



Comparative Analysis of Combustion Properties between Waste Automotive Oil and Light Diesel Oil as Alternative Fuels

Israa Jafar¹, Jameel Al-Naffakh², Mohammed R. Al-Qassab³, Zaid Mohammed Al-Makhzumi⁴

¹ Basic Sciences Department, University of Kufa, College of Dentistry

^{2,3} Mechanical power Department, AL-Furat Al-Awsat Technical University, Najaf Technical engineering college

⁴Ministry of Oil /Director of the Oil Product Distribution Company /Najaf Branch (OPDC)

Corresponding Author E-mail: jameeltawfiq@gmail.com

Received: 07 Feb 2024; Revised: 08 Mar 2024; Accepted: 15 Mar 2024; Available online: 10 Apr 2024

Abstract—

Given the extensive and widespread utilization of fossil fuels in various sectors, there is a pressing need to explore and develop novel alternative fuels in order to effectively address the increasing global energy demand. The finite nature of fossil fuel reserves has resulted in their rapid depletion, thus highlighting the need to explore sustainable alternatives. Additionally, the utilization of fossil fuels is associated with environmental issues such as the phenomenon of global warming, the release of detrimental emissions, and the instability of prices. Within this particular context, Waste Automotive Oil (WAO) presents itself as a potentially advantageous substitute fuel and additive, providing economically viable resolutions to the dual concerns of fuel requirements and waste management. This study aims to conduct a comparative analysis of the combustion characteristics of waste motor oil obtained from the wet air oxidation (WAO) process and conventional Light Diesel Oil (LDO). The utilization of waste motor oils as fuel was investigated in a cylindrical combustor equipped with a coil-over liquid oil burner under various operating conditions. The process of preheating waste automobile oil to a temperature of 90 °C inside the combustion chamber was found to be effective in reducing viscosity and improving compatibility with the properties of light diesel oil. In order to evaluate the fuel characteristics, a comprehensive examination of waste motor oils was carried out, following the guidelines set by the American Society for Testing and Materials (ASTM). This involved conducting both physical and chemical analyses. The study involved conducting an experimental assessment of the combustion characteristics of an oil burner, specifically focusing on the utilization of waste motor oils and light diesel oil. This evaluation encompassed the analysis of axial and radial flame temperatures, concentrations of exhaust gas emissions, and overall combustion efficiency. The results of the study indicated that raising the initial air pressure led to higher exhaust gas temperatures for both LDO and WAO. When comparing the indicated CO₂ emission values, it was observed that LDO exhibited a higher level of emissions in comparison to WAO. Furthermore, it was observed that waste motor oils demonstrated elevated levels of hydrocarbon emissions when compared to low-density oil (LDO). Moreover, it was observed that the heat transfer proportion to the combustion wall was higher in the case of WAO compared to LDO. Variations in heat release at a higher parity ratio can explain the observed difference in radial flame temperature between the WAO and LDO. The presence of a greater carbon content within the chemical composition of waste motor oils was observed to result in a heightened flame intensity in comparison to diesel oil. In summary, this research offers valuable insights into the combustion properties of Waste Automotive Oil as a potential alternative fuel in comparison to conventional Light Diesel Oil. The results of this study make a valuable contribution to the ongoing endeavors aimed at identifying sustainable solutions to the challenges presented by conventional fossil fuels. These challenges include their limited availability and the negative environmental consequences they entail.

Keywords— Alternative fuels, Combustion characteristics, Environmental impacts, Environmental impacts, and Waste Automotive Oil (WAO).

1. INTRODUCTION

Global energy consumption has continued to increase in recent years, with total primary energy demand growing at an average annual rate of 2.3% between 2010 and 2018 [1]. Fossil fuels still dominate the energy mix, accounting for around 80% of total primary energy supply [2]. However, oil, natural gas and coal reserves are ultimately finite, geographically restricted and their continued use raises serious environmental issues [3-5].

Burning of fossil fuels remains the prime anthropogenic source of air pollutants and carbon emissions driving climate change [6-8]. Extreme weather events and changing weather patterns tied to global warming have intensified in recent years [9-11]. Energy security concerns also persist due to the uneven distribution and trade of fossil fuel resources [12,13]. Oil price volatility and supply disruptions continue to have macroeconomic consequences [14-16].

