Evaluation of the Combustion and Emission Parameters of Waste Transformer Oil and Its Diesel Blends

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ABSTRACT*:* *The production of fuel from Waste Transformer Oil (WTO) is an excellent way to produce alternative fuels. The aim of research in this paper is to obtain fuel by mixing WTO with diesel fuel in different mass ratios that can be used as an alternative fuel for low-power heat generators as well as for internal combustion engines. Waste oils are a serious problem for the environment due to their disposal, and are considered useful energy sources for their high calorific value. Taking these facts into account, research was conducted to evaluate the combustion and emission parameters in a boiler furnace of 40 kW using Waste Transformer Oil (WTO) and its four diesel blends by varying WTO mass fractions from 20% to 50%. The results were analyzed and compared with diesel fuel. An increase of NO, CO, CO_2 emissions were observed for WTO and its diesel blends and compared to diesel. The flue gas temperature in the kiln is high for the WTO, which indicates the efficiency of the input energy. During the flue gas purification in a gas washing bottle, concentrates of sulfate, sulfide, nitrate, and nitrite were recorded.*

KEYWORDS: *Diesel fuel; Emission; Waste transformer oil; Parameters; Combustion.*

INTRODUCTION

Energy necessity in the world is on a steep rise. Fossil fuel stocks (coal, oil, and natural gas) are decreasing. Some studies say that crude oil will last for the next 80 years, gas fuels for about 150 years and coal for about 230 years [1]. Natural gas reserves in the world were estimated at approximately $340.6 \cdot 10^{12}$ m^3 [2], and oil estimates are

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at approximately $1.64 \cdot 10^{12}$-$1.66 \cdot 10^{12}$ barrels including oil sand reserves [3].

Therefore, there is a necessity for alternative fuels such as agricultural and forest biomass, communal solid waste, waste tires, waste oils (transformer and motor oils), and other waste materials. This is highly significant for the area of Bosnia and Herzegovina since a high percentage of crude oil is being imported from other countries. Mass usage of road vehicles causes numerous environmental concerns. Next to the emission of gaseous pollutants (SO_x, NO_x, CO, CO_2) and soot, waste tires also have a detrimental effect on the environment. Car manufacturers are continuously improving engine performances and fuel emissions to prolong the life span of automobiles and protect the environment. High emissions from diesel and petrol engines motivate alternative fuels development. Recently, many researchers are exploring the possibility of using WTO as an alternative fuel for diesel engines. WTO was examined as an alternative fuel in a single-cylinder, four-stroke diesel engine developing a power of 4.4 kW and 5.7 kW with a maximum cylinder pressure of about $86 \cdot 10^5$ Pa.

High-efficiency insulation oils used in transformers are called transformer oils. Transformer oil is produced from various vegetable oils such as sunflower, soybean, and coconut oil. They are used as insulation materials and coolers in equipment used to produce and distribute electric power such as transformers, oil-filled cables, and others. During operation, transformer oil is exposed to increased temperatures, the effect of transformers' metal parts (catalytic effect by copper), and oxygen, and sometimes to an electric arc. Oil characteristics change and oil oxidation (oil aging) happens due to these effects. Oil aging creates acid, subsidy, and moisture that deteriorates electric oil characteristics [4,5]. Another important role of transformer oil is cooling a transformer's insulation system and for that purpose, oil has to be mobile enough. That is why viscosity and oil density are very important [6].

Saidulu E. et al [7] researched diesel engine performances in which they combusted blends of WTO in different mass ratios with diesel fuel. They noticed an increase in the emission of NO and CO in exhaust gases. The temperature of exhaust gases was high for all blends used which indicated the efficiency of the input energy.

Qasim M. and his associates [8] also researched the performance of diesel engines in which they combusted blends of biodiesel and diesel fuels. They came to similar conclusions, an increase of NO emission and high temperature of exhaust gases as well as with *Saidulu E.* and his associates.

