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Refining and Reuse of Waste Lube Oil in SI Engines: A Novel Approach for a Sustainable Environment

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Abstract: The protection of the environment and pollution control are issues of paramount importance. Researchers today are engrossed in mitigating the harmful impacts of petroleum waste on the environment. Lubricating oils, which are essential for the smooth operation of engines, are often disposed of improperly after completing their life. In the experimental work presented in this paper, deteriorated engine oil was regenerated using the acid treatment method and was reused in the engine. The comparison of the properties of reused oil, the engine's performance, and the emissions from the engine are presented. The reuse of regenerated oil, the evaluation of performance, and emissions establish the usefulness of the regeneration of waste lubricating oil. For the used oil, total acid number (TAN), specific gravity, flash point, ash content, and kinematic viscosity changed by 60.7%, 6.7%, 4.4%, 96%, and 15.5%, respectively, compared with fresh oil. The regeneration partially restored all the lost lubricating oil properties. The performance parameters, brake power (BP), brake specific fuel consumption (BSFC), and exhaust gas temperature (EGT) improved with regenerated oil in use compared with used oil. The emissions CO and NO_x contents for acid-treated oil were 9.7% and 17.3% less in comparison with used oil, respectively. Thus, regenerated oil showed improved performance and oil properties along with significantly reduced emissions when employed in an SI engine.

Keywords: environment; pollution; spark-ignition engine; lubricating oil regeneration; engine performance; exhaust emissions

1. Introduction

Lubricating oils are indispensable for the proper operation of any engine. In internal combustion (IC) engines, the lubricating oil serves many purposes including prevention of the direct contact of moving surfaces, reduction in excessive frictional losses, ejection of heat for maintaining temperature, protection from wear, and guarding against corrosion [1]. In providing the services mentioned, the properties of lubricating oil alter significantly from the optimum values due to fluctuations in temperature and contamination by dust, metal pieces, and soot. Researchers have extensively used the additive method over the past few years to mitigate this issue [2–4]. The engine oil, being in operation for a specific time, must be periodically changed to ensure efficient performance. The evacuated oil is

usually discarded inappropriately, which is hazardous to the environment [1,2,5,6]. The regeneration of lubricating oil seems to be the most effective remedy to solve this problem, which simply involves the removal of undesirable substances from deteriorated oil. The regeneration not only reduces the quantity of oil being disposed but also the amount of waste of petroleum products [7]. The recycling of oil can contribute to mitigating climate damage [8]. The dwindling renewable resources have urged us more than ever to adopt recycling techniques or look for other resources [9–11]. Regenerated oil can later either be reused or simply used as a raw material for various valuable lubricants [12,13]. The regeneration increases the life cycle of oil and the efficiency of the engine due by reducing frictional losses [14–16].

Over the years, the dire need for regeneration has consequently opened a new area of research that led to the development of various refining techniques. Jesusa Rinco'n et al. [17] used polar solvents for the extraction of base oil from waste lubricating oil and deduced that the magnitude of impurity removal depends on the solvent/oil ratio. They found that quantities of polymeric and metallic compounds were significantly lower in refined oil compared with used oil [17]. Similarly, two different states of propane, liquid and supercritical, were employed for investigating the effects of pressure and temperature to identify optimum conditions for the refining of used lubricating oil [18]. J.D conducted a comparative study of single solvent, composite solvent, and acid treatment methods for recycling engine oil. All the methods were effective, producing noticeable improvements in lubricating oil properties after regeneration [19]. In another study, the ultra-filtration of degraded oil using an inorganic membrane was presented as a potential lubricating oil regeneration technique. The results showed that an increase in temperature is favorable for decreasing the viscosity and improving the infiltration of waste oil [20]. Widodo et al. studied recent advances in lubricating oil regeneration technologies and highlighted the attractiveness of membrane technology owing to its low energy consumption [21]. Among the multiple methods available, the acid treatment method is historically proven, cost-efficient, and feasible [1,22,23].

Due to excessive CO₂ emissions and fear of the depletion of natural fuels, extensive efforts have been devoted to finding a less detrimental and more sustainable substitute for gasoline [24–26]. Ahmed et al. [27] conducted a comparative assessment of methanol-blended gasoline with pure gasoline and found a 17% reduction in CO₂ emissions for 15% methanol at high load condition. Hydrogen, alcoholic, and alkane fuels were compared in terms of performance and exhaust emissions by Pourkhaesalian and Shamekhi. The CO emissions of all substituted fuels were lower compared with gasoline [28]. Similarly, the effect of hydrogen addition to CNG was found to be noticeable in reducing CO emissions [29]. Di Blasio et al. found glycerol-derived ether mixtures valuable in terms of particulate matters and NO_x emissions due to the oxygen content of mixtures [30]. Similarly, low cetane oxygenated fuels used in a diesel engine produced reduced soot emissions [31]. Moreover, the use of techniques for mitigating exhaust gases has also been the focus of interest of researchers over the last two decades. Yoon et al. found that NO_x and CO emissions reduced by 87% and 98%, respectively, using stoichiometric combustion with a three-way catalyst instead of lean-burning CNG buses [32]. The application of exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) using multidimensional simulation tools on rail diesel engines was conducted by Beatrice et al. They reported that the developed simulation techniques can be effectively used for containing NO_x emissions [33]. Similarly, the effect of port-injected alcoholic fuel showed the potential to reduce NO_x and soot emissions at high load, as reported by Di et al. [34].

During the operation of an engine, the lubricating oil is consumed in the combustion process. The lubricating oil properties degrade over time, which affects engine performance and emissions. In this regard, Usman et al. used two different grades of octane gasoline for the assessment of lubricating oil deterioration, emissions, and performance. The worsening of lubricating oil properties for both fuels increased exhaust emissions. Similarly, for LPG, CNG, and hi-octane gasoline, the degradation of oil showed unfavorable results in terms

of performance and emissions [35]. The effect of gasoline, CNG, and the CNG-HHO blend on lubricating oil and emissions were also comparatively studied, which revealed that CNG-HHO fuel is more likely to deteriorate engine oil [36,37].

All the past research typically focused on the regeneration of waste oil and the comparison of its properties with fresh oil. However, in the current work, in addition to the regeneration of lubricating oil, the regenerated oil was reused in a spark-ignition engine, and the properties, performance, and emissions were assessed for fresh, used, and regenerated oil. This extension to the research firmly establishes the effectiveness of regenerated oil, which can be used to alleviate the effects of petroleum waste on the environment.

