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The Effect of Carbon Nanotubes on Emitted Pollutants from a Domestic Boiler Powered by Diesel and Biodiesel Fuels

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ABSTRACT

In the present study, the effect of biofuel and nano biofuel on the performance of a domestic boiler was investigated and compared with the pollutants emitted during the burning of diesel fuel. The biofuel was produced from waste cooking oil using potassium hydroxide (KOH) as a catalyst. Carbon nanotubes (CNT) with different concentrations of 0.05% /L, 0.1% /L, 0.15% /L, 0.2% /L, and 0.25% /L were added to the produced biodiesel to form a nano biofuel that was used to power a domestic boiler for demonstration purposes. The obtained performance results were compared using the same boiler when operating with biofuel and nano biofuel, respectively. When operated with different CNT concentrations, the emitted species from the boiler were also investigated by sampling the exhaust gases in each studied case. This study revealed that the performance of the boiler when operated with CNT was enhanced by decreasing the toxic emitted gasses and increasing the outlet water temperature compared to the case of the boiler with the biofuel alone. It increased the outlet water temperature and decreased the NO_x (ppm) emissions.

Keywords: domestic boiler, diesel, biodiesel, carbon monoxide, nitrogen oxide.

INTRODUCTION

Domestic boilers are a significant source of emissions, particularly of pollutants such as particulate matter, carbon, sulfur, and nitrogen oxides. These species have a detrimental impact on the environment and human health. Reducing these emitted species helps mitigate their negative impact on air quality and overall environmental health. Alternatively, biodiesel has multiple advantages over traditional diesel fuel as a renewable and environmentally friendly alternative. Biodiesel is produced from renewable resources, such as vegetable oils, animal fats, or recycled cooking grease. This fuel is typically produced by converting fats and oils through a chemical process known as transesterification, where fatty acids (fats and oils) are reacted with an alcohol – most commonly methanol – to make methyl esters. Kulkarni et al. [2006] showed that waste cooking oil can be readily converted into biodiesel using various processing techniques and tested the biodiesel in a common diesel engine. Additionally, researchers also observed the fundamental chemical processes occurring during frying and how the resultant substances produced during frying affected the quality of biodiesel. Tondo et al. [2017] explored utilizing diesel blends using biodiesel derived from frying oil. The room temperature diesel blends containing soda spanned from B0 to B100 in ten percent increments, while heated to 50.63 °C. The blends measured parameters such as density, viscosity, calorific value, and fuel consumption, which provided information about the delivered power. Without preheating, the blend with liquid fuel is driven down, because fuel consumption rose as a function of the proportion of the mix of the fuel blend. However, preheating showed an increased power level. As a result, the power output decreases when using biodiesel without preheating are relatively small compared to using conventional diesel oil. When using preheating, the power decreases substantially.

Ayodeji et al. [2018] studied the production of biodiesel from soybean oil using a transesterification process. For this purpose, they examined how various processing conditions, including the ratio of methanol/oil, catalyst concentration, and reaction time, affected the biodiesel yield. The X-ray fluorescence (XRF) determined that the calcium oxide composition of the eggshell catalyst increased from 96 to 97% after the calcination process. Furthermore, the researchers found that the biodiesel yields exhibited similar trends after processing with both the calcined eggshell catalyst and the pure CaO catalyst.

Kumar et al. [2018] reviewed the latest approaches in the development of enzyme-based biofuel cells (EBCs) for designing cells to operate on glucose biofuel. The article also highlighted the type of nanomaterials employed in the design of the EBCs as well as other astounding developments. They planned to address the features of the biofuel cell system with an emphasis on the use of nanoparticles for creating novel electrodes and their fabrication. In order to give details of the latest development, they used a table that described enzymatic system mediators, bio-sensing electrodes and output power density.