Das R., *Kumar R.*, and *Sharma A.K.* [9] also investigate alternative fuels and their use in diesel engines. In their research, they use WTO and compare it with conventional diesel fuel in a mixture with mass ratios of 25%, 50%, 75% and 100%. This alternative fuel is used in diesel engines to assess the performance of diesel engines and emissions of gaseous combustion products. They came to the conclusion that diesel fuel and its mixtures with the WTO in the considered mass ratios can be used as an alternative fuel in a diesel engine with reduced emissions of gaseous products.

Yadav A.K., *Khan M.E.*, and others [10] in their research use biodiesel from various inedible oils (Oleander, Kusum, and Bitter Groundnut) as an alternative fuel in diesel engine in order to assess the performance of diesel engines and emissions of gaseous products. Research has shown that the thermal efficiency of the brakes is improved, specific fuel consumption is lower and emissions of gaseous products are lower. They also conclude that biodiesel from various inedible oils such as Oleander, Kusum, and Bitter Groundnut may become an alternative fuel source in the future.

The rapidly growing demand for automobiles and the growing consumption of fossil fuels have inspired *Bibi C.*, *Seeni P.*, *Devan P.* [11] to use Punnai oil, which is not edible as an alternative fuel in diesel engines, in their research. Analysis of gas chromatography revealed that Punnai oil biodiesel contains linoleic, oleic, and palmitic fatty acids that improve the characteristics of the fuel combustion process. Experimental research was conducted on a four-stroke single-cylinder diesel engine. The results of the research indicated a decrease in the thermal efficiency of the brakes and an increase in NO_X and CO_2 emissions. CO and HC emissions are significantly reduced.

In further literature review [12-20] many researchers, also, worked on the use of different kinds of oil blends, like edible oil, inedible plant oils, palm oil, motor oil, and transformer oil with diesel fuel. They came to similar conclusions that those blends could be successfully used as alternative fuels for internal combustion engines, low-power heat generators, agricultural machinery, and various fireboxes used in different branches of the process engineering (kilns, cement plants, brick production and others). It was shown that internal combustion engine performances were improved in sense of economical fuel consumption and influence on environment.

In this paper, we tried to estimate combustion and emission of gaseous products CO, CO_2 and NO characteristics with WTO and its blends with diesel fuel in furnace of 40kW under atmospheric pressure in regard to diesel fuel combustion. It was shown that WTO and its blends with diesel fuel could be used in 40 kW generators and could decrease problems of environmental protection, which is the aim of research in this paper. This is especially important for the development of circular economy that uses renewable energy sources, which is especially important for Bosnia and Herzegovina, country highly dependent on resources.

THEORETICAL SECTION

Waste Transformer Oil (WTO) used in this experiment has been collected from the work units of the power distribution company "Elektro-Bijeljina", joint-stock company Bijeljina, Bosnia and Herzegovina. For the experimental investigation, WTO was blended with diesel in different mass ratios: 20% WTO and 80% diesel, 25% WTO and 75% diesel, 33% WTO and 67% diesel, 50% WTO and 50% diesel that are denoted as WTO20, WTO25, WTO33 and WTO50. A comparison of the chemical composition of the WTO and diesel is shown in Tables 1 and 2.

Thermal power of diesel fuel and its blends with WTO is approximately uniform, and increase of mixture density can have fuel consumption increase (Table 2).

The chemical composition of WTO shows that this fuel contains almost the same value of carbon and hydrogen as diesel. Table 1 shows that WTO contains a significant amount of oxygen which can be useful for better combustion of the mixture.

The composition of WTO and diesel blends was calculated using the expression given below:

$$X(\text{blend}) = xX(\text{WTO}) + (1-x)X(\text{diesel}) \quad (1)$$

The lower heating value of the WTO and diesel was calculated using the expression given below [22]:

$$H_d = 33900C + 121400\left(H - \frac{O}{8}\right) + 10460S - 2510W \quad (2)$$

Table 1: Chemical properties of the WTO and diesel [21].

