

In an effort to introduce alcohol fuels for SI engines, the use of alcohol-gasoline blends is often considered as a very effective and useful way. However, with such blends, the problem of phase-separation is most important. The solubility of alcohols in gasoline is limited when water is present even in minute quantities at room temperature. When small amounts of water are added to blends of alcohols with gasoline, hydrogen bonds form between the water and alcohol molecules and blends separate into two phases. Paraffinic hydrocarbons are predominant in the upper phase, while the lower phase consists primarily of alcohols and water. Additionally, alcohol-gasoline blends are hygroscopic. Water tolerance also significantly decreases at lower temperatures. The occurrence of phase separation in a vehicular fuel system leads to poor driveability and acceleration due to differences in the mixture's stoichiometric requirements. The water sensitivity of alcohol-gasoline blends requires a separate fuel distribution system. Nevertheless, a number of methods are available to increase the water tolerance limit of alcohol-gasoline blends. The most promising ways are:

- (1) Use of additives such as higher alcohols, particularly the branched alcohols like isopropanol and tertiary butyl alcohol [25].
- (2) In-fuel-line mechanical emulsification devices (such as hydro shear) to emulsify both phases [26].

Unfortunately, both the above methods are expensive, and the complexity of the fuel system is an added disadvantage in the case of the mechanical emulsifier.

In the present investigation, eucalyptus oil has been considered as an additive to lower the phase separation problems associated with the alcohol-gasoline blends. Eucalyptus oil is a co-solvent which prevents the alcohol-gasoline blended fuel from phase separation. One of the reasons is the fact that as the eucalyptus oil is quite similar to naphthionic base in its chemical structure, it plays the role as the third material which can easily combine both the alcohol and gasoline. Fig. 2 shows the iso-water tolerance line of ethanol-gasoline-eucalyptus oil at 0°C temperature [14]. Only 0.1% of water content in 8% of ethanol blended in gasoline causes phase separation, but even 5.0% water content in eucalyptus oil blended fuel (Ethanol 33% + Eucalyptus oil 33% + gasoline 34%) did not cause phase separation. It was found from the present study that for blends of 20% methanol and 20% ethanol with gasoline, the percent volume of eucalyptus oil required to prevent the phase separation is about 5% and 20% by volume, respectively, at room temperature (28°C). The resultant blend of ethanol/methanol-eucalyptus oil-gasoline is stable and clear and did not cause any problem in the fuel line system.

Fig.2 Iso-water tolerance lines of ethanol-gasoline eucalyptus oil blends

EXPERIMENTAL PROGRAM

A small capacity (145.45 cc displacement volume, 4.2 kW at 5200 rpm), loop scavenged, air-cooled, single-cylinder, carbureted two-stroke spark ignition engine with a compression ratio of 7.4 was employed for the present investigations. This engine was coupled to an eddy current dynamometer (Vibrometer) for torque and speed measurements. Calibrated standard instrumentation was used to measure fuel and air flow rates. An infra-red gas analyzer (HORIBA, Mexa 324 FB type) was used for measuring hydrocarbons (HC) (n-hexane equivalent) and carbon monoxide (CO) emission levels in the engine exhaust. The cylinder pressure measured by a piezo-electric pressure transducer (Kistler) was fed to a digital data acquisition system (Iwatsu) for subsequent analysis of various combustion parameters. To obtain the high compression ratio of 9:1, the clearance volume was adjusted by machining the cylinder head seating surface. Carburetor fuel jet sizes were suitably altered for the blends to account for the differences in theoretical air-fuel requirements. For orange oil and eucalyptus oil, the standard fuel jet size of 0.84 mm was employed, whereas for methanol and ethanol blends a jet size of 0.98 mm was used. Fuel blends were prepared with their respective proportions and constituents by volume using volumetric flasks. The mixed fuel blend was agitated vigorously for one minute with slightly compressed air to make the blend stable and uniform. Variable load tests were conducted at a constant engine speed of 3000 rpm. MBT (minimum spark advance for the best torque) spark time was maintained throughout the experimentation. At each operating point, about 10-15 values of speed and torque were continuously recorded and averaging was done to minimize the effects of variations. Similarly, fuel and air consumption rates were recorded on an average basis. After calculating the performance parameters, a polynomial curve fitting (least square) method was employed to draw the mean curves. The deviation of points from the mean curve based on the above method was kept minimum, and the maximum deviation was less than 2 percent.