2. Materials and Methods

The performance and emission analyses were conducted on a LOMBARDINI SI engine (Model: IM-359), as shown in Figure 1, using PSO CARINET 20W-50 lubricating oil (physicochemical properties listed in Table 1). Figure 2 shows a schematic of the used setup, which includes a hygrometer, air filter, digital dynamometer (THEPRA), thermocouples, and environmental pollutant analyzer (EMS-5002). The fuel used was gasoline (G-97) whose flow rate for calculating BSFC was noted using a measuring cylinder. Initially, the dynamometer was coupled for the performance analysis of fresh oil with the test engine throttle opening set to 80%. The performance was analyzed using the SAE-J1349 standard. The experimental readings were recorded in two stages. In the first stage, speed was changed from 1200 to 2400 rpm in 3 equal steps. In the second stage, the increase in rate from 2400 to 3200 rpm was achieved in four similar steps.



Figure 1. Illustration of test bench.

Table 1. Lubricating oil properties.

Oil	Total Acid Number (TAN) (mg. KOH/g)	Specific Gravity	Ash Content %	Kinematic Viscosity (cSt)	Flash Point °C
Standards	D974 1.69	D1298 0.905	D482 0.1	D445 10.52	D92 250

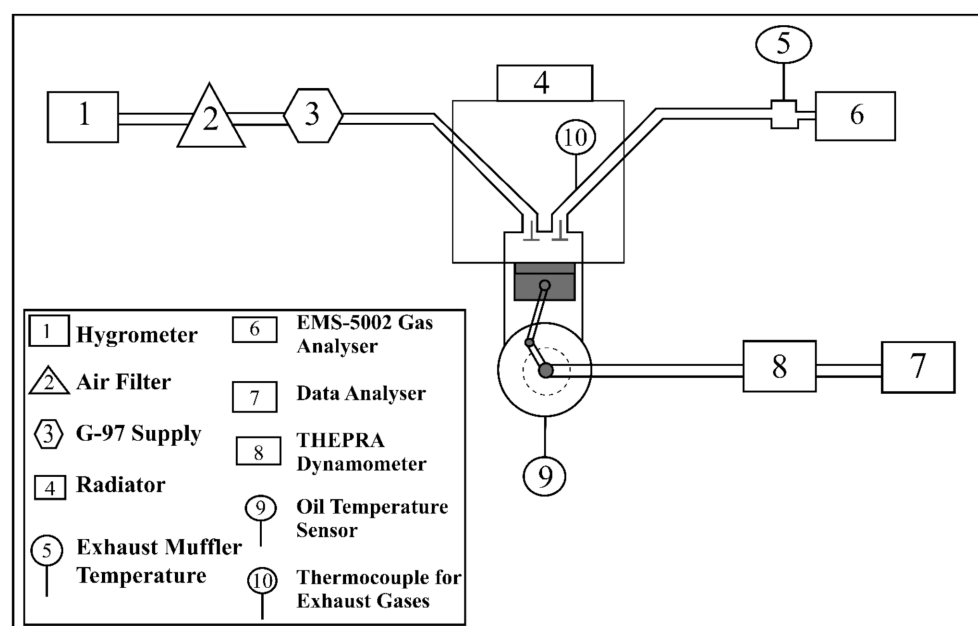


Figure 2. Experimental setup.

The value of BSFC was calculated by considering the time needed for a specific quantity of G97 (properties mentioned in Table 2) consumption. The emissions were recorded using an EMS-5002 apparatus at a constant speed for the torque percentages of 0%, 10%, 25%, 50%, 75%, and 100%. In the next step, oil functioning was determined by subjecting the engine to the test run for 100 h, as recommended by the manufacturer. The same method used above was applied for grading the performance and emissions of the used oil. Later, the used oil was extracted from the oil sump and tested against the properties mentioned in Table 1.

Table 2. Properties of fuel.

Properties	Gasoline
Octane Number	97
Color	Reddish
Density g/mL	0.70–0.8
Benzene (vol %)	4 max.
Oxygenate Contents	0.76

The apparatus, which included a calibrated conical flask, measuring cylinder, filter paper, and pH indicator, was employed for reconditioning the used oil. The process flow diagram for regeneration using the acid treatment method is shown in Figure 3. First, for 24 h, the degraded oil was settled, which resulted in the accumulation of various materials and dirt at the bottom. Water and light HC were removed by filtering 300 mL of used oil and heating it to 45 °C with continuous stirring using a magnetic stirrer. We added 30 mL of acetic acid to a beaker followed by constant stirring to remove acetate and nitrogen compounds. The test sample was then allowed to settle for a complete day. Then, upper and lower layers were discarded as they bore acidic sludge and heavy particles. Afterward, acidic oil was treated using liquid bleach (12 mL) for a span of 15–20 min. Subsequently, the acidic nature of under-treatment oil was neutralized by titrating it with KOH. The pH was closely monitored until the oil started falling within the desired pH range. In the last step, the treated oil was again allowed to settle for one day and later filtered using a filter cloth. The regenerated oil sample was tested in accordance with standards (shown in Table 1). The regenerated oil emissions and performance were measured using the same procedure as for fresh and used oil.

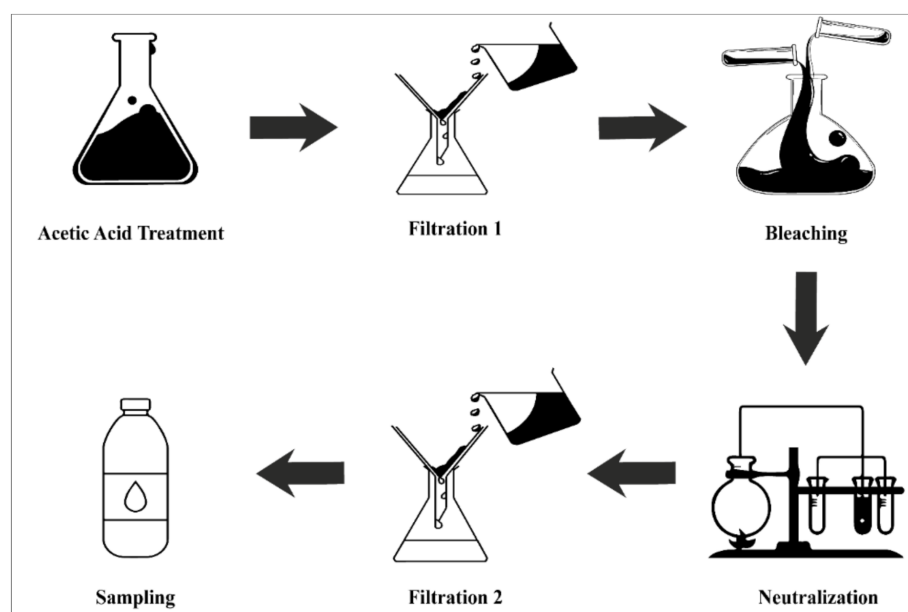


Figure 3. Regeneration procedure.