Description [mas.%]	Diesel	WTO	Test method
C	85.76	86.31	ASTM D 5291 (procedure A): 2016
H	14.00	12.51	ASTM D 5291 (procedure A): 2016
N	0.20	0.02	ASTM D 5291 (procedure A): 2016
S	0.0043	0.06	Own method
O by difference	0.0080	0.55	-
Wettness (W)	0.0077	0.55	HRN EN 14346 B 2007
Ashes (A)	0.0200	0.00	HRN EN ISO 6245:2003

Table 2: Fuel properties of test fuel.

Fuel	Fuel ratio [mas.%]	Density [kg/m^3]	Lower heating value [kJ/kg]
Diesel	0/100	821.30	46068
WTO20	20/100	827.25	45779.18
WTO25	25/100	828.75	45707.05
WTO33	33/100	831.16	45591.65
WTO50	50/100	836.33	45346.42
WTO	100/0	851.92	44124

The density of WTO and diesel blends was calculated using the expression given below:

$$\rho_m = \frac{x_1}{\frac{x_1}{\rho_1} + \frac{x_2}{\rho_2}} + \frac{x_2}{\frac{x_1}{\rho_1} + \frac{x_2}{\rho_2}} \quad (3)$$

Fig. 1. Photography of WTO and diesel fuels used in experiments.

EXPERIMENTAL SECTION

Fig. 2 Photography of experimental installation with its fuel combustion parameter points.

Examination of the combustion parameters of diesel fuel, WTO and WTO diesel blends of different mass ratios varying from 20% to 50% was done in the rotary kiln (Fig. 2). The blends are denoted as WTO20, WTO25, WTO33 and WTO50. The blend was stirred well to get a homogeneous stable mixture. Prior to combustion, the samples of different fuel blends were kept in a burette (2)

(a) (b)

***Fig. 1:** Photos of fuels a) WTO, b) Diesel fuel.*

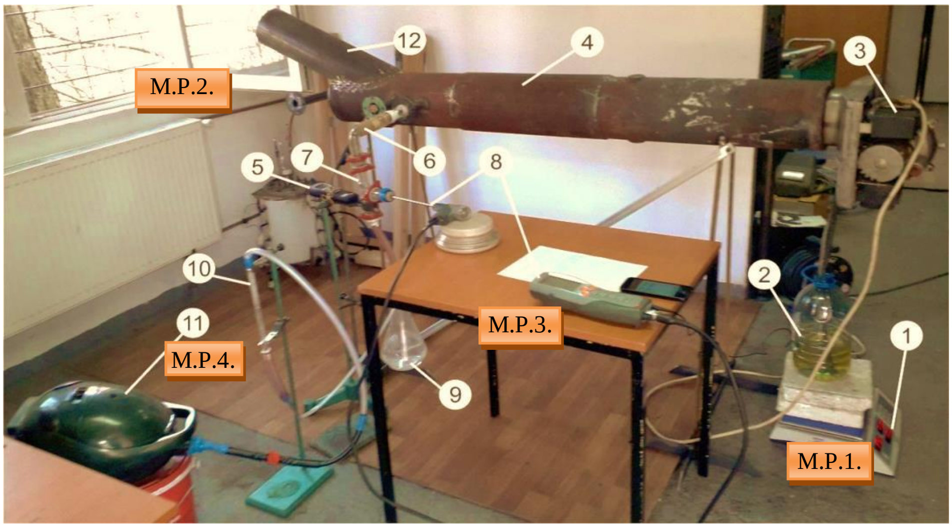

***Fig. 2:** Experimental setup: (1) fuel consumption measuring device, (2) burette, (3) burner, (4) rotary kiln, (5) temperature indicator, (6) partial flue gas flow, (7) smoke analysis bottle, (8) smoke analyzer, (9) flue gas washing bottle, (10) flue gas flow meter, (11) pump, (12) exhaust pipe, (M.P.1.) fuel consumption, (M.P.2.) flue gas temperature in the rotary kiln, (M.P.3.) flue gas analysis (O_2, CO, CO_2, NO, t), (M.P.4.) flue gas volumetric flow rate.*