For convenience, the following abbreviations are used in referring to various fuels: M-Methanol, E-Ethanol, G-Gasoline, Or-Orange oil and Eu-Eucalyptus oil.

RESULTS AND DISCUSSION

The effect of fuel blends on the engine brake thermal efficiency, HC and CO emission levels, cylinder peak pressure, ignition delay and combustion duration characteristics at the normal compression ratio of 7.4 are discussed below based on the present test results.

Figure 3 shows the variation of brake thermal efficiency with brake power for various fuel blends, viz., orange oil blend, eucalyptus oil blend, methanol and ethanol blends with test gasoline at constant engine speed of 3000 rpm. It is observed that eucalyptus oil blend and methanol blend gave an improvement in the brake thermal efficiency over test gasoline fuel. Also, ethanol blend performance is nearly equivalent to that of test gasoline fuel, whereas orange oil blend shows an inferior performance, in particular at higher loads, compared to the test gasoline fueled engine. The maximum improvement in absolute brake thermal efficiency obtained with eucalyptus oil blend increases from 17.7% to 21.4% and with methanol fuel blend, from 17.7% to 19.2% at 2 kW power output compared to test gasoline fuel. With ethanol fuel blend, the improvement in brake thermal efficiency is very marginal. The percentage drop in brake thermal efficiency for orange oil blend is about 6.9% at 3 kW power output.

The effects of fuel blends on brake thermal efficiency could be explained by their energy content on a volume basis and the stoichiometry of the blends. In addition to that, the flame propagation velocities and ignition limits play a key role in bringing about changes in the performance of each fuel blend. Among the four

Fig.3 Variation of brake thermal efficiency with brake power for different fuel blends

different fuel blends tested, eucalyptus oil blend and methanol blend gave maximum improvement in the brake thermal efficiency. This is possibly due to their higher flame propagation velocities, lower air requirement (lean operation) for a given fuel for complete combustion and high energy density (on a volume basis) compared to test gasoline and other fuel blends tested. Methanol fuel's superior characteristics, such as high flame velocities and lean mixture acceptance, are well-known. The methanol-gasoline blend gave better performance due to the intrinsic properties of the methanol in the blend. Similar results of improved performance with methanol-gasoline blends are widely reported in a number of studies [8,13,27,28]. It has been shown [28,29] that the higher the methanol content in the blend, the higher the engine efficiency. Among possible reasons for the increased efficiency is that combustion losses are lower for higher methanol content in the blend. It is also observed that both methanol blend and eucalyptus oil blend operate with relatively lean mixtures. As a result, peak combustion temperatures are lower than for a stoichiometric mixture and there is an increase of thermal efficiency due to reduced cooling losses, lower combustion losses, greater specific heat ratio of leaner charge and reduced dissociation losses. It can also be seen from Fig. 3 that the improvement in brake thermal efficiency is significant at higher brake outputs than at part loads with the eucalyptus oil blend and methanol blend. It is known that at higher engine brake outputs, the combustion chamber surface is relatively hot, and this might assist in better vaporization of the fuel at these conditions, and hence an improvement in the brake thermal efficiency. During part load operation, the improvements are less significant, presumably due to relatively poor vaporization characteristics at these conditions. This is also reflected in the distillation characteristics, with higher distillation temperatures for eucalyptus oil blend compared to gasoline fuel, as depicted in Fig. 1.

Orange oil blend has a relatively higher heating value than gasoline and lower specific gravity than eucalyptus oil blend, but its performance is inferior compared to gasoline fuel. The reason for this conflicting trend is unclear. In the absence of in-cylinder measurements to evaluate the flame propagation velocity, it is difficult to point out its possible influence on the engine performance. Hence, further in-depth combustion studies are necessary to identify and to support the actual mechanism involved in the performance differences with these fuel blends. Ethanol-eucalyptus-gasoline blend shows only a marginal improvement in brake thermal efficiency because of the variation in mixture strength and energy content of the blend compared to test gasoline fuel. From the above test results of different fuel blends, the improvement in brake thermal efficiency is in the following descending order: eucalyptus oil blend - methanol blend - ethanol blend - orange oil blend.