3. Results

3.1. Properties of Lubricating Oil

The effect of regeneration was determined by comparing the properties of the refined oil with those of the fresh and used oil. The parameters governing the performance of engine oil are flashpoint, TAN, ash content, appearance, specific gravity, and kinematic viscosity [38].

Figure 4a shows the flashpoints of the three different oils. The flashpoint of used oil decreased 4.4% in comparison with fresh oil. The decline could be attributed to the breakdown of large molecules into smaller ones [39,40]. The regeneration showed an improvement of 2.1%. The figure depicts that half of the lost numerical value of the flashpoint is recovered after the acetic acid treatment.

Figure 4b shows the TAN of fresh, used, and regenerated oil. Initially, the TAN was low for fresh oil (1.7 mg/g. KOH), which later increased by 60.70% (4.3 mg/g. KOH) for used oil. Oxides formed as a result of oxidation reacting instantly with compounds in the vicinity to produce acid [41]. As such, the acids produced increased the acidity, which in turn increased the TAN. The neutralization process improved pH and, consequently, the acidity decreased by 48.8% (2.2 mg/g. KOH) in comparison with used oil. The specific gravity for the three oils is shown in Figure 4c, which was high for fresh oil (0.91) but decreased 6.74% (0.84) for used oil. The decrease can be attributed to reduced oil film thickness and high temperatures in the engine cylinder [2]. The refining procedure produced an increase of 1.7% (0.89) compared with used oil due to the restoration of the oil's properties. The ash content of non-deteriorated oil was significantly low, i.e., 0.1%, as shown in Figure 4d. However, the used oil had a relatively high ash content (2.5%), which could be accredited to the presence of combustion products. When treated with acetic acid, a visible drop was observed (1%).

Figure 4e shows a comparison of the kinematic viscosities of the three oils. The kinematic viscosity dropped significantly, i.e., by 15.5%, for used oil. The decline could be ascribed to ample oxidation, wearing of additives, and thinning of the oil [2,17,42]. Acetic-acid-treated oil showed an increase of 12.2%.

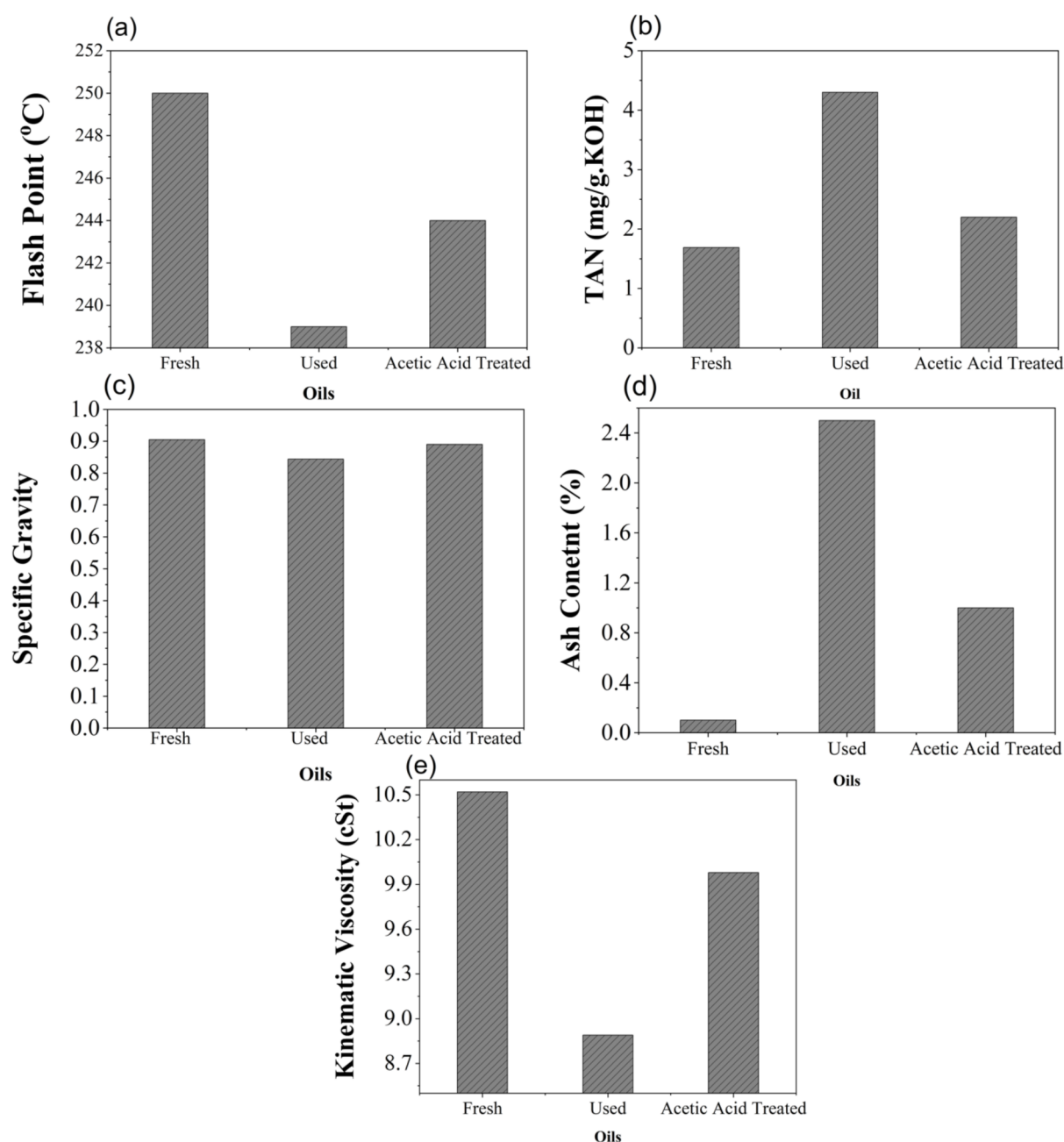


Figure 4. Comparison of (a) flashpoint (b) TAN (c) specific gravity (d) ash content (e) kinematic viscosity of fresh, used, and regenerated lubricating oils.

3.2. Engine Performance

Figure 5 displays the increasing-decreasing trend of brake power variation with engine speed for the three oils with a dashed curve. The brake power increased up to 3000 rpm and then abruptly decreased. This curve behavior could be explained by the large power losses at high speed. At 3000 rpm, a brake power of 4176.2 W was recorded, which decreased to 3799.4 W for used oil. This decrease could be due to the wearing of the engine oil and a decrease in the kinematic viscosity (Figure 4e) [2]. The regenerated oil with improved kinematic viscosity had a brake power of 3934.4 W at the same speed. However, an average increase of 4.3% in brake power was found for regenerated oil compared with used oil. The engine-power-producing mechanism involves the vertical linear movement of the piston, which is hindered by friction. In reducing the friction, the energy is used in the form of work. Thus, the greater the friction, the lesser the power produced [43]. For refined oil,

the kinematic viscosity increased and, consequently, the oil thickness. So, increased oil thickness resulted in less frictional losses, and the BP produced was high [2,44–46].