in an open atmosphere. The fuel from the beaker was injected with a burner (3) and was burnt in a rotary kiln (4). Using a pump (11) placed at the end of the sampling line, partial smoke gas flow was sampled, and in the smoke analysis burette (7) flue gas composition was determined (CO, CO_2, O_2, NO) as well as the extra air coefficient and temperature of the sampled gas. After the composition of the sampled flue gas, the flue gas then passes through the flue gas washing bottle filled with distilled water (9) for sulphate removal. Flue gas flow is measured by a rotameter (10). To gain reliable data, the experiment was repeated four times for each fuel variation. Experimental results were consistent. No larger deviations were noticed. Standard deviation (S) and variation coefficient (Cv) were determined as experimental measures of variability for gaseous components NO, CO, and CO_2. Values are shown in Figs. 4-6.

During the experimental examination of the combustion process of the WTO and its diesel blends the following instruments were used: digital scale QZ-161 for fuel consumption measurement (M.P.1.), measuring range: 0-5000g, measurement error ±1 g, burner WL2V

Table 3: Fuel combustion parameters in 40 kW kiln.

Parameter	Type of fuel					
	Diesel	WTO20	WTO25	WTO33	WTO50	WTO
Mass flow rate [kg/h]	1.90	2.21	2.37	2.66	3.38	4.14
Gas temperature in rotary kiln [°C]	500	571	602	640	692	800
Temperature of the sampled gas [°C]	156	186	211	179	209	242
Volume ratio of oxygen in flue gas [%]	11.15	10.18	9.20	9.25	7.00	6.58
Excess air coefficient	2.20	1.94	1.78	1.79	1.51	1.46
Volume flow rate [m^3/h]	1.10	1.11	1.12	1.08	1.14	1.14

consumption kg/h 1.6-3/A, digital temperature indicator Testo 925 with type K probe (NiCr-Ni) (M.P.2.), measuring range: 50-1000 °C, measurement error ±0.2%, and flue gas analyzer Testo 330-2 LL for composition analysis of the sampled flue gas (CO, NO, O_2, CO_2, λ, t) (M.P.3).

RESULTS AND DISCUSSION

Combustion analysis

The values of the combustion parameters of the WTO and the WTO diesel fuel blends are presented in Table 3. Fuel consumption during the experimental investigation was in the range of 1.90 kg/h for diesel to 4.14 kg/h for the WTO. Increased consumption for the WTO and WTO20, WTO25, WTO33, and WTO50 blends in comparison to diesel fuel is a consequence of the higher density of the observed fuels in comparison to diesel density. This resulted in a decrease of the coefficient of extra air from 2.20 to 1.46 for WTO. The flow of the sampled gas during the experiment was kept approximately constant and in range from 1.10 m^3/h to 1.14 m^3/h.

The flue gas temperature in the rotary kiln was from 500 °C to 800 °C while its exiting temperature (temperature of the sampled gas) was from 156 °C to 242 °C (Fig. 3). The higher temperatures of flue gases in case of the WTO and the WTO and its diesel blends compared to the diesel fuel are a result of the higher density of the WTO and the WTO and its diesel blends which also results in a higher rate of heat release.

Emission Parameters

Nitric oxide (NO) emission

The variation of NO emission for the WTO and the WTO and its diesel fuel blends is shown in Fig. 4.

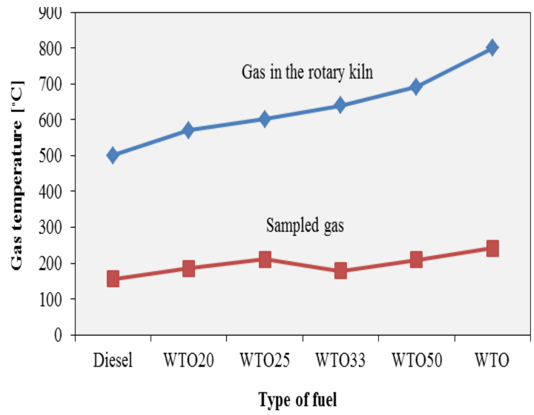

Fig. 3: Flue gas temperature variations for different fuel types.