Exhaust emissions of hydrocarbons and carbon monoxide are shown in Figs. 4 and 5, respectively, for the four different fuel blends at a constant engine speed of 3000 rpm. A conventional two-stroke SI engine emits a

Fig.4 Variation of hydrocarbon emissions with brake power for different fuel blends

Fig.5 Variation of carbon monoxide emission with brake power for different fuel blends

large amount of hydrocarbons in the engine exhaust compared to its four-stroke counterpart. A major contribution of exhaust hydrocarbons is due to short-circuiting during the scavenging period of the engine cycle [30]. A considerable amount of HC emissions also arise due to incomplete combustion, combustion of fuel lubricant blend, trapping of unburned charge in the crevices and flame quenching. To achieve smoothness in engine operation and to compensate for the fresh charge loss, rich fuel-air mixtures are normally utilized in two-stroke SI engines. This, however, results in higher CO emission levels. The unburned HC emission and CO emission levels can be lowered to a certain extent by complete combustion of charge in the cylinder and lean mixture operation with the help of high octane fuel blends. From the test results it is observed that HC emissions are

generally lower with all the fuel blends compared to the test gasoline-fueled engine, as illustrated in Fig. 4. Among the four different fuel blends, eucalyptus oil shows the maximum reduction in HC emissions over the entire range of engine operation, in particular at higher throttle openings. At wide open throttle (WOT) conditions, corresponding to 3.1 kW power output, HC emissions decrease from 7800 ppm to 3400 ppm for eucalyptus oil blend. Similarly, the reduction in HC emissions is about 4000 ppm for ethanol blend, 3700 ppm for orange oil blend and 3100 ppm for methanol blend at WOT conditions.

The CO emissions are generally lower with all the four different blends compared to test gasoline fuel. The eucalyptus oil blend shows a considerable reduction in CO emissions over the entire range of engine operation at this constant engine speed of 3000 rpm, as shown in Fig. 5. The maximum reduction in CO emissions obtained with eucalyptus oil blend is about 3.1% vol. at 2 Kw brake output. Orange oil blend also exhibits lower CO emission levels at all operating conditions than test gasoline fuel, but these reductions are less considerable than those obtained with eucalyptus oil blend. Both methanol and ethanol fuel blends show a reduction in CO emissions at part load to medium load range but at higher throttle openings slightly higher CO emission levels were recorded. Fig. 6 shows the variation of equivalence ratio (fuel-air ratio) with brake power, which indicates relatively lean mixture operation with eucalyptus oil blend and methanol blend compared to test gasoline fuel. These significant reductions in hydrocarbon and carbon monoxide emissions obtained with these high-octane fuel blends are attributed to the mixture equivalence ratio effects and possibly to complete combustion of the mixtures under these operating conditions, in particular with eucalyptus oil blend. The increase in CO emissions with methanol and ethanol blends at higher outputs can be verified from the mixture strength. From Fig. 6, it can be corroborated that slightly rich mixture operation of methanol and ethanol fuel blends at higher outputs causes relatively higher CO emission levels compared to gasoline.

Fig.6 Variation of equivalence ratio with brake power

The major combustion parameters such as cylinder peak pressure, ignition delay and combustion duration are plotted against brake power in Fig. 7 for the four different fuel blends at 3000 rpm. The results are compared with test gasoline fueled engine. It can be observed from this figure that both eucalyptus oil blend and orange oil blend gave higher cylinder peak pressures, whereas, with methanol blend and ethanol blend the peak cylinder pressures are nearly equivalent to that of test gasoline fuel. The increase in maximum cylinder pressure is highest for orange oil blend, about 4.5 bar, followed by eucalyptus oil blend, 3.8 bar, at 3 Kw power output. The increase in peak cylinder pressure can also be seen from the actual pressure-time traces obtained at WOT conditions, as illustrated in Fig. 8 for all four fuel blends. As expected, the higher flame propagation speeds associated with orange oil blend and eucalyptus oil blend help to burn the mixture more completely and hence yield higher peak cylinder pressures. Note that the orange oil blend presents a positive picture, indicating higher maximum cylinder pressures, but its influence on brake thermal efficiency is relatively poor. A detailed heat release analysis might help to resolve these issues.