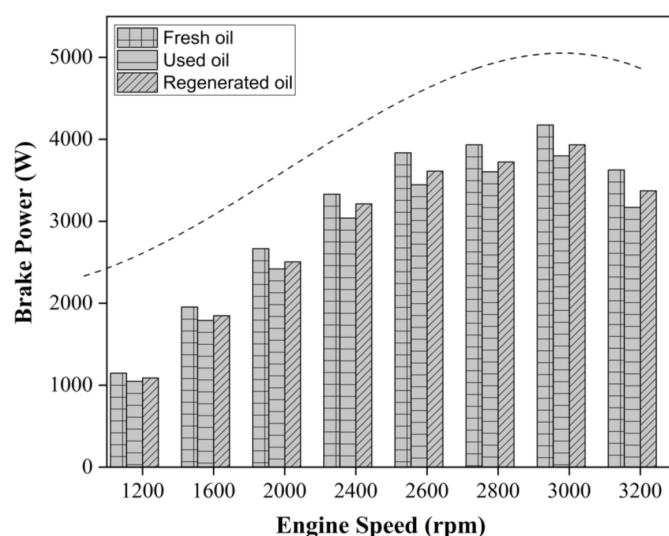


Figure 5. Brake power variation with speed.

The decreasing-increasing trend of the three oils for BSFC with engine speed is shown by a dashed curve in Figure 6. BSFC declined up to 2400 rpm and then increased onwards because of an increase in the rate of friction losses with rpm demanding more fuel for the production of power [47]. For the fresh oil at 1200 rpm, BSFC (0.60 kg/kWh) was the highest due to ample heat losses from the relatively cold walls of the engine chamber. The parameter increased to 0.67 kg/kWh for the used oil. The regenerated oil showed a decrease in BSFC (0.62 kg/kWh) due to significant improvements in engine oil characteristics [7,48]. However, an average decrease of 5.8% was observed for regenerated oil in comparison with used oil. The engine using deteriorated oil experienced greater frictional resistance and thus required more fuel to produce unit power. In the case of acid-treated oil, the improved oil properties caused lesser frictional resistance. Therefore, the fuel demand for producing unit power decreased [36,49,50].

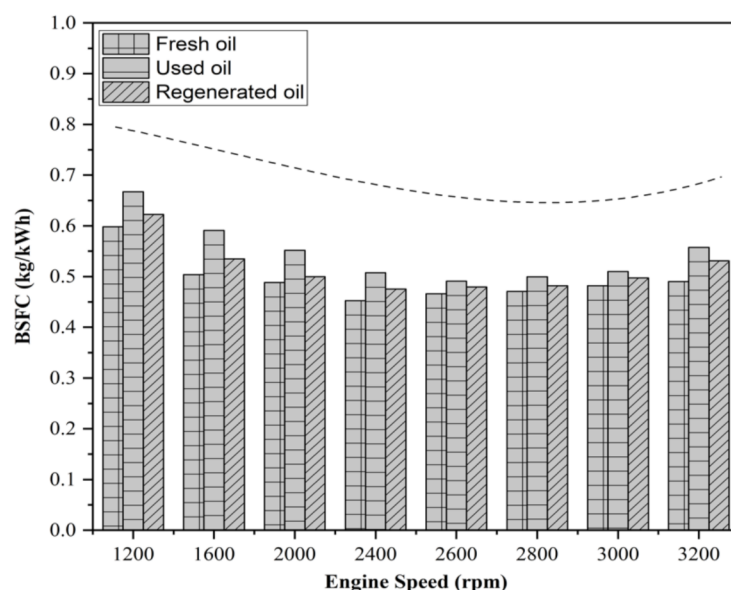


Figure 6. BSFC variation with speed.

3.3. Exhaust Gas Temperature

Exhaust gas temperature (EGT) provides important insights into the combustion process [33]. A large numerical value corresponds to a high temperature in the combustion chamber [51]. Figure 7 shows the EGT variations of the three oils with torque percentages. The comparison shows that the EGT was highest for the deteriorated engine oil. Engine operation consumes as well as deteriorates lubricating oil. Therefore, after 100 h of operation, the quantity of lubricating oil decreased and properties deteriorated (Section 3.1), which thereby decreased the oil's heat-absorbing capacity. With less heat being absorbed, the temperature inside the cylinder increased, which could be the reason for a high EGT compared with fresh and refined oil. The EGT values for regenerated oil were in between those for the fresh and deteriorated oil. This beneficial change by regeneration can be understood by the viscosity variation of the three oils (Figure 4e). Kinematic viscosity reduces the friction, which consequently maintains the inside temperature of the cylinder. The improved viscosity of refined oil compared with deteriorated lubricating oil reduces exhaust gas temperature [35].

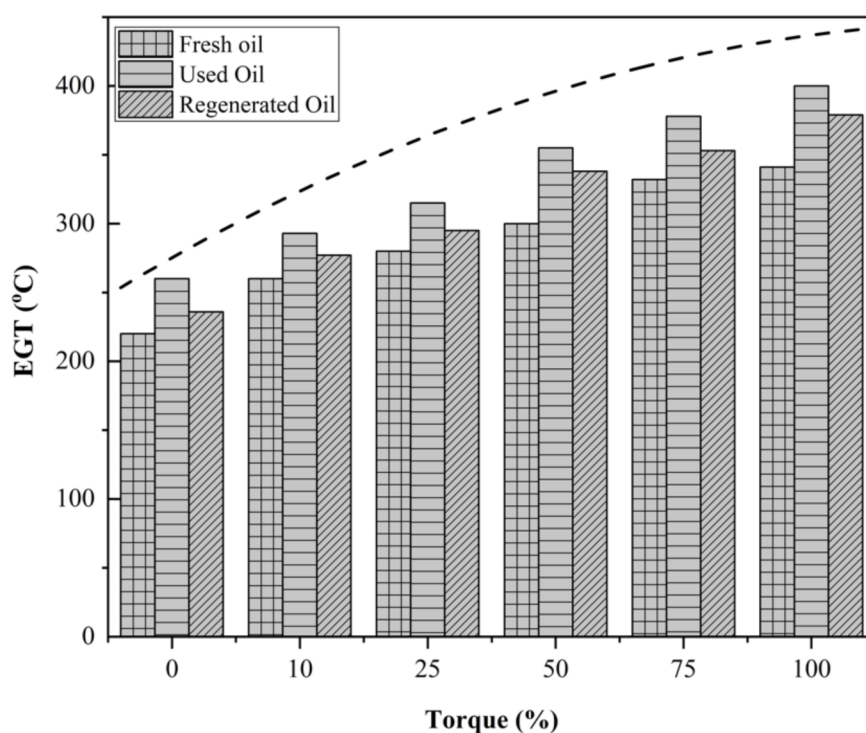


Figure 7. EGT variation with torque (%).