It can be observed from the figure that the NO emission for the WTO and the WTO diesel blends is higher compared to that of diesel fuel. The higher NO emissions are the consequence of higher gas temperatures in the rotary kiln for the WTO and blends compared to the gas temperature of diesel fuel combustion. Compared to diesel fuel, by combustion of WMO50 the temperature of flue gas in rotary kiln increased by approximately 38%. Literature data [7,23,24] also show a slight increase in NO emission.

Carbon-monoxide (CO) emission

The variation of the carbon-monoxide emission for the combustion of the WTO, diesel fuel blends, and diesel is shown in Fig. 5. The emission of CO for the WTO and WTO diesel blends is higher than diesel combustion emission. CO emission for diesel fuel was 0.0032%, for WTO20, WTO25, WTO33, WTO50 (0.0048%, 0.0048%, 0.0050%, 0.0065%) and 0.0080% for WTO. The higher CO emissions for the WTO may be attributed to poor

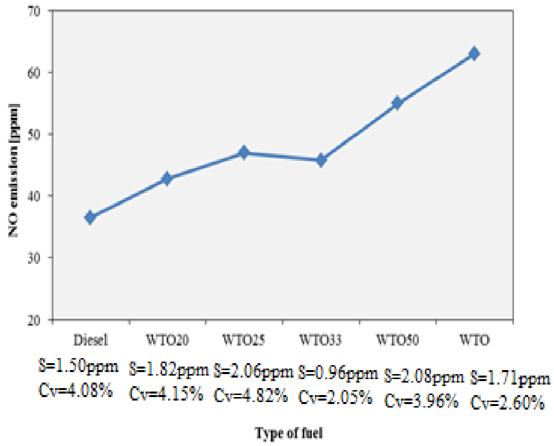

Fig. 4: NO variations for different fuel types.

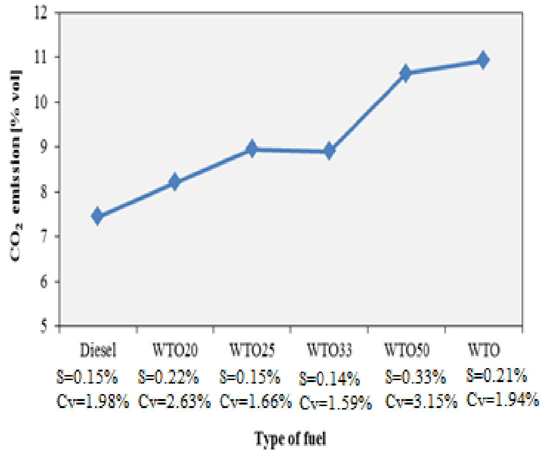

Fig. 6: CO_2 variations for different fuel types.

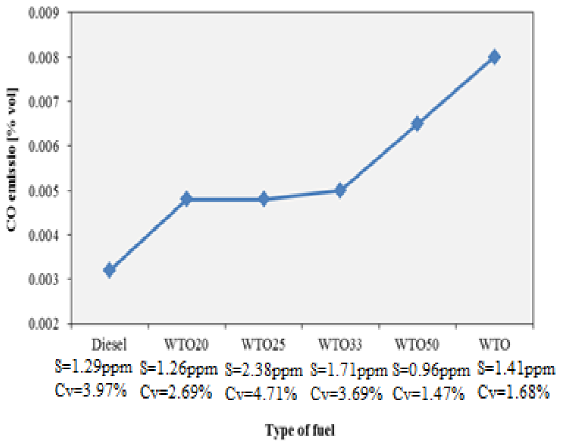

Fig. 5: CO variations for different fuel types.