Ghorbani et al. [2011] investigated the production of biodiesel and petroleum diesel using various blends in an experimental boiler. This comparison specifically focused on two key aspects: the efficiency of combustion and the emissions of flue gases. The study also investigated the influence of varying airflow rates at two different energy levels, specifically 219 kJ/h and 249 kJ/h. The findings revealed that, at a higher energy level, diesel exhibited slightly better combustion efficiency than biodiesel. However, at the lower energy level, biodiesel outperformed diesel in terms of efficiency. Except for B10, biodiesel and other blends emitted fewer pollutants, including CO, SO_2, and CO_2, compared to diesel. B10 had lower emissions of CO_2 and NO_x but higher levels of SO_2 when compared to diesel.

A research investigation was carried out to assess the generation of nitrogen oxide (NO) in a non-pressurized combustion chamber with water cooling. Bazooyar et al. [2016] researched non-blended biofuel and modified biofuel, the NO amounts generated in the combustion involved estimating quantities of NO concentrations in the exhaust gases under various operational conditions of the burner. The subsequent phase involved measuring and comparing thermal and prompt NO results for six different biodiesel methyl esters as well as pure petroleum diesel. The primary objective was to determine the factors that had a substantial role in the emission of thermal and prompt NO differentiating these different burns of fuels.

Hamdan and Almomani [2015] used a household boiler as a test setup to measure its performance when fueled by pure diesel fuel or diesel from rapeseed oil biodiesel. They evaluated the efficiency and exhaust gas balance using complete combustion and other algorithms, essentially evaluating the boiler performance on fuel, NO_x, NO_2, NO, SO_2, CO_2, and HC. The results demonstrated a decrease in boiler performance when using biodiesel fuel, accompanied by an increase in specific fuel consumption. However, the boiler performance with the B20, B5, and B10 blends exhibited comparable fuel consumption and efficiency to that observed with petroleum diesel fuel. Furthermore, the emissions from biodiesel fuel were found to be more environmentally friendly compared to those from petroleum diesel, as the concentrations of all pollutants decreased with higher proportions of biodiesel in the blends.

Zhang et al. [2017] analyzed the cost and benefit of retrofitting a waste heat recovery system in a biodiesel production facility. The assessment was done to determine the economic and environmental impact of the integration of the waste heat recovery system into the biodiesel plant by comparing the simulation results obtained from Aspen Plus and Aspen Economic Analyzer. It was established that the application of waste heat recovery retrofits helps to attain the goal of decreasing the CO_2 emissions of biodiesel plants. However, the economic benefits of these changes needed to be understood, since such retrofitting could lead to costly penalties.

Bahadorizadeh et al. [2022] examined emissions from a semi-industrial boiler operated via waste cooking oil biodiesel (WCO) containing various nanoparticles (CeO_2, Al_2O_3, and Co_3O_4). In their studies, they identified the proportions of WCO biodiesel mixed with additives at fifty parts per million of cerium oxide, cobalt oxide, and aluminum oxide known as B-Ce-Co-Al50 that emitted the least CO. The emissions of CO from this specific fuel blend were considerably lower by 74% than the emissions from the pure diesel and 43% than that from the WCO biodiesel. Moreover, one B-Ce-Co100 fuel blend containing WCO biodiesel with 100 ppm of cerium oxide and cobalt oxide showed the lowest flame temperature and the least amount of NO_x emission. The NO_X emissions from this fuel blend were lower than those from diesel fuel standards by 10 percent and WCO biodiesel by 39 percent.

Alahmer et al. [2023] performed and studied the effect of adding, 5–30% water and 2% polysorbate 20 on brake torque and the engine quartet. They employed support vector regression (SVR) with machine learning and the sea-horse optimizer (SHO) to identify that 15% water addition at 1848 rpm yielded an optimal BT and minimized the emissions of CO, UHC, and NO_x. The SVR-SHO model was found more reliable with an R-squared of value greater than 0.98 and a low MSE below 0.003, and hence, has the possibility of enhancing the performance of an engine and reducing the level of emissions.This study demonstrated that incorporating CNT into biodiesel improved the boiler performance. The research examined the boiler emissions and monitored the outlet water temperature for each sample. The results indicated that the most favorable outcomes were achieved when 0.25% CNT was mixed with biodiesel, resulting in the lowest emissions of carbon monoxide (CO) and nitrogen oxides (NO_x) and the highest outlet water temperature.