3.4. Engine Emissions

The oil used to lubricate the moving parts of the engine formed a thin layer of liquid film on the walls of the cylinder. The absorption and desorption phenomena associated with oil film during the four-stroke cycle were identified as a source of hydrocarbon emissions [52–55]. The emission levels of exhaust UHC were higher when deteriorated oil was used compared with the use of fresh and regenerated oil (shown in Figure 8).

The decreased viscosity of deteriorated oil (Figure 4e) increased the fuel absorption in the oil film, which produced more HC [49]. Similarly, due to improved viscosity after regeneration (Figure 4e), less fuel was consumed in oil film; therefore, the average emissions reduced 9.7% compared with used oil. HC emissions showed a peak value of 0.30 g/kWh with deteriorated oil under an operating condition of 100% torque. Moreover, the increasing-decreasing dashed curve shows the general trend in HC emissions for the three oils.

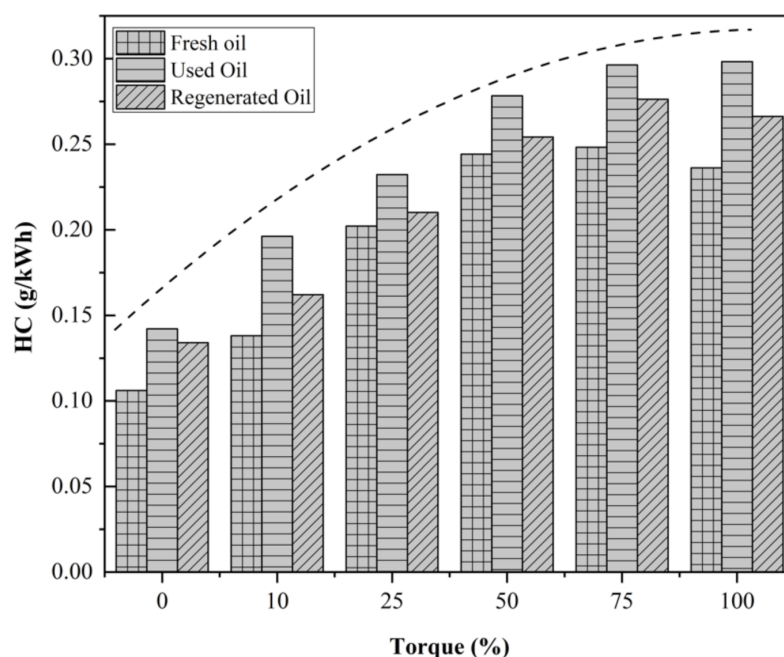


Figure 8. HC emissions variation with torque (%).

Variations in the emissions of greenhouse gases for fresh (non-deteriorated), deteriorated (used), and regenerated oils with torque percentages are shown in Figure 9. As a general observation, the production of high power necessitates high fuel consumption, which in turn is possible by increased combustion [56]. Thus, CO_2 followed an increasing trend at higher torque percentages for the three oils, as more grams of gas are released when producing more kWh of energy. The bars show that for regenerated oil, the emissions contents were lower than those of used oil at low torque percentages, but higher for higher torque percentages. Compared on an average scale, regenerated oil generated 0.3% more CO_2 than used oil. The use of fresh oil showed maximum emissions contents at high percentages of torque, which could be attributed to improved burning and lesser dilution of gasoline fuel in the engine [57–59].

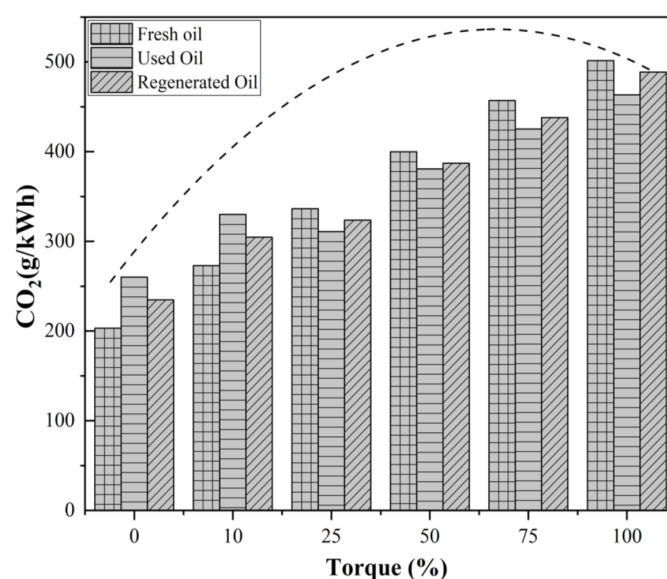


Figure 9. CO_2 emissions variations with torque (%).

The emissions of NO_x in Figure 10 follow a trend similar to exhaust gas temperature (Figure 7). The dotted curve in Figure 10 depicts NO_x emissions for the three oil conditions. At lower torque percentages, the emissions contents for the three oils were almost negligible, but they were significantly higher for larger values, as NO_x formation is highly temperature-dependent [36,60–63]. The regenerated oil produced 17.9% less emissions compared with used oil. The higher NO_x emissions with deteriorated oil could be due to lubricating oil properties variations and the EGT (Figures 4e and 7). In the case of deteriorated oil, due to decreased kinematic viscosity, the frictional effects between the engine's moving parts in contact were significant, which increased the NO_x emissions due to the high temperature in the combustion chamber [49]. Moreover, the maximum of 2.7 g/kWh of NO_x emissions was recorded for the engine operating on waste oil with a torque percentage of 100%.