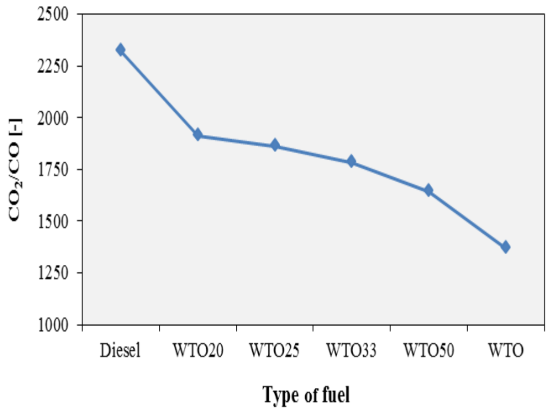

Fig. 7: CO_2/CO emission ratio for different fuel types.

mixture formation because of the lower oxygen share in the combustion chamber. However, the CO value for all the tested fuels are less than 0.008%. Literature data [7,23,24] also show a slight increase in NO emission.

Carbon-dioxide (CO_2) emission

During the experimental investigation of the fuel combustion process, marginally higher emissions of CO_2 (10.92%) were observed for the WTO and its diesel blends WTO20, WTO25, WTO33, WTO50 (8.32%, 8.95%, 8.90%, 10.64%) in comparison to CO_2 emission for diesel (7.44%) (Fig. 6).

The CO_2:CO ratio in the flue gases in relation to the CO volume fraction for all types of fuel combustion is lower for the WTO and WTO diesel blends compared to diesel. For the WTO combustion $CO_2:CO \approx 1.37 \cdot 10^3:1$, and for diesel fuel combustion $CO_2:CO \approx 2.32 \cdot 10^3:1$ as was expected (Fig. 7).

Flue gas purification

Flue gas purification was performed in the smoke analysis bottle (7) with distilled water (Fig. 2). The purification was done for the purpose of determining the composition of the liquid mixture after the combustion process of different fuel types and sulfate removal. The following parameters were determined: pH value, sulfates, sulphides, nitrates and nitrites [25]. The results are shown in diagrams Fig. 8 to Fig. 12.

In the smoke analysis bottle (7) all the observed parameters were detected. The highest concentration of sulphates (SO_4) was observed during the combustion process of the WTO of 18 mg/L. The lowest one was observed

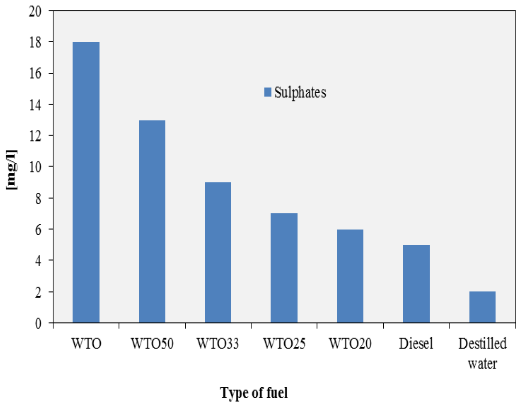

Fig. 8: Sulphates fraction in the solution during the flue gas purification for different fuel types.

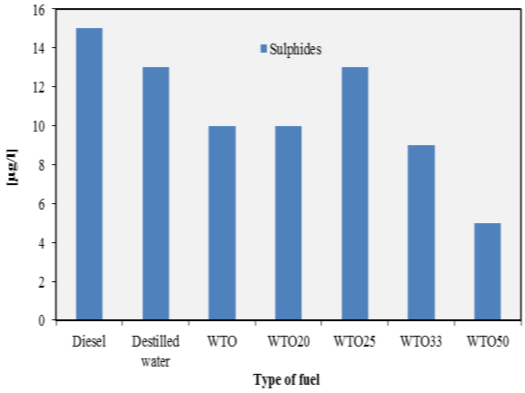

Fig.10: Sulphides fraction in the solution during the flue gas purification for different fuel types.