MATHERIAL AND METHODS

Biofuel was produced with the WCO collected from the University of Jordan restaurant. The product was mixed with methanol in a small bottle with a ratio of (1:9) for a few seconds to ensure that the produced component was pure biodiesel. The operation success was measured by the successful conversion if the biodiesel was dissolved in methanol. However, if the product did not dissolve, the conversion failed and needed more washing until biodiesel dissolved. On the other hand, the triglyceride does not dissolve in methanol.

After producing a significant quantity of biodiesel, 30 liters were obtained from 50 liters of waste cooking oil (WCO). This biodiesel was then combined with CNT to evaluate the performance of a boiler. To observe the behavior of the boiler, CNT was mixed with the biodiesel at five different concentrations: 0.05%/L, 0.1%/L, 0.15%/L, 0.2%/L, and 0.25%/L. The experiment employed an electronic scale with specific specifications: a maximum capacity of 120 g, a minimum sensitivity of 10 mg, an increment of 1 mg, and a decimal precision of 0.1 mg. Each concentration was tested individually. Due to the lightweight nature of the CNT, precautions were taken during the weighing process to isolate it from any air disturbance that could affect the measurements. Since the CNT particles were solid and not sufficiently heavy to settle, achieving a homogeneous mixture posed no issues. The experiment was performed using the configuration depicted in Figure 1. This setup primarily comprises a domestic boiler, a gas analyzer, a load (in this case, a domestic radiator),

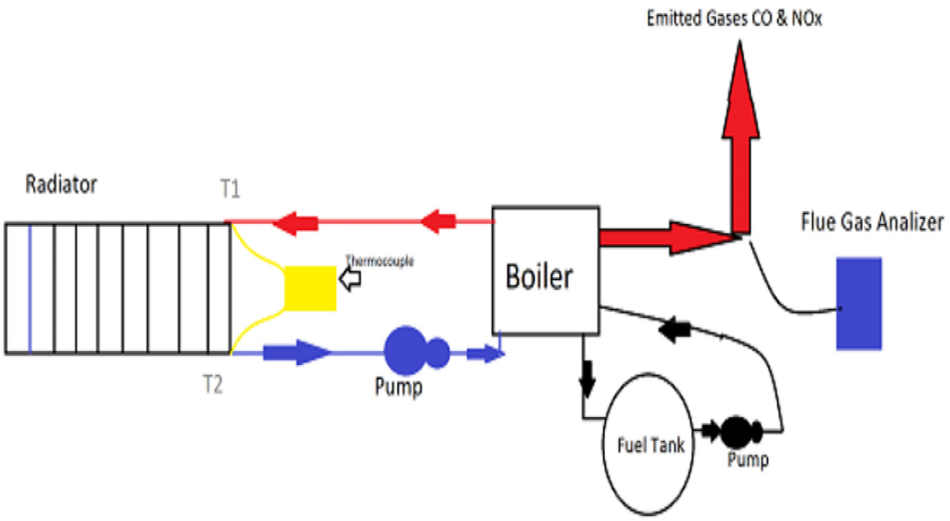

Figure 1. Boiler schematic diagram

and a fuel tank. In the initial phase, a domestically manufactured domestic boiler was operated using pure diesel fuel, and the mass flow rate of the fuel was measured using a flowmeter. Once steady-state conditions were achieved (indicated by a constant water outlet temperature, measured with a K-type thermocouple), samples were extracted from a specific location along the chimney to measure the concentrations of CO, CO_2, and NO_x using a gas analyzer. This procedure was repeated when the boiler was powered by both produced biodiesel fuel and nan biofuel, with varying concentrations of CNT.

In the present work, tests were conducted using pure-produced biofuel and blends of biodiesel and five different concentrations of CNT; these concentrations are 0.05, 0.1, 0.15, 0.2, and 0.25 % by volume. During each test, the emitted concentration of carbon monoxide (which indicated how complete the combustion process was) and nitrogen oxides (which sums up both thermal and prompt) were functions of CNT concentration and the outlet water temperature (which gives insight into the combustion temperature).