These factors have driven research and adoption of renewable energy sources. Considerable progress has been made in first generation biofuels from sugar, starch and oil crops [17,18]. However, their large-scale use competes with food production and requires significant land and water resources [19-21]. Hence, focus has shifted to advanced biofuels from non-food biomass including lignocellulosic materials, municipal waste, used cooking oil and algae [22-25]. Recent techno-economic assessments find waste cooking oil and algal oils to be attractive and relatively low-cost feedstocks for biodiesel production [26-28]. Additionally, direct combustion of waste vegetable oils in furnaces and boilers can displace fossil fuel use [29-31]. Detailed studies comparing key fuel properties and combustion characteristics of waste oils to petroleum fuels remain vital [32-36]. This study aims to address these open questions by conducting a direct experimental comparison of WAO and light diesel oil (LDO) combustion in a test furnace under varying conditions. The key research objectives are to Measure and contrast flame temperatures, pollutant emissions, and thermal efficiencies. Also, Elucidate the impacts of fuel chemical composition and physical properties on observed combustion characteristics. Determine the feasibility and potential of WAO as an alternative to replace or supplement diesel fuels. Fulfilling these aims will provide novel insights into WAO combustion properties and its viability as a sustainable fuel option. Findings will advance knowledge on substituting WAO in combustion systems previously designed for diesel fuels.

2. PROPERTIES OF WASTE AUTOMOTIVE OIL

Waste automotive oil, referring to contaminated lubricating oils previously used in internal combustion engines, possesses a number of properties that differ significantly from fresh engine oils or diesel fuels and present challenges for its use as a fuel substitute. In particular, waste automotive oils exhibit higher densities ranging from 0.87-0.95 g/cm³, substantially increased viscosities from 100-500 cSt due to accumulation of combustion byproducts compared to 10-20 cSt in fresh oils, lowered flash points below 100°C owing to fuel dilution and volatiles loss, variable chemical compositions containing oxidation products, metals, residues and additives dependent on engine types, reduced heating values around 35-40 MJ/kg versus approximately 45 MJ/kg for diesel fuels, heightened acidity with acid numbers of 3-7 mg KOH/g arising from hydrocarbon oxidation to carboxylic acids, and contamination from chlorinated compounds, paint, plastics, and heavy metals. The elevated viscosity, corrosion from acidity, decreased energy density, and prevalence of impurities present significant challenges for waste oil combustion and

emission performance that necessitate careful evaluation and treatment before these oils can serve as effective substitutes for conventional liquid fuels. In summary, while waste automotive oils hold potential as alternative fuels, their specific properties must be analyzed in detail to determine viability as substitutes for typical diesel fuels as shown in Table 1.

Table 1 Properties of waste automotive oil [5]

Property	Typical Value
Density	0.87 - 0.95 g/cm ³
Viscosity	100 - 500 cSt
Flash Point	< 100°C
Heating Value	35 - 40 MJ/kg
Acid Number	3 - 7 mg KOH/g

Table 2 quantitatively compares the chemical and physical properties of waste automotive oil and light diesel oil. In comparison to diesel fuel, waste oil possesses inferior fuel properties such as increased density and viscosity. Specifically, the heating value of waste oil becomes reduced due to contaminants accumulated from previous use. Oxidation of the waste oil lowers the cetane number. Furthermore, waste oil exhibits heightened levels of sulfur, ash, carbon residue, and acidity relative to diesel fuel standards. The flash point decreases as well in waste oil because of dilution by residual fuels. In summary, key fuel performance metrics like density, viscosity, heating value, cetane number, contaminants, acidity, and flash point are negatively impacted in waste oils compared to diesel fuels. These inferior fuel properties present technical challenges for direct substitution of waste oils in diesel engines and would necessitate upgrading of waste oils to improve fuel quality before they could be utilized as effective diesel replacements.

Table 2 Chemical and Physical properties of waste Automotive oil and light diesel oil [13]

Properties	Light Diesel Oil	Waste Automotive Oil
Density at 15°C (kg/m ³)	830-860	0.87-0.95
Viscosity at 40°C (cSt)	2-4.5	100-500
Lower heating value (MJ/kg)	43	35-40
Cetane number	40-55	15-30
Sulfur content (ppm)	<500	1000-5000
Carbon residue (%)	0.1	0.5-2.0
Ash content (%)	<0.01	0.1-0.4
Flash point (°C)	>55	<100
Acid number (mg KOH/g)	<0.6	3-7

Gas chromatography analysis reveals the fatty acid profile of waste automotive oils shifts significantly from fresh lubricants due to engine use. Saturated acids like palmitic and stearic increase through oxidation while unsaturated acids including oleic and linoleic decline as shown in Table 3. Contaminants from combustion, dilution, breakdown of oils, and environmental pollutants also accumulate, altering the composition away from original oil formulations. The complex mixture presents technical challenges for direct use as fuel.