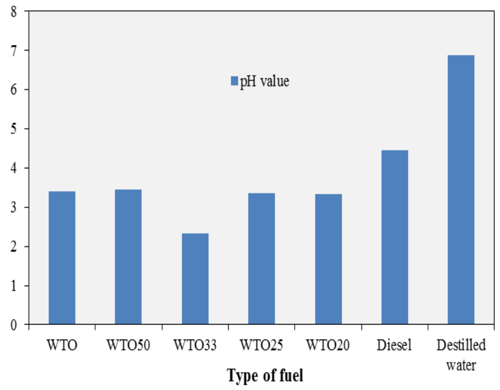

Fig. 9: pH variations in the solution during the flue gas purification for different fuel types.

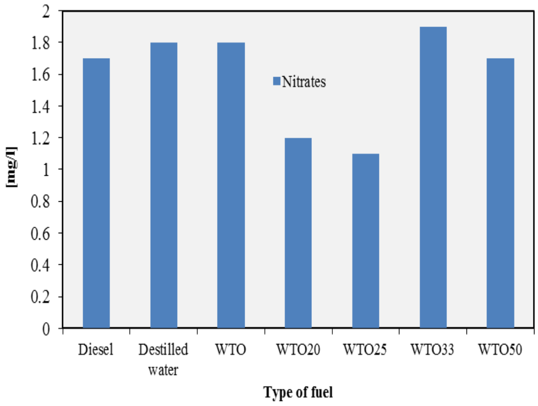

Fig. 11: Nitrates fraction in the gas washing bottle for different fuel types.

in distilled water less than 2 mg/L (Fig. 8). This was expected due to the WTO plant origin and sulfur content of 0.06%. When found in the atmosphere, these concentrations of sulphates contribute to the formation of acid rain, which through precipitation can degrade soil and reach groundwater, thus having an irreversible effect on the environment. The presence of sulfates in water increases the solution's acidity, as can be seen from Fig. 9.

The pH values for WTO20, WTO25, WTO50, and WTO fuels are approximately uniform and the values are app. 3.4. The lowest pH value was observed for WTO33 fuel and is app. 2.3. It is lower by app. 32% than the value of other blends of WTO and diesel fuel.

Fig. 10 shows a sulfide decrease during the combustion of the WTO and its blends as compared to diesel. The highest sulfide concentration is expected in diesel and in distilled water due to their physical, chemical and electric properties.

The nitrate content of the solution ranges from 1.1 mg/L when using WTO25 fuel to 1.8 mg/L when using WTO fuel (Fig. 11). All recorded nitrate values in the solution are 22 to 36 times higher than the allowed values of 0.05 mg/L [26]. Nitrates can be useful in production of mineral fertilizers, paint production, explosive materials production as well as in medicine.

The highest nitrite concentration of 0.19 mg/L was recorded in the use of diesel and it is 6.33 times higher than the allowed value of 0.03 mg/L [26]. The nitrite concentration in the use of the WTO and its diesel blends is within the allowed limits (Fig. 12).

CONCLUSIONS

Global warming caused by fossil fuels emission, use of petroleum products and increase of crude oil prices, motivated researchers to explore ecologically acceptable

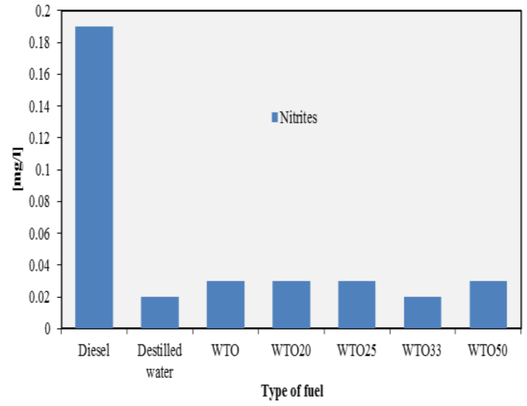

Fig. 12: Nitrites fraction in the gas washing bottle for different fuel types.

alternative energy sources. In that sense, the aim of this paper was to study combustion parameters and emissions in fireboxes of low heat power of 40 kW by using Waste Transformer Oil (WTO) and four blends with diesel fuel with variations of mass ratios of WTO from 20% to 50%.