RESULTS AND DISCUSSIONS

CO emissions

Figure 2 shows the variation of emitted concentration (PPM) of CO with the boiler outlet water temperature. As indicated in the figure, the formation of CO increases with the water outlet temperature and, hence, with the flame temperature inside the combustion zone. This behavior may be attributed to the fact that at high temperatures, carbon dioxide (CO_2) can dissociate into carbon monoxide (CO), a process known as thermal decomposition. This reaction occurs due to the breaking chemical bonds within the CO_2 molecule, driven by the energy provided by the elevated temperatures. It is to be noted that the minimum flame temperature in the Oil-Fired Fuel-Burning boiler is somewhere between 2750 and 2850 °F [Belyea and Holland, 1967].

Different concentrations (0.05%, 0.1%, 0.15%, 0.2%, 0.25%) of CNT fuels with respect to the outlet water temperature from the boiler.

Figure 3, illustrates the variation of the CO emitted with the boiler outlet water temperature as the amount of CNT added to the biodiesel increases from 0.05 to 0.25.% It can be noticed that the CO emissions for pure biodiesel and the biodiesel containing 0.05% of CNT decreased; however, this amount of emitted CO when CNT was added is less than those emitted by pure biodiesel and at all values of water outlet temperatures. Furthermore, it may be noticed from the figure that for a given fixed temperature, the emitted concentration of CO decreases with the added amount of CNT. These findings agree with those of Hosseini et al. [2017]. As indicated, the maximum reduction in the emitted CO is associated with 0.25% concentration of CNT.

This decrease in emitted CO amounts might be attributed to the fact that CNTs can act as catalysts to enhance the oxidation of CO. They possess a high surface area and unique electronic properties, promoting the adsorption and reaction of CO with oxygen. By facilitating the conversion