Table 3 Fatty Acid Composition for waste Automotive oil [13]

Fatty Acid Methyl Ester	Fatty Acid Composition (wt. %)
Palmitic acid (C16:0)	15-20
Stearic acid (C18:0)	5-10
Oleic acid (C18:1)	15-30
Linoleic acid (C18:2)	10-15
Linolenic acid (C18:3)	1-5
Erucic acid (C22:1)	<5
Lignoceric acid (C24:0)	<2
Other/unidentified	15-30

The automobile oils contain a complex mixture of fatty acids and other organic compounds that differ significantly from the composition of the original lubricating oil. Specifically, saturated fatty acids including palmitic and stearic acids are increased in waste oils as the base oil undergoes oxidation during engine operation. In contrast, unsaturated fatty acids such as oleic and linoleic acids are reduced because the C=C double bonds are broken through oxidation reactions. Polyunsaturated linolenic acid is particularly susceptible to hydrolysis under oxidative conditions. Longer chain fatty acids such as erucic and lignoceric acids may also be introduced from fuel residues and oil additives. In addition, oxidation processes generate other organic compounds not attributable to specific fatty acid peaks. Contaminants from combustion and contamination also contribute to compounds detected in chemical analysis. In summary, the fatty acid profile of waste motor oils shifts significantly away from the original lubricant formulations due to oxidation, fuel dilution, further breakdown, and environmental pollutants accumulating during use in engines.

3. EXPERIMENTAL TESTING FACILITIES

These experiments were conducted in the Continuous Combustion Laboratory, Department of Power Mechanics, College of Engineering Technology, Najaf, Al-Furat Al-Awsat University. Fig1 shows the schematic diagram of the experimental setup. The system consists of a heavy oil burner with a heating load of 150 kW.



Fig. 1 Experimental design of the burner

Three repeated tests were performed at each equivalence ratio for both diesel and waste oil to evaluate consistency. Fuel was supplied from separate tanks through a gravity feed system at a constant flow rate of 2 ml/min and monitored with a rotameter. Temperatures were recorded using a K-type thermocouple with an uncertainty of $\pm 1^\circ\text{C}$. Exhaust emissions were measured using a portable gas analyzer with a $\pm 2\%$ uncertainty for CO_2 , CO and NO_x readings.

Uncertainty analysis was performed on the calculated combustion efficiency and heat transfer values based on standard error propagation methods. The measuring equipment was calibrated prior to testing and calibration curves were used to account for instrument uncertainties. The data in each condition of the replicate tests were averaged to improve consistency in the results. The standard deviations were less than 2.5% of the mean values, indicating good repeatability.

The burner is cylindrical with a diameter of 6 inches and contains a cylindrical head with a diameter of 2 in and a length of 18 cm. It contains holes with a diameter of 3 mm and a number of 33. The burner is supplied with air using a fan. It is equipped with an automatic control system in the air mass flow rates. Fuel is supplied by gravity using a separate fuel tank connected to the combustion chamber of the burner. Where the fuel is burned up to 90°C as an initial burn to heat it, and then the air is expelled through the holes in the burner head at certain flow rates, and a thermostat to adjust to the required temperature (depending on the type of fuel). The burner is inserted vertically into the combustion chamber for use in various industrial applications.

4. RESULTS AND DISCUSSIONS

The exhaust emissions analysis reveals some key advantages of using waste automotive oil (WAO) as an alternative fuel compared to light diesel oil (LDO) under different equivalence ratios. WAO demonstrated substantially lower carbon monoxide (CO) emissions, with a maximum reduction of 71.4% observed at an equivalence ratio of 0.94. The elevated oxygen content of WAO improves oxidation reactions, facilitating more complete combustion and conversion of CO to CO_2 . However, elevated WAO viscosity led to issues with improper fuel-air mixing, resulting in around 72% higher unburned hydrocarbon emissions relative to LDO. This indicates the need for enhanced injection systems and atomization methods optimized for WAO's higher viscosity. WAO did provide the benefit of reduced NO_x emissions attributed to its lower combustion temperatures. For both fuels, exhaust gas

temperatures increased with higher primary air pressures as greater fuel mass flow rates were achieved. The thermal heat balance calculations revealed the percentage of heat transferred to the combustor walls was consistently higher for WAO fuel compared to LDO, with a maximum rise of 12% observed. This divergence suggests increased heat loss associated with WAO combustion, likely resulting from its higher fuel consumption and the impact of its elevated viscosity. Greater heat transfer to the walls may also relate to differences in flame geometry between the fuels. Optimizing the combustor insulation and cooling design could help reduce excessive WAO heat loss to improve thermal efficiency.