The conclusions based on experimental research of diesel fuel combustion, WTO, and its blends with diesel fuel in the kiln of 40 kW are:

● Temperatures in the reactor (in a rotary kiln) and the output of the kiln is high for WTO and its blends, and it varied in the range from 571 °C up to 800 °C compared with diesel fuel temperature which was about 500 °C. This fact indicates the efficiency of the input energy during the combusting process.

● Use of WMO blend with diesel fuel in mass ratios 20%, 25%, 33%, and 50%, and it can be used in low-power heat generators, agricultural machinery, diesel engines of low power, and in various branches of process engineering (kilns, cement plants, brick production, oil mills, etc.).

● Emission of NO varying from 37ppm for diesel fuel up to 65ppm for WTO50 fuel, as it is shown in Fig. 4. The increase is as much as 76%. The increase of NO is the cause of increased temperature in the rotary kiln. Most of the literature data, for example [7,23,24], shows an increase of NO by combusting of WTO and its blends with diesel fuel in internal combusting engines compared to diesel fuel.

● The emission of CO for used WTO blends with diesel fuel and significantly higher than the emission of CO obtained by diesel fuel combustion.

● Emission of CO_2 is higher for used blends of WTO with diesel fuel from emission of CO_2 obtained by diesel fuel combustion. By combustion of WTO volumetric emission of CO_2 is around 11%, which is about 15% higher than the emission of CO_2 obtained by diesel fuel combustion.

● Ratio of CO_2:CO in flue gases is lesser for WMO and it blends with diesel fuel compared to diesel fuel. For the combustion of WTO, the ratio of $CO_2:CO=1.37\cdot10^3:1$, and for the combustion of diesel fuel it is $CO_2:CO=2.32\cdot10^3:1$. That ratio was expected due to the small volume of CO in gas.

● The flue gas purification resulted in recording concentrations of sulfates, sulfides, nitrates and nitrites. When found in flue gases these can have detrimental effects on the environment. The nitrates concentrations are significantly higher than allowed, while the nitrites concentrations are significantly higher only for diesel.

● Increased fuel consumption for all diesel and WTO blends, high furnace flue gas temperatures, increased CO and NO_x emissions, and reduced CO_2 values: CO for all diesel and WTO blends in flue gases are in line with data from researchers in the cited literature, who conducted their research exclusively on a four-stroke single-cylinder diesel engine with a thermal power of about 5.5 kW. This indicates that the tests conducted by the authors of this paper by burning a mixture of diesel fuel and WTO in the specified mass ratios in a rotary kiln with a power of 40 kW whose values are presented in this paper can be used as an alternative fuel for diesel engines with lower thermal power with similar impact on performance of diesel engines such as good heat exchange, delay in ignition of the fuel mixture in the cylinder, the duration of fuel combustion in the cylinder, pressure in the cylinder.

The conclusion is that WTO and its blends with diesel fuel in different mass ratios can be used as an alternative fuel in low heat power generators as well as the internal combustion engines. Taking into account especially low fuel consumption values obtained for WTO-diesel fuel ratio, it presents significant value and reduces additional costs.

Nomenclatures

Cv	Coefficient of variation, %
S	Standard deviation, ppm, %
WTO	Waste transformer oil
X(blend)	Mass fraction of *X* in a blend, %
X(WTO)	Mass fraction of *X* in WTO, %

X(diesel)	Mass fraction of *X* in diesel, %
x	Mass fraction of WTO in the blend (0.20, 0.25, 0.33, 0.50), kg/kg
1-x	Mass fraction of diesel in the blend, kg/kg
H_d	Lower heating, kJ/kg
C, H, O, S, W	Mass fraction of carbon, hydrogen, oxygen, sulphur and moisture in the blend, kg/kg
ρ_m	Density of WTO and diesel blends, kg/m^3
x_1	Mass fraction of WTO in the blend, kg/kg
x_2	Mass fraction of diesel in the blend, kg/kg
ρ_1	Density of WTO, kg/m^3
ρ_2	Density of diesel, kg/m^3
λ	Ecess air coefficient, -t temperature, °C

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