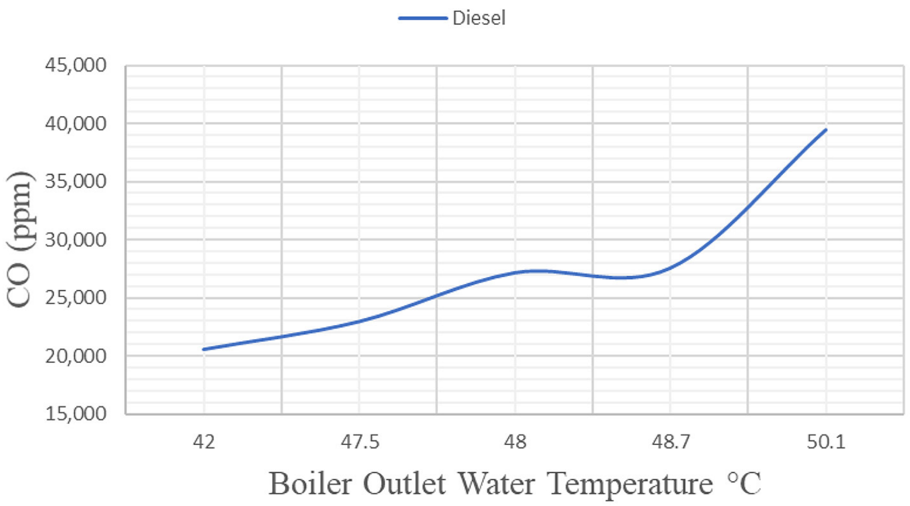

Figure 2. CO emissions with outlet water temperature for diesel

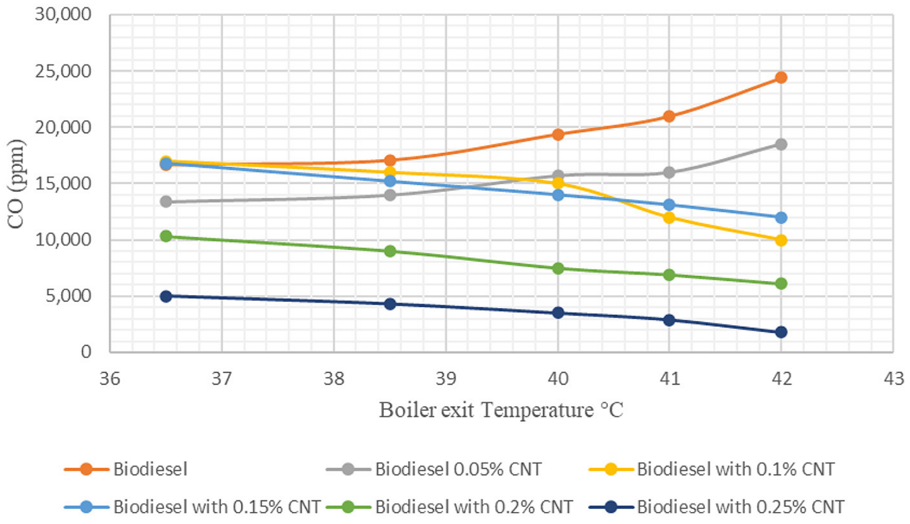

Figure 3. CO emissions with outlet water temperature for biodiesel and biodiesel with different CNT concentrations

of CO to carbon dioxide (CO_2), CNTs can help reduce the amount of CO emitted. In addition to this, when CNTs are incorporated into the fuel or used as additives, they can improve combustion efficiency. The presence of CNTs in the combustion system can enhance the mixing of fuel and air, leading to more complete combustion. Higher combustion efficiency generally results in reduced CO emissions.

Further work was conducted to compare the effect of 0.25% concentration of CNT to that emitted when pure diesel and biodiesel were used to power the boiler. The obtained comparison is presented in Figure 4, which presents the variation of the emitted CO with the outlet water temperature from the boiler when it was powered by diesel, biodiesel, and the biodiesel containing 0.25% of CNT. As indicated in the figure, the amount of CO emitted decreases with increasing the outlet water temperature during the burning of diesel and biodiesel fuel, while lesser emitted amount of CO was observed when biofuel was used compared to when diesel fuel was used. This decrease could be attributed to the higher oxygen content of biodiesel than diesel, which can result in more complete combustion, leading to less CO in the exhaust stream. For investigation purposes, these findings agree with a previous study, which indicated that CV increased with the CNT content in biodiesel [Hosseini et al., 2017]. Biodiesel has more oxygen content, so boiler combustion was complete compared to diesel. Furthermore, it may be realized that, as expected, the amount of CO emitted will decrease further once CNT is added to biodiesel.

NO_x emissions

Figure 5 shows the variation of NO_x emitted while burning pure diesel with the boiler outlet water temperature. As indicated in the Figure, a higher water outlet temperature indicates a more efficient heat transfer from the combustion process to the water. When the thermal efficiency is optimized, it may indirectly contribute to reduced fuel consumption and lower NO_x emissions since a more efficient combustion process can result in better fuel-to-air mixing, improved combustion completeness, and reduced excess air requirements, all of which can help mitigate NO_x formation.

Figure 6 presents the variation of emitted NO_x with the outlet water temperature for different concentrations of added CNT. It can be easily seen that the increase in the outlet water temperature resulted in the decrease of the emitted NO_x. This reduction in the emitted NO_x might be because, when CNTs are introduced into the combustion process, they can act as catalysts and facilitate the selective reduction of nitrogen oxides. CNTs can adsorb nitrogen oxides and promote their conversion to nitrogen gas (N_2) through selective catalytic reduction (SCR) or non-thermal plasma processes. The unique properties of CNTs, such as high surface area and electron conductivity, contribute to their catalytic activity. Furthermore, it may be noticed from this figure that the amount of NO_x emitted at any fixed water outlet temperature decreases with the amount of CNT added to biodiesel fuel.