Figure 7 shows that the ignition delays are generally higher by about 2 to 4°CA in the entire range of engine operation for all the fuel blends compared to test gasoline fuel operation. The relatively poor volatility characteristics (as depicted in Fig. 1) and high specific gravity of the fuel blends would possibly make the physical delay of the mixtures longer than their chemical delay, leading to an overall increase in ignition delay for all the fuel blends compared to test gasoline fuel. The high latent heat of evaporation of the methanol/ethanol-gasoline blends in comparison with gasoline result in a longer period of evaporation and ignition of the mixtures. Hence, the ignition delay characteristics of methanol and ethanol blends are no better than gasoline fuel. The combustion duration is relatively shorter than the test gasoline fuel for all the fuel blends due to higher flame speeds.

The influence of high-octane fuel blends on the engine brake thermal efficiency, knock-limited brake power, exhaust emissions and combustion characteristics at the higher compression ratio of 9:1 are discussed below based on the test results.

The performance obtained at a high compression ratio of 9:1, for the four different fuel blends and test gasoline fuel, is presented in Fig. 9 at a constant engine speed of 3000 rpm. It is observed that with all the fuel blends there is an improvement in the brake thermal efficiency, more significantly with eucalyptus oil blend and methanol blend. The maximum percentage improvement in brake thermal efficiency is about 20.5% (at 2 Kw) with eucalyptus oil blend, 20.0% (at 2.5 Kw) with methanol blend, 6.0% (at 2.0 Kw) for orange oil blend and 5.0% (at 2.0 Kw) with ethanol blend over test gasoline fuel. Higher brake thermal efficiencies were obtained with eucalyptus oil blend and methanol blend as a result of faster combustion of the mixtures due to their higher flame propagation velocities in comparison with gasoline-air

Fig.7 Variation of combustion parameters with brake power for different fuel blends

Fig. 8 Pressure-time traces for different fuel blends at normal compression ratio

Fig.9 Variation of brake thermal efficiency with brake power for different fuel blends

mixtures, which in turn results in closer proximity of the thermodynamic cycle to the Otto cycle. As a result of faster combustion, combustion losses are also lower; that is, combustion is more complete and more perfect. The improvement in brake thermal efficiency with all four fuel blends is considerable at higher compression ratio. This can be explained on the basis of improved vaporization characteristics of the fuel mixtures due to high combustion temperatures that prevail when operating at a high compression ratio of 9:1.

In addition to the improvement in brake thermal efficiency, knock-limited power output of the engine also increases with the high-octane fuel blends at higher compression ratio compared to test gasoline fuel. At a high compression ratio of 9:1, the knock-limited power output increases from 2.6 kW for the test gasoline fuel to 3.23 kW for eucalyptus oil blend; 3.36 kW for methanol blend; 3.1 kW for orange oil blend and 3.21 kW for ethanol-eucalyptus-gasoline blend fuel. The maximum power output of the test gasoline fueled engine dropped from 3.1 kW to 2.6 kW when the compression ratio increased from 7.4 to 9 due to onset of knock. The loss in power output at the high compression ratio could also be due to higher heat-transfer losses as a result of higher cylinder temperatures and low octane rating of the test gasoline fuel. However, with the high-octane fuel blends, the knock limit was considerably extended over test gasoline fuel. This is presumably due to enhanced octane quality of the fuel blends. The higher heat of evaporation associated with methanol and ethanol blends, resulted in a higher temperature drop in the venturi nozzle of the carburetor, and therefore higher delivery ratio can be obtained. Also, the high in-cylinder temperatures at the high compression ratio were effectively utilized to vaporize the fuel blends better, and as a result, the density of the trapped charge would be relatively higher compared to test gasoline. Hence, a considerable improvement in the knock-limited power output is obtained with the fuel blends over test gasoline fuel.