The in-flame temperature analysis showed that for both WAO and LDO, increasing primary air pressure led to higher in-flame temperatures attributed to greater heat release rates. However, peak in-flame temperatures were generally greater for WAO, especially at higher equivalence ratios where its central in-flame temperatures exceeded those of LDO. The improved oxygenation of WAO facilitates more energetic combustion reactions upon sufficient heating, despite its lower heating value relative to LDO. The study also found radial in-flame temperatures declined moving outwards from the center for both fuels due to the cooling effect of the water-jacketed combustor walls. Visual observation of the combustion flames revealed key distinctions between WAO and LDO.

LDO exhibited wider, more luminous and soot-laden yellowish flames compared to dimmer blue flames for oxygenated WAO. The increased luminosity and sooting arise from LDO's higher carbon content. Superior fuel-air mixing in WAO flames due to intrinsic oxygen enables cleaner, more complete combustion. However, the narrowing of WAO flames suggests potential issues with flame stability that should be addressed through combustor design modifications. Swirl injection, chamber geometry and flow turbulence should be optimized for WAO's viscosity. While WAO has some technical challenges remaining, it demonstrates viability as an alternative fuel with the advantage of substantially lower emissions of pollutants like CO, NO_x and soot compared to conventional diesel fuels. Further efforts to engineer improved combustors tailored to WAO's unique fuel properties are recommended to enhance performance as shown in Fig 2 to Fig 6.

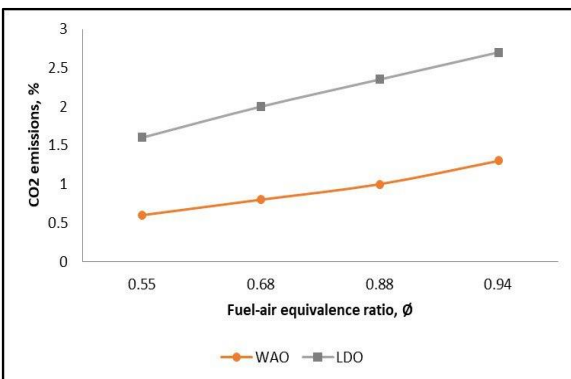


Fig 3 CO₂ Emissions for Waste Cooking Oils and Diesel Fuels at Varying Fuel-Air Equivalence Ratios

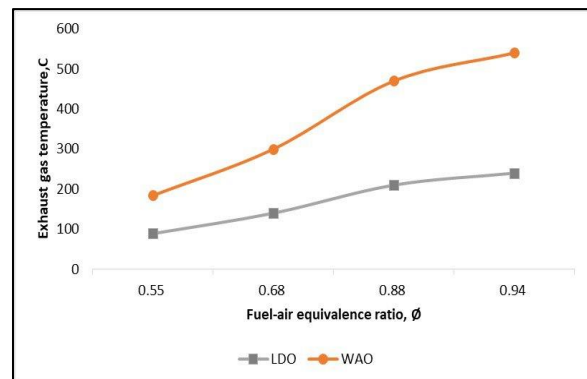


Fig 2 Effects of Air Pressure on Exhaust Gas Temperatures across Fuel-Air Equivalence Ratios