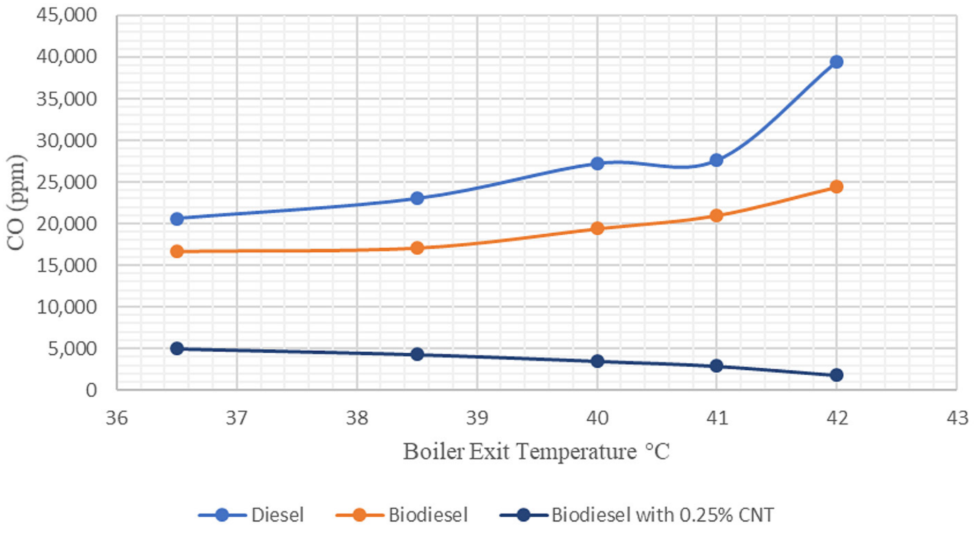

Figure 4. CO emissions with outlet water temperature °C for diesel, biodiesel, and biodiesel with 0.25% CNT

