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Emission factors of biodiesel combustion in industrial boiler: A comparison to fossil fuel

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Boiler is one of industrial facilities, which has energy intensive in producing steam or hot water, through fuel combustion. The large use of industrial boilers contributes to large emission. Emission factor is one of the most common methods to quantify emissions from combustion appliances such as boilers. As the biodiesel is an alternative fuel that has great potential to reduce emissions, it can be potentially used as boiler fuel. In this study, biodiesel combustion emission factor is determined through fuel analysis and direct measurements (stack sampling). A series of test was performed on a fire tube boiler, in which pressure of 3 bar, using palm biodiesel and its blend with petrodiesel in a variety of composition of biodiesel of 10%, 20%, and 30%. It is known that SO_2 and CO emission factors in biodiesel combustion in boiler was significantly lower than petrodiesel, while CO_2 and NOx emission factors tend to higher. Inconsistently, the stack sampling data showed that the emission of CO and CO_2 was higher than petrodiesel, instead NOx emission of biodiesel combustion was 10% and 27% lower than petrodiesel.
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I. INTRODUCTION

Emission inventories are fundamental tools for air quality management. They are used for identifying major contributors of atmospheric pollutants, developing emission control strategies, determining applicability of permitting programs, and other related applications by an array of users including federal, state, and local agencies, consultants, and industry.[8] Among several methods in quantifying emission, the emission factors are frequently the best method available. Emission factor is typically defined as the amount of a concerned pollutant emitted per unit mass per a defined task performed. The former is often referred as mass-based factor and has a unit such gr pollutant/kg fuel or lb/lb. The unit of task or activity-based emission factor depends on the definition of the task. In case of boiler operation, the activity unit is fuel consumption or heat energy input in the fuel.

As occurred in internal combustion, everytime fuels burn in boiler, they are converted into carbon dioxide (CO_2) and water. The noncombustible portion of the fuel remains as a solid residue or ash. Products of incomplete combustion are also common, and can include carbon monoxide (CO), sulfur oxides (SO_x), oxides of nitrogen (NO_x), particulate matters (PM), and other organic compounds. The respective amounts and chemical composition of the emissions formed in boilers' stack are dependent upon variables occurring within the combustion process.[7,18,19] Fuel properties are known as the major parameters which influenced the quality and quantity of the emissions.

The dominance of fossil fuel utilization for industrial boiler undoubtedly leads to a potential opportunities of the substitution to the new and renewable energy utilization. Biodiesel use

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in boiler is very straightforward as it is produced to have flow and combustion properties very similar to those of petroleum diesel. Some exhaustive engine tests showed that biodiesel can be adopted as an alternative fuel for existing conventional diesel engine without requiring any major modifications in the mechanical system of the engine.[1,2,23] In order to prove the potential use of biodiesel in the boiler, especially from the aspect of reducing emissions, the emission factor calculation needs to be studied in a comparison to fossil fuels.

II. EFFECTS OF BIODIESEL COMBUSTION ON EMISSION

Biodiesel has very favorable energy balance, it can be blended in any properties with petroleum diesel fuel, having higher cetane number and excellent lubricity, and having high flash-point (>300 °F).[11,12] Due to higher content of oxygen, biodiesel has potential in promoting good combustion. Biodiesel is said to be carbon neutral as more carbon dioxide absorbed by biodiesel production than what it added to the atmosphere when it is burnt as fuel.[12] The major advantages of biodiesel attributed to lesser exhaust emissions in terms of carbon monoxide, hydrocarbons, and particulate matter. These lower emission levels were likely due mostly to the fact that biodiesel contains about 10% oxygen by weight, and this oxygen helps to oxidize the combustion products in the boiler cylinder. As expected, application biodiesel in engines would produce less smoke and particulates than standard engines for reasons such as high gas temperatures and high temperatures of the combustion chamber wall.

Some tests of biodiesel combustion were founded a significant reductions in PM emissions. It was reported that PM emissions of biodiesel use was roughly ten times lower than the distillate fuel oil.[17,18,22] The reduction trend in PM is due to lower aromatic and sulfur compounds and higher cetane number of biodiesel, besides the factor of higher oxygen content.[23,24] Carbon monoxide emissions were generally correlated to PM emissions trend. Sulfur emissions are essentially eliminated with the use of pure biodiesel.[6,18]

In a combustion process, biodiesel resulted fewer CO_2 emissions due to the lower carbon to hydrogen ratio.[6] This is also attributed to the fact that biodiesel is a low carbon fuel and has a lower elemental carbon to hydrogen ratio than diesel fuel. CO_2 emission rise or keep similar due to more efficient combustions proceed.[15,16,21,23] Instead, while soybean biodiesel tested on boiler, the net CO_2 emissions would drop by about 79% compared to diesel oil.[18]

However, biodiesel generally produces more nitrogen oxides (NO_x) than petroleum diesel. NO_x and other emission limits are requiring engine manufacturers to develop new technologies to limit petroleum diesel emissions, hence any increase is problematic.[10,15] The source of these increased emissions is unclear and still under debate. Most of the authors who tested biodiesel in diesel engine found that only the oxides of nitrogen (NOx) emission which was increased in boiler emission due to higher temperatures in combustion chamber.[6,17,23] Moreover, Miller (2008) was tested some blends of soy based and animal based biodiesel on a commercial-institutional boiler with heat input of 85 000 Btu/h. They reported that the largest emission reductions were identified on the pollutants of SO_2, total hydrocarbon (HC) and CO_2, while the emissions of NO_x and CO found to be higher than petroleum diesel oil.[18]

Technically, a boiler's excess air supply provides for safe operation above stoichiometric conditions. As known, the stoichiometri air to fuel ratio for biodiesel was about 13.8.[14] A typical burner is usually set up with 10%–20% excess air (2%–4% O_2).[5] It is set in order to perform good combustion with lesser exhaust emissions.

III. EMISSION FACTORS DEVELOPMENT

In quantification of boiler emission, the most