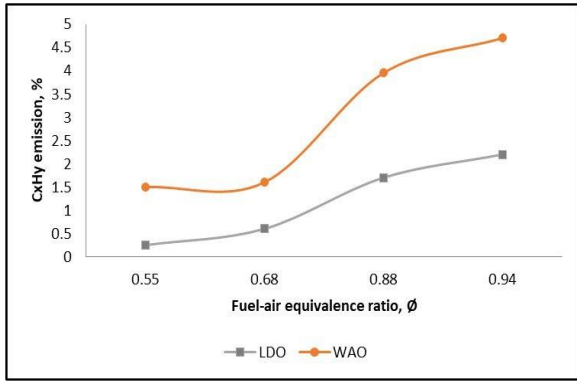


Fig 6 Hydrocarbon Emissions across Varying Fuel-Air Equivalence Ratios

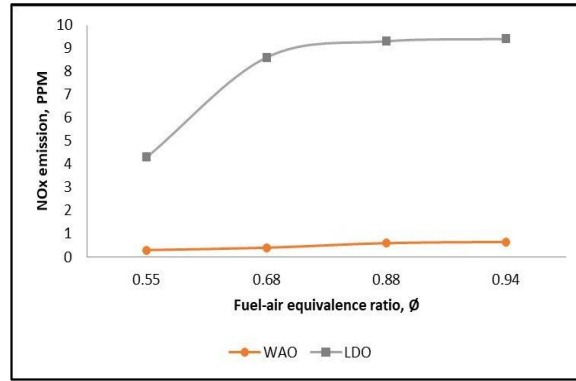


Fig 5 NO_x emissions at different equivalence ratios.

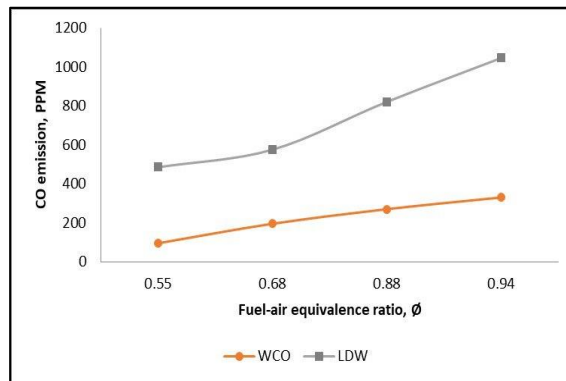


Fig 4 CO emissions at different equivalence ratios.

Looking at thermal heat balance, the percentage of heat transferred to the combustor walls increased for WAO compared to LDO, with a maximum rise of 12% for WAO. This heat transfer difference can likely be explained by WAO's higher fuel consumption and subsequent increased heat loss. The study also analyzed in-flame temperatures radially from the center to the cooled combustor walls. Here, in-flame temperatures increased with primary air pressure for both LDO and WAO, but were higher for WAO due to greater heat release. At higher equivalence ratios, in-flame temperatures were greater in the center for WAO compared to LDO.

Finally, visual analysis of the flames revealed key differences between LDO and WAO. LDO flames were wider, more luminous, and yellow/orange in color - indicating more soot compared to the less luminous WAO flames. The authors attributed the cleaner, bluer WAO flames to improved fuel-air mixing from oxygen content, allowing more complete combustion as shown in Fig 7 and Fig 8.



Fig 7 Effect of primary air pressure on flame visual observation of WCO



Fig 8 Effect of primary air pressure on flame visual observation of LDO

5. CONCLUSION

In conclusion, this study provides valuable insights into the combustion properties and feasibility of using Waste Automotive Oil (WAO) as an alternative fuel compared to conventional Light Diesel Oil (LDO).

The key findings show that WAO demonstrated substantially lower carbon monoxide and nitrogen oxide emissions due to its higher oxygen content enabling more complete combustion. However, WAO did produce higher levels of unburned hydrocarbons resulting from its higher viscosity and improper fuel-air mixing. WAO also showed increased heat transfer to the combustor walls attributed to greater fuel consumption and heat loss.

Analysis of in-flame temperatures and visual flame characteristics revealed additional differences between the fuels. WAO exhibited higher in-flame temperatures at increased primary air pressures and equivalence ratios because of greater heat release. Flame imaging showed LDO had wider, more luminous and sooty flames compared to the cleaner, bluer flames of WAO.

In summary, while challenges remain regarding viscosity, atomization, and unburned hydrocarbons, WAO shows promise as an alternative fuel with comparable or improved performance over conventional diesel oil in key aspects like lower emissions of pollutants. With further research to optimize fuel properties and design improved combustors tailored to WAO, waste automotive oils could prove to be an effective and more sustainable substitute for diesel fuels. The insights from this study make a valuable contribution to ongoing efforts assessing and developing alternative fuels to address the environmental and supply issues associated with continued fossil fuel dependence.