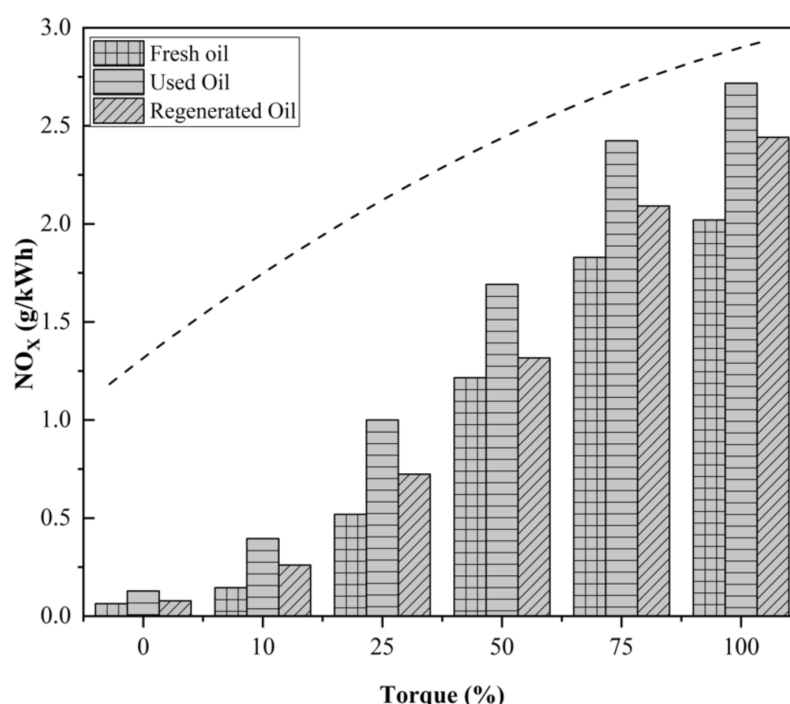


Figure 10. NO_x emissions variations with torque (%).

4. Conclusions

Water contamination, either geologically or anthropogenically, due to the disposal of engines' lubricating oil in water bodies, is of growing concern. This experimental study presented the results of refining waste lubricating oil and reusing it in an SI engine. The outcomes of the study can be summarized as:

- The flashpoint, specific gravity, kinematic viscosity, ash content, and TAN of regenerated oil varied by 2.1%, 5.2%, 10.9%, 60%, and 48.8%, respectively, compared with degraded oil. The refined oil recovered 50% of the lost numerical values of oil properties, which make the oil worthy of being reused.
- The average brake power (BP) decreased with the deterioration in the lubricating oil. The used and fresh oils showed a BP of 2790.4 and 3084.9 W, respectively. However, refined oil showed an improved value of 2912.7 W. The restored values of brake power for regenerated oil were between those of fresh and used oil. The regeneration decreased the BSFC. It was 0.49 kg/kWh for fresh oil, which increased to 0.55 kg/kWh for deteriorated oil and decreased to 0.51 kg/kWh after acid-\ treatment.
- HC, CO₂, and NO_x emissions increased by 22.8%, 10.3%, and 44.3%, respectively, in the case of used oil, with NO_x most significantly changing. After regeneration, all of the emissions decreased, which demonstrates that this regeneration is practical and advantageous in terms of environmental protection.

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References

- Armioni, M.; Benea, M.; Rațiu, S. Used Engine Oil Recycling Techniques: A Comparison. In Proceedings of the Student Scientific symposium, Hunedoara, Romania, May 2020.
- Usman, M.; Saqib, S.; Zubair, S.W.H.; Irshad, M.; Kazmi, A.H.; Noor, A.; Zaman, H.U.; Nasir, Z.; Malik, M.A.I. Experimental assessment of regenerated lube oil in spark-ignition engine for sustainable environment. *Adv. Mech. Eng.* **2020**, *12*, 168781402094045. [\[CrossRef\]](#)
- Al-Zahrani, S.M.; Putra, M.D. Used lubricating oil regeneration by various solvent extraction techniques. *J. Ind. Eng. Chem.* **2013**, *19*, 536–539. [\[CrossRef\]](#)
- Abdel-Azim, A.; Nasser, A.M.; Ahmed, N.S.; Kamal, R.S. Multifunctional Lube Oil Additives Based on Octadecene-Maleic Anhydride Copolymer. *Pet. Sci. Technol.* **2011**, *29*, 97–107. [\[CrossRef\]](#)
- Botas, J.A.; Moreno, J.; Espada, J.J.; Serrano, D.P.; Dufour, J. Recycling of used lubricating oil: Evaluation of environmental and energy performance by LCA. *Resour. Conserv. Recycl.* **2017**, *125*, 315–323. [\[CrossRef\]](#)
- Bailey, P.D.; Air, W.; Pollution, S. Modelling future vehicle exhaust emissions in Europe. *Water Air Soil Pollut.* **1995**, *85*, 1879–1884. [\[CrossRef\]](#)
- Usman, M.; Saleem, M.W.; Saqib, S.; Umer, J.; Naveed, A.; Hassan, Z.U. SI engine performance, lubricant oil deterioration, and emission: A comparison of liquid and gaseous fuel. *Adv. Mech. Eng.* **2020**, *12*, 1687814020930451. [\[CrossRef\]](#)
- Pajunen, N.; Rintala, L.; Aromaa, J. Recycling—The importance of understanding the complexity of the issue. *Int. J. Sustain. Eng.* **2016**, *9*, 93–106. [\[CrossRef\]](#)
- Mitsch, W.J.; Jørgensen, S.E.J.E. Ecological engineering: A field whose time has come. *Ecol. Eng.* **2003**, *20*, 363–377. [\[CrossRef\]](#)
- Raghuwanshi, S.S.; Arya, R. Renewable energy potential in India and future agenda of research. *Int. J. Sustain. Eng.* **2019**, *12*, 291–302. [\[CrossRef\]](#)
- Kudelfko, J.J.I.J.o.M. Reclamation and Environment, Effectiveness of mineral waste management. *J. Min. Reclam. Environ.* **2018**, *32*, 440–448. [\[CrossRef\]](#)
- Rincon, J.; Cañizares, P.; García, M.T. Regeneration of used lubricant oil by ethane extraction. *J. Supercrit. Fluids* **2007**, *39*, 315–322. [\[CrossRef\]](#)
- Emam, E.A.; Shoaib, A.M.J.P. Re-refining of used lube oil, i-by solvent extraction and vacuum distillation followed by hydrotreating. *Pet. Coal* **2013**, 179–187.
- Zhang, C.-G.; Zhao, Y.-J.; Deng, Y.-S.; Wang, H.J.L.O. The status quo of regeneration technology for used lubricating oils and the thoughts of industry development. *Lubr. Oil* **2008**, *2*, 9–12.
- Pinheiro, C.T.; Quina, M.J.; Gando-Ferreira, L.M. Management of waste lubricant oil in Europe: A circular economy approach. *Crit. Rev. Environ. Sci. Technol.* **2020**, 1–36. [\[CrossRef\]](#)
- Arpa, O.; Yumrutaş, R.; Argunhan, Z. Experimental investigation of the effects of diesel-like fuel obtained from waste lubrication oil on engine performance and exhaust emission. *Fuel Process. Technol.* **2010**, *91*, 1241–1249. [\[CrossRef\]](#)
- Rincón, J.; Cañizares, P.; García, M.T. Regeneration of Used Lubricant Oil by Polar Solvent Extraction. *Ind. Eng. Chem. Res.* **2005**, *44*, 4373–4379. [\[CrossRef\]](#)
- Rincon, J.; Cañizares, P.; García, M.T.; Gracia, I. Regeneration of Used Lubricant Oil by Propane Extraction. *Ind. Eng. Chem. Res.* **2003**, *42*, 4867–4873. [\[CrossRef\]](#)
- Udonne, J.D.G. A comparative study of recycling of used lubrication oils using distillation, acid and activated charcoal with clay methods. *J. Pet. Gas Eng.* **2011**, *2*, 12–19.
- Cao, Y.; Feng, Y.; Jiaxin, L. Used lubricating oil recycling using a membrane filtration: Analysis of efficiency, structural and composing. *Desalination Water Treat.* **2009**, *11*, 73–80. [\[CrossRef\]](#)
- Widodo, S.; Ariono, D.; Khoiruddin, K.; Hakim, A.N.; Wenten, I.G. Recent advances in waste lube oils processing technologies. *Environ. Prog. Sustain. Energy* **2018**, *37*, 1867–1881. [\[CrossRef\]](#)
- Boadu, K.O.; Joel, O.F.; Essumang, D.K.; Evbuomwan, B.O. A Review of Methods for Removal of Contaminants in Used Lubricating Oil. *Chem. Sci. Int. J.* **2019**, 1–11. [\[CrossRef\]](#)
- Jafari, A.J.; Hassanpour, M. Analysis and comparison of used lubricants, regenerative technologies in the world. *Resour. Conserv. Recycl.* **2015**, *103*, 179–191. [\[CrossRef\]](#)