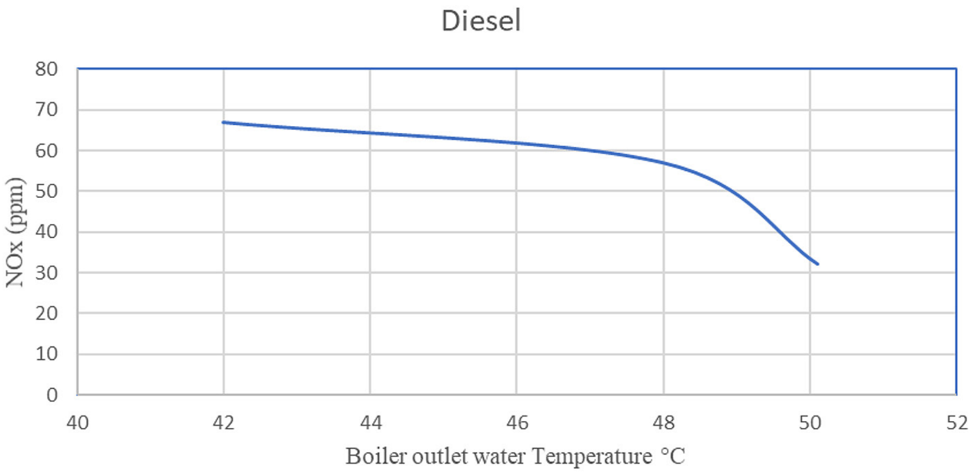

Figure 5. NO$_x$ emissions with outlet water temperature for diesel

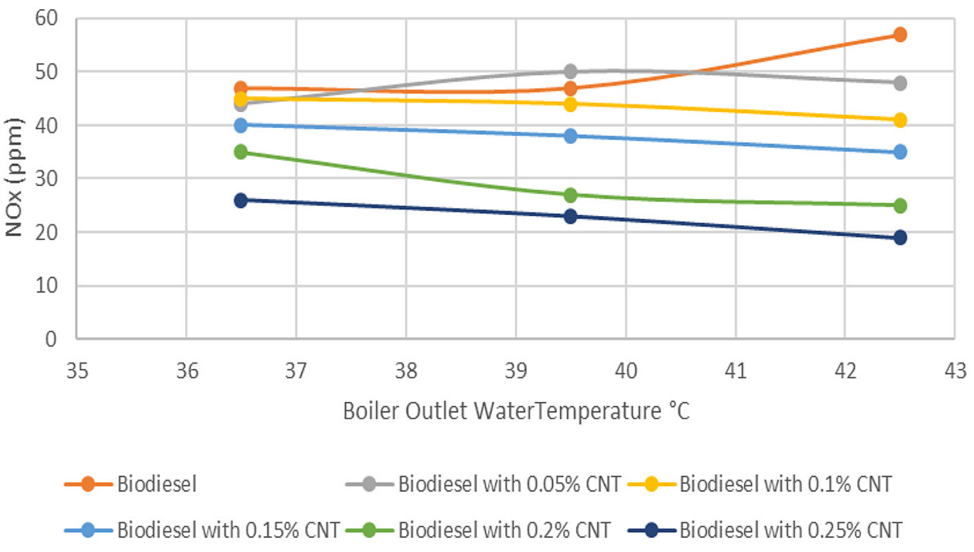

Figure 6. NO$_x$ emissions with outlet water temperature for biodiesel and biodiesel with different CNT concentrations

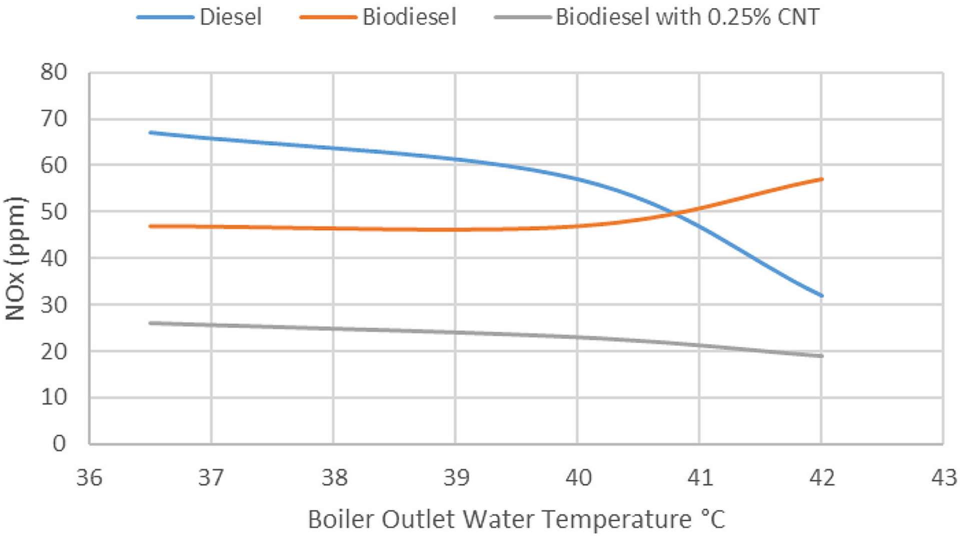

Figure 7. NO_x emissions with outlet water temperature for diesel, biodiesel, and biodiesel with 0.25% CNT concentrations

It is to be noted that when biodiesel powers the boiler, the amount of NO_x emitted increases at higher outlet temperatures. This increase in the emitted NO_x may be attributed to the decrease in the viscosity of biodiesel as the temperature in the combustion chamber increases, leading to the burning of nitrogen compounds in the fuel. This agrees with the findings of [Sathasivam et al., 2014] when they burnt diesel and biodiesel. Figure 7 shows the variation of the NO_x emissions with the boiler outlet temperature during the burning of pure diesel, pure biodiesel, and biodiesel with 0.25% CNT. The figure indicates that the outlet water temperature increased when pure biodiesel powered the boiler. At the same time, the emitted amount of NO_x remained almost constant initially and then increased with the water outlet temperature. On the other hand, when diesel and biodiesel powered the boiler mixed with 0.25% CNT, the boiler outlet water temperature increased while the NO_x decreased. At the boiler full load, the biodiesel contained 0.25% CNT, compared with the Diesel.

CONCLUSIONS

This study investigated the impact of adding CNT to biodiesel fuel in domestic boilers, focusing on emissions and performance. Biodiesel significantly reduced carbon monoxide (CO) emissions compared to diesel, a reduction further enhanced by the catalytic properties of CNTs. However, biodiesel alone increased nitrogen oxide (NO_x) emissions due to higher combustion temperatures. The addition of CNTs mitigated this by facilitating the selective catalytic reduction of NO_x, converting it to nitrogen gas (N_2), and also improved boiler performance by increasing outlet water temperature through enhanced combustion efficiency. Overall, adding CNTs to biodiesel makes it a more environmentally friendly and efficient fuel alternative by reducing both CO and NO_x emissions.