6. REFERENCES

- [1] D. Singh, D. Sharma, S. L. Soni, S. Sharma, and D. Kumari, “Chemical compositions ,properties , and standards for different generation biodiesels : A review,” *Fuel*, vol.253, no. May, pp. 60–71, 2019.
- [2] P. K. Sharma et al., “Characterization of the non-road modified diesel engine using anovel Entropy-VIKOR approach: Experimental investigation and numericalsimulation,” no. c, 2019.
- [3] V. S. Yadav, D. Sharma, and S. L. Soni, “ScienceDirect Performance and combustionanalysis of hydrogen-fuelled C . I . engine with EGR,” *Int. J. Hydrogen Energy*, pp. 1–10, 2015.
- [4] A. J. & D. S. & S. L. S. & P. K. S. & S. Sharma1, “A comprehensive review on water-emulsified diesel fuel : chemistry , engine performance and exhaust emissions,”*Environ. Sci. Pollut. Res.*, 2019.
- [5] C. Bae and J. Kim, “Alternative fuels for internal combustion engines,” *Proc.Combust. Inst.*, vol. 36, no. 3, pp. 3389–3413, 2017.
- [6] K. Dev, A. Nayyar, and M. S. Dasgupta, “E ff ect of compression ratio on combustionand emission characteristics of C . I . Engine operated with acetylene in conjunctionwith diesel fuel,” *Fuel*, vol. 214, no. June 2017, pp. 489–496, 2018.
- [7] S. Sharma, D. Sharma, S. L. Soni, D. Singh, and A. Jhalani, “Performance ,combustion and emission analysis of internal combustion engines fuelled withacetylene – a review,” vol. 0750, 2019.
- [8] R. Raman and N. Kumar, “The utilization of n-butanol / diesel blends in AcetyleneDual Fuel Engine,” *Energy Reports*, vol. 5, pp. 1030–1040, 2019.
- [9] M. S. P. P. V Manieniyar, “Emission reduction in diesel engine with acetylene gas andbiodiesel using inlet manifold injection,” *Clean Technol. Environ. Policy*, no. x, 2020.
- [10] P. Dimitriou and T. Tsujimura, “ScienceDirect A review of hydrogen as a compressionignition engine fuel,” *Int. J. Hydrogen Energy*, pp. 1–17, 2017.
- [11] S. Basha, P. Rao, K. Rajagopal, and R. Kotturi, “Design and analysis of swirl inacetylene aspirated diesel engine and its effects on performance & emissions,” *Int. J.Latest Trends Eng. Technol.*, vol. 8, no. 2, pp. 390–399, 2017.
- [12] J. Al-naffakh, M. Al-Qassab , Experimental Investigation of Blending Acetylene with Iraqi LPG to Determine a Flame Stability Map. <https://doi.org/10.52716/jprs.v12i1.607>
- [13] İ. Mehmet, R. Do, and S. Orhan, “Experimental study on an SI engine fueled bygasoline , ethanol and acetylene at partial loads,” vol. 261, no. May 2019, 2020.
- [14] E. Vural and S. Özer, “Buji Ateşlemeli Motorlarda Yakıtta Asetilen Gazı İlavesininEgzoz Emisyonlarına Etkisinin Deneysel Analizi The Experimental Analysis of theEffect of Acetylene Gas Addition to the Fuel on Exhaust Emissions in Spark IgnitionEngines,” *BEU J. Sci.*, vol. 3, no. 1, pp. 24–34, 2014.
- [15] M. O.f and H. Education, “STUDY OPERATION OF STEAM GENERATIONSYSTEM USING

DIFFERENT FUELS Asst . Prof . Dr . Wisam A . Abd Al-Wahid June 2020 Lecturer . Dr . Hasan Hadi Salman,” 2020.