There was no appreciable deposit formation or gumming observed in the engine combustion chamber with the fuel blends after about 20 hours of testing. Spark plugs were also free from fouling at both the compression ratios tested. During the experimentation, no difficulties in the fuel line system or in the carburetor (such as vapor lock) were encountered with the fuel blends. Eucalyptus oil was found to be very effective as a co-solvent in controlling the phase separation problems of methanol/ethanol-gasoline blends. There were no problems in starting and acceleration with the fuel blends. Cold starting may not be a problem with the blends under the warm climate conditions (26-42°C) which prevail in India.

Based on the present investigations, it has been shown that addition of high-octane fuels to gasoline influences favorably the brake thermal efficiency, brake power and knock limit at higher compression ratio. The substantial improvements obtained are possibly due to a combination of several effects, such as energy content, mixture stoichiometry, octane rating, extension of lean

limit and burning velocity of the fuel blends. Further research work is recommended to identify the influence of each of these parameters. Among the four different fuel blends, eucalyptus oil blend and methanol blend performed superior to other fuel blends with regard to brake thermal efficiency and knock-limited power output at a high compression ratio of 9:1.

The variations in HC and CO emissions with brake power for all four fuel blends tested are presented in Figs. 10 and 11, respectively, at CR=9, 3000 rpm. It is observed that eucalyptus oil blend and orange oil blend give lower HC emission levels, whereas methanol blend and ethanol blend show higher HC emission levels at part loads and slightly lower levels at higher outputs compared

Fig.10 Variation of hydrocarbon emissions with brake power for different fuel blends

Fig.11 Variation of carbon monoxide emissions with brake power for different fuel blends

to test gasoline fuel. The reduction in HC emission levels for both eucalyptus oil blend and orange oil blend are in line with those obtained at CR 7.4. The maximum reduction in HC emission is about 1500 ppm for eucalyptus oil blend, 1400 ppm for orange oil blend, 500 ppm for ethanol blend and 250 ppm for methanol blend at the operating point corresponding to 2.6 kW power output. These reductions in HC emissions are partly due to the relatively leaner operation possible (Fig. 12) at higher compression ratio and more complete combustion.

CO emissions are lower with eucalyptus oil blend and orange oil blend but relatively higher with methanol blend and ethanol blend, as shown in Fig. 11. The maximum reduction in CO emission obtained with eucalyptus oil blend is about 1.4% by volume and for orange oil blend, it is about 0.8% by volume at 2.5 kW power output, compared to test gasoline fuel. Fig. 12 depicts the equivalence ratio (fuel-air) variations for all the fuel blends at 3000 rpm, CR = 9. It is observed that all the fuel blends were operated close to the stoichiometric mixture strength except at part loads, where the mixtures are relatively rich. As the mixture strength is rich, the corresponding CO emission is high. Hence, the mixture strength and CO emissions with various fuel blends can be correlated from Figs. 11 and 12. Methanol blend and ethanol blend were operated with relatively rich mixtures, and hence an increase in CO emission levels, compared to other fuel blends and test gasoline fuel.

Figure 13 indicates the variation of peak cylinder pressure, ignition delay and combustion duration with brake power for the four different fuel blends at a constant engine speed of 3000 rpm. It is observed from the above figure that methanol blend exhibits the highest peak cylinder pressure, followed by orange oil blend and eucalyptus oil blend, compared to the test gasoline fuel.

Fig.12 Variation of equivalence ratio with brake power for different fuel blends

The increase in peak cylinder pressure is about 5.0 bar for methanol blend, 4.64 bar for orange oil blend, and 1.45 bar for eucalyptus oil blend compared to test gasoline at 2.5 kW power output. The ethanol blend shows a decrease in peak pressure over that for the test gasoline fueled engine. Fig. 14 also depicts the actual pressure-time traces obtained at WOT operating condition for all the four fuel blends.