24. Olivier, J.; Bouwman, A.; Van der Hoek, K.; Berdowski, J. Global air emission inventories for anthropogenic sources of NO_x, NH₃ and N₂O in 1990. *Environ. Pollut.* **1998**, *102*, 135–148. [\[CrossRef\]](#)
25. Surisetty, V.R.; Dalai, A.K.; Kozinski, J. Alcohols as alternative fuels: An overview. *Appl. Catal. A Gen.* **2011**, *404*, 1–11. [\[CrossRef\]](#)
26. Vedenov, D.V.; Duffield, J.A.; Wetzstein, M.E.J.J.o.A.; Economics, R. Entry of alternative fuels in a volatile US gasoline market. *J. Agric. Resour. Econ.* **2006**, *31*, 1–13.
27. Ahmed, E.; Usman, M.; Anwar, S.; Ahmad, H.M.; Nasir, M.W.; Malik, M.A.I. Application of ANN to predict performance and emissions of SI engine using gasoline-methanol blends. *Sci. Progr.* **2021**, *104*, 1–27. [\[CrossRef\]](#) [\[PubMed\]](#)
28. Pourkhesalian, A.M.; Shamekhi, A.H.; Salimi, F. Alternative fuel and gasoline in an SI engine: A comparative study of performance and emissions characteristics. *Fuel* **2010**, *89*, 1056–1063. [\[CrossRef\]](#)
29. Banapurmath, N.; Gireesh, N.; Basavarajappa, Y.; Hosmath, R.; Yaliwal, V.; Pai, A.; Navale, K.G.; Jog, P.; Tewari, P. Effect of hydrogen addition to CNG in a biodiesel-operated dual-fuel engine. *Int. J. Sustain. Eng.* **2015**, *8*, 332–340. [\[CrossRef\]](#)
30. Di Blasio, G.; Bonura, G.; Frusteri, F.; Beatrice, C.; Cannilla, C.; Viscardi, M. Experimental Characterization of Diesel Combustion Using Glycerol Derived Ethers Mixtures. *SAE Int. J. Fuels Lubr.* **2013**, *6*, 940–950. [\[CrossRef\]](#)
31. Di Blasio, G.; Beatrice, C.; Dijkstra, R.; Boot, M. *Low Cetane Number Renewable Oxy-fuels for Premixed Combustion Concept Application: Experimental Investigation on a Light Duty Diesel Engine*; SAE International: Warrendale, PA, USA, 2012.
32. Yoon, S.; Collins, J.; Thiruvengadam, A.; Gautam, M.; Herner, J.; Ayala, A. Criteria pollutant and greenhouse gas emissions from CNG transit buses equipped with three-way catalysts compared to lean-burn engines and oxidation catalyst technologies. *J. Air Waste Manag. Assoc.* **2013**, *63*, 926–933. [\[CrossRef\]](#)
33. Beatrice, C.; Rispoli, N.; Di Blasio, G.; Patrianakos, G.; Kostoglou, M.; Konstandopoulos, A.; Imren, A.; Denbratt, I.; Palacin, R. *Emission Reduction Technologies for the Future Low Emission Rail Diesel Engines: EGR vs SCR*; SAE International: Warrendale, PA, USA, 2013.
34. Di Blasio, G.; Beatrice, C.; Molina, S. *Effect of Port. Injected Ethanol on Combustion Characteristics in a Dual-Fuel Light Duty Diesel Engine*; SAE International: Warrendale, PA, USA, 2013.
35. Usman, M.; Hayat, N. Lubrication, emissions, and performance analyses of LPG and petrol in a motorbike engine: A comparative study. *J. Chin. Inst. Eng.* **2020**, *43*, 47–57. [\[CrossRef\]](#)
36. Usman, M.; Hayat, N.; Bhutta, M.M.A. SI Engine Fueled with Gasoline, CNG and CNG-HHO Blend: Comparative Evaluation of Performance, Emission and Lubrication Oil Deterioration. *J. Therm. Sci.* **2020**, *29*, 1–13. [\[CrossRef\]](#)
37. Usman, M.; Naveed, A.; Saqib, S.; Hussain, J.; Tariq, M.K. Comparative assessment of lube oil, emission and performance of SI engine fueled with two different grades octane numbers. *J. Chin. Inst. Eng.* **2020**, *43*, 734–741. [\[CrossRef\]](#)
38. Abu-Elella, R.; Ossman, M.E.; Farouq, R. Used motor oil treatment: Turning waste oil into valuable products. *Int. J. Chem. Biochem. Sci.* **2015**, *7*, 57–67.
39. De Lima, A.E.A.; Sales, H.B.; de Lima, L.C. Natural clay applied to the clarification of used automotive lubricating oil. *Cerâmica* **2017**, *63*, 517–523.
40. Scapin, M.; Duarte, C.; Sampa, M.; Sato, I. Recycling of the used automotive lubricating oil by ionizing radiation process. *Radiat. Phys. Chem.* **2007**, *76*, 1899–1902. [\[CrossRef\]](#)
41. Cutler, E.L.; Cutler, E.T. Re-Refining Used Automotive Lubricating Oil. U.S. Patent 3919076, 1975.
42. Rahman, M.; Siddique, T.; Samdani, S.; Kabir, K. Effect of Operating Variables on Regeneration of Base-Oil from Waste Oil by Conventional Acid-Clay Method. *Chem. Eng. Res. Bull.* **2008**, *12*, 24–27. [\[CrossRef\]](#)
43. Forson, F.; Oduru, E.; Hammond-Donkoh, E. Performance of jatropha oil blends in a diesel engine. *Renew. Energy* **2004**, *29*, 1135–1145. [\[CrossRef\]](#)
44. Umer, J.; Morris, N.; Leighton, M.; Rahmani, R.; Balakrishnan, S.; Rahnejat, H. Nano and microscale contact characteristics of tribofilms derived from fully formulated engine oil. *Tribol. Int.* **2019**, *131*, 620–630. [\[CrossRef\]](#)
45. Hamdan, M.; Al-Subaih, T. Improvement of locally produced gasoline and studying its effects on both the performance of the engine and the environment. *Energy Convers. Manag.* **2002**, *43*, 1811–1820. [\[CrossRef\]](#)
46. Mathai, R.; Malhotra, R.; Subramanian, K.; Das, L. Comparative evaluation of performance, emission, lubricant and deposit characteristics of spark ignition engine fueled with CNG and 18% hydrogen-CNG. *Int. J. Hydrogen Energy* **2012**, *37*, 6893–6900. [\[CrossRef\]](#)
47. Jahirul, M.; Masjuki, H.; Saidur, R.; Kalam, M.; Jayed, M.; Wazed, M. Comparative engine performance and emission analysis of CNG and gasoline in a retrofitted car engine. *Appl. Therm. Eng.* **2010**, *30*, 2219–2226. [\[CrossRef\]](#)
48. Evans, R.L.; Blaszczyk, J. A comparative study of the performance and exhaust emissions of a spark ignition engine fuelled by natural gas and gasoline. *Proc. Inst. Mech. Eng. Part. D J. Automob. Eng.* **1997**, *211*, 39–47. [\[CrossRef\]](#)
49. Usman, M.; Farooq, M.; Naqvi, M.; Saleem, M.W.; Hussain, J.; Naqvi, S.R.; Jahangir, S.; Usama, H.M.J.; Idrees, S.; Anukam, A. Use of Gasoline, LPG and LPG-HHO Blend in SI Engine: A Comparative Performance for Emission Control and Sustainable Environment. *Process* **2020**, *8*, 74. [\[CrossRef\]](#)
50. Usman, M.; Hayat, N. Part A: Recovery, Utilization, and E. Effects, Use of CNG and Hi-octane gasoline in SI engine: A comparative study of performance, emission, and lubrication oil deterioration. *Energy Sources Part A Recovery Util. Environ. Eff.* **2019**, 1–15.
51. Agrawal, A.K.; Singh, S.K.; Sinha, S.; Shukla, M.K. Effect of EGR on the exhaust gas temperature and exhaust opacity in compression ignition engines. *Sadhana* **2004**, *29*, 275–284. [\[CrossRef\]](#)
52. De Albuquerque, P.C.C.; de Andrade Ávila, R.N.; Zárante, P.H.B. Lubricating oil influence on exhaust hydrocarbon emissions from a gasoline fueled engine. *Tribol. Int.* **2011**, *44*, 1796–1799. [\[CrossRef\]](#)