- [16] M. T. Chaichan, J. A. Kadhum, and K. S. Riza, “Spark Ignition Engine Performance When Fueled with NG , LPG and Gasolin,” Saudi J. Eng. Technol., pp. 105–116, 2016.
- [17] C. Sayin and M. Canakci, “Effects of injection timing on the engine performance and exhaust emissions of a dual-fuel diesel engine,” Energy Convers. Manag., vol. 50, no.1, pp. 203–213, 2009.
- [18] “Iraqi standard specification for LPG fuel., <http://www.zanagas.com/English/information/lpg-in-iraq>.
- [19] B. L. and G. VON ELBE, Combustion Flames and Explosions of Gases., vol. 31, no.1. New York, 1988.
- [20] J. Truffaut, J. Quinard, A. Wangher, and G. Searby, “Experimental and numerical study of premixed flame flashback,” Sci. direct, vol. 31, pp. 1275–1282, 2007.
- [21] P. Sayad, A. Schönborn, and J. Klingmann, “Experimental investigation of the stability limits of premixed syngas-air flames at two moderate swirl numbers,” Combust. Flame, vol. 164, pp. 270–282, 2016.
- [22] B. Shaffer and V. McDonnell, “Study of Fuel Composition Effects on Flashback Using a Confined Jet Flame Burner,” J. Eng. Gas Turbines Power, vol. 135, no. January, pp. 1–10, 2013.
- [23] X. X. Tag and D. X. X. Vincent, “Boundary layer flashback of non-swirling premixed flames : Mechanisms , fundamental research , and recent advances,” Prog. Energy Combust. Sci., vol. 61, 2017.
- [24] M. Al-fahham, A. V. Medina, and R. Marsh, “Experimental Study to Enhance Resistance for Boundary Layer Flashback in Swirl Burners Using Microsurfaces,” in Turbomachinery Technical Conference and Exposition, 2017, pp. 1–10.
- [25] P. Taylor, S. Chaudhuri, and B. M. Cetegen, “Combustion Science and Technology Blowoff Characteristics of Bluff-Body Stabilized Conical Premixed Flames in a Duct with Upstream Spatial Mixture Gradients and Velocity Oscillations,” Combust. Sci. Technol., no. October 2014, pp. 37–41, 2009.
- [26] M. Li, Y. Tong, M. Thern, and J. Klingmann, “Investigation of methane oxy-fuel combustion in a swirl-stabilised gas turbine model combustor,” Energies, vol. 10, no.5, 2017.
- [27] Mohammed Al-Fahham and Qahta, Jameel Al-Naffakh, “Experimental Investigate the Effect of Burner Geometry on the Operation Window of the Burner,” Energy Res. J., pp. 3–6, 2019.
- [28] J. Al-naffakh, M. Al-fahham, and Q. A. Abed, “Burner rim geometry effect on flame stability,” in IOP Conference Series: Materials Science and Engineering, 2020.
- [29] Q. A. A. Jameel Al-Naffakh, Mohammed Al-fahham, “The blowoff limits and flashback limits for

- different diameter to length ratio burner,” Multi-KnowledgeElectron. Compr. J. Educ. Sci. Publ. (MECSJ), vol. 9, no. 24, pp. 1–11, 2019.
- [30] A. V.-M. a Fares A. Hatema, b, Ali S. Alsaegha, c, Mohammed Al-Fahama, d, “Enhancement flame flashback resistance against CIVB and BLF in swirl burners,” Energy Procedia, vol. 142, pp. 1071–1076, 2017.
- [31] Zhang, M.; Hu, Y.; Wang, H.; Li, H.; Han, X.; Zeng, Y.; Xu, C.C. A review of bio-oil upgrading by catalytic hydrotreatment: Advances, challenges, and prospects. Mol. Catal. 2021, 504, 111438, <https://doi.org/10.1016/j.mcat.2021.111438>.
- [32] Iribarren, D.; Peters, J.F.; Dufour, J. Life cycle assessment of transportation fuels from biomass pyrolysis. Fuel 2012, 97, 812–821, <https://doi.org/10.1016/j.fuel.2012.02.053>.
- [33] Zhu, C.; Gamliel, D.P.; Valla, J.A.; Bollas, G.M. Fischer-tropsch synthesis in monolith catalysts coated with hierarchical ZSM-5. Appl. Catal. B Environ. 2020, 284, 119719, <https://doi.org/10.1016/j.apcatb.2020.119719>.
- [34] Akorede, M.F.; Hizam, H.; Pouresmaeil, E. Distributed energy resources and benefits to the environment. Renew. Sustain. Energy Rev. 2010, 14, 724–734, <https://doi.org/10.1016/j.rser.2009.10.025>.
- [35] Resasco, D.E.; Wang, B.; Sabatini, D. Distributed processes for biomass conversion could aid UN Sustainable Development Goals. Nat. Catal. 2018, 1, 731–735, <https://doi.org/10.1038/s41929-018-0166-6>.
- [36] Chen, G.; Liang, L.; Cheng, Z. Upgrading of Bio-Oil Model Compounds and Bio-Crude into Biofuel by Electrocatalysis: A Review. ChemSusChem 2021, 14, 1037–1052, <https://doi.org/10.1002/cssc.202002063>.