REFERENCES

1. Alahmer H., Alahmer A., Alamayreh M.I., Alrbai M., Al-Rbaihat, R., Al-Manea A., Alkhazaleh R. 2023. Optimal water addition in emulsion diesel fuel using machine learning and sea-horse optimizer to minimize exhaust pollutants from diesel engines. Atmosphere, 14(3), 449. https://doi.org/10.3390/atmos14030449
2. Ayodeji A.A., Modupe O.E., Rasheed B., Ayodele J. M. 2018. Data on Cao and eggshell catalysts used for biodiesel production. Data in Brief, 19, 1466–1473. https://doi.org/10.1016/j.dib.2018.06.028
3. Bahadorizadeh O., Sobati M.A., Shahnazari S. 2022. Emission characteristics of a semi-industrial boiler fueled by waste cooking oil biodiesel containing different metal oxide nanoparticles. Process Safety and Environmental Protection, 158, 199–209. https://doi.org/10.1016/j.psep.2021.11.050
4. Bazooyar B., Hashemabadi S.H., Shariati A..2016. Nox Formation of Biodiesel in utility power plant boilers; part B. Comparison of no between Biodiesel and Petrodiesel. Fuel, 182, 323–332. https://doi.org/10.1016/j.fuel.2016.05.018

5. Belyea H.A., Holland W.J. 1967. Flame temperature in oil-fired fuel-burning equipment and its relationship to carbonaceous particulate emissions. Journal of the Air Pollution Control Association, 17(5), 320–323. https://doi.org/10.1080/00022470.1967.10468987
6. Ghorbani A., Bazooyar B., Shariati A., Jokar S.M., Ajami H., Naderi, A. 2011. A comparative study of combustion performance and emission of biodiesel blends and Diesel in an experimental boiler. Applied Energy, 88(12), 4725–4732. https://doi.org/10.1016/j.apenergy.2011.06.016
7. Hamdan M., Almomani D. 2015. Performance study of a domestic boiler fueled by Biodiesel produced from rapeseed. International Journal of Thermal and Environmental Engineering, 12(2). https://doi.org/10.5383/ijtee.12.02.001
8. Hosseini S.H., Taghizadeh-Alisaraei A., Ghobadian B., Abbaszadeh-Mayvan A. 2017. Performance and emission characteristics of a CI engine fuelled with carbon nanotubes and diesel-biodiesel blends. Renewable Energy, 111, 201–213. https://doi.org/10.1016/j.renene.2017.04.013
9. Kulkarni M.G., Dalai A.K. 2006. Waste cooking oil economical source for Biodiesel: A Review. Industrial & Engineering Chemistry Research, 45(9), 2901–2913. https://doi.org/10.1021/ie0510526
10. Kumar A., Sharma S., Pandey L.M., Chandra P. 2018. Nanoengineered material based biosensing electrodes for enzymatic biofuel cells applications. Materials Science for Energy Technologies, 1(1), 38–48. https://doi.org/10.1016/j.mset.2018.04.001
11. Sathasivam, K., Elango, A., Prathima, A. 2014. Performance and emission study on zinc oxide nano particles addition with pomolion stearin wax biodiesel of CI engine. Journal of Scientific and Industrial Research, 73(3), 187–190.
12. Tondo W.L., Gurgacz F., Santos R.F., Werncke I., Klajn F.F., Lenz A.M. 2017. Biodiesel as fuel for boilers. Acta Scientiarum Technology, 39(5), 609. https://doi.org/10.4025/actascitechnol.v39i5.29501
13. Zhang C., Khaqqi K.N., Hadinoto Ong K., Romagnoli A., Kraft M. 2017. Assessment of biodiesel plant waste heat recovery with respect to economics and CO_2 emission. Energy Procedia, 142, 1100–1105. https://doi.org/10.1016/j.egypro.2017.12.363