-
53. Gatellier, B.; Trapy, J.; Herrier, D.; Quelin, J.; Galliot, F. Hydrocarbon Emissions of SI Engines as Influenced by Fuel Absorption-Desorption in Oil Films. *SAE Technical. Paper Ser.* **1992**. [[CrossRef](#)]
 54. Frølund, K.; Schramm, J. Simulation of HC-Emissions from SI-Engines—A Parametric Study. *SAE Technical. Paper Ser.* **1997**. [[CrossRef](#)]
 55. Salazar, V.M.; Gandhi, J.B. Discussion of the Role of Fuel-Oil Diffusion in the Hydrocarbon Emissions from a Small Engine. *SAE Technical. Paper Ser.* **2008**, *1*, 1347–1356.
 56. Guido, C.; Beatrice, C.; Di Iorio, S.; Fraioli, V.; Di Blasio, G.; Vassallo, A.; Ciaravino, C. Alternative Diesel Fuels Effects on Combustion and Emissions of an Euro5 Automotive Diesel Engine. *SAE Int. J. Fuels Lubr.* **2010**, *3*, 107–132. [[CrossRef](#)]
 57. Putrasari, Y.; Praptijanto, A.; Nur, A.; Wahono, B.; Santoso, W.B. Evaluation of Performance and Emission of SI Engine Fuelled with CNG at Low and High Load Condition. *Energy Procedia* **2015**, *68*, 147–156. [[CrossRef](#)]
 58. Hsieh, W.-D.; Chen, R.-H.; Wu, T.-L.; Lin, T.-H. Engine performance and pollutant emission of an SI engine using ethanol–gasoline blended fuels. *Atmos. Environ.* **2002**, *36*, 403–410. [[CrossRef](#)]
 59. Bata, R.M.; Elrod, A.C.; Rice, R.W. Emissions From IC Engines Fueled With Alcohol–Gasoline Blends: A Literature Review. *J. Eng. Gas. Turbines Power* **1989**, *111*, 424–431. [[CrossRef](#)]
 60. Agarwal, D.; Singh, S.K.; Agarwal, A.K. Effect of Exhaust Gas Recirculation (EGR) on performance, emissions, deposits and durability of a constant speed compression ignition engine. *Appl. Energy* **2011**, *88*, 2900–2907. [[CrossRef](#)]
 61. Yontar, A.A.; Doğu, Y. Investigation of the effects of gasoline and CNG fuels on a dual sequential ignition engine at low and high load conditions. *Fuel* **2018**, *232*, 114–123. [[CrossRef](#)]
 62. Geok, H.H.; Mohamad, T.I.; Abdullah, S. *Experimental Investigation of Performance and Emissions of a Sequential Port Injection Compressed Natural Gas Converted Engine*; SAE Technical Paper; SAE International: Warrendale, PA, USA, 2009.
 63. Dijkstra, R.; Di Blasio, G.; Boot, M.; Beatrice, C.; Bertoli, C. Assessment of the Effect of Low Cetane Number Fuels on a Light Duty CI Engine: Preliminary Experimental Characterization in PCCI Operating Condition. *SAE Tech. Paper Ser.* **2011**. [[CrossRef](#)]