The ignition delay period is considerably reduced (Fig. 13) with methanol blend compared to other fuel blends and test gasoline fuel. The high-temperature environment in the combustion chamber, due to the higher compression ratio would help to vaporize the fuel mixture completely, especially with methanol fuel blend on account of its high latent heat of vaporization. Together with improved vaporization characteristics, the higher burning velocities of methanol fuel blend, lower the ignition delay considerably, as indicated in Fig. 13. The reduction in ignition delay varies from about 2 to 8° CA for the methanol blend, depending upon the operating conditions, whereas with other fuel blends the reduction in ignition delay is marginal compared to test gasoline fuel. Between the two compression ratios tested, ignition characteristics are considerably improved for the fuel blends at a higher compression ratio. The high in-cylinder temperatures that prevail at the higher compression ratio would help to prepare the mixtures better by overcoming their high specific gravity and relatively poor volatility characteristics. Hence, there is an improvement in the ignition characteristics for the fuel blends between the normal and high compression ratios (Figs. 7 and 13). The combustion duration of all the fuel blends is relatively short compared to test gasoline fuel in the entire test operating range of the engine, in particular with methanol blend and eucalyptus oil blend, as shown in Fig. 13. The effect of increasing compression ratio with lean mixtures permits higher flame speeds and higher expansion rates, leading to effective utilization of the available energy [4]. The combustion period of eucalyptus oil blend and methanol blend is short due to greater flame speed and takes place closer to TDC, which makes the thermodynamic cycle more similar to the Otto cycle. It is also reported in the literature [14] that the flame propagation velocity increases with an increase in the ratio of eucalyptus oil under stoichiometric mixture conditions. Hence, the combustion duration characteristics are considerably improved at a high compression ratio of 9:1.

CONCLUSIONS

Based on the present investigation of four different fuel blends, at two different compression ratios, the following conclusions are drawn with regard to engine performance, combustion and emission characteristics.

1. High-octane fuels, such as methanol, ethanol, eucalyptus oil and orange oil, can be blended by about 20% by volume with low-octane commercial gasoline to increase the octane quality of the fuel blend and thereby to increase the knock limit at a higher compression ratio.

Fig.13 Variation of combustion parameters with brake power for different fuel blends

Fig. 14 Pressure-time traces for different fuel blends at high compression ratio

2. The maximum improvement in the brake thermal efficiency with high-octane fuel blends was obtained at a high compression ratio of 9:1. The percentage improvement in the brake thermal efficiency is about 20.5% (at 2 kW) with eucalyptus oil blend; 20.0% (at 2.5 kW) with methanol blend; 6.0% (at 2 kW) with orange oil blend; and 5.0% (at 2kW) with ethanol blend, compared to the test gasoline-fueled engine.
3. Knock-limited maximum brake output increases due to extension of knock limit with the high-octane fuel blends. The extension of knock limit at a high compression ratio of 9:1 with various fuel blends is in the following descending order: methanol blend-eucalyptus oil blend-ethanol blend-orange oil blend.
4. The eucalyptus oil blend and orange oil blend reduce both the HC and CO emission levels considerably at a high compression ratio of 9:1. The maximum reduction in HC emission is about 1500 ppm for eucalyptus oil blend and 1400 ppm for orange oil blend. The CO emission is lowered by about 1.4% and 0.8% by volume for eucalyptus oil blend and orange oil blend, respectively, compared to test gasoline fuel. However, with methanol and ethanol fuel blends, the reductions in HC and CO emissions are only marginal over test gasoline fuel.
5. To control the phase-separation problems of alcohol-gasoline fuel blends, eucalyptus oil can be added as a co-solvent. For blends of 20% methanol and 20% ethanol in gasoline, the eucalyptus oil required to prevent the phase separation at room temperature (28°C) is about 5% and 20% by volume, respectively.

6. Among all the fuel blends tested, methanol blend and eucalyptus oil blend provide a potential for high thermal efficiency concomitant with low exhaust emissions, extension of knock limit at higher compression ratio and knock-limited brake output and are worthy of considering for two-stroke SI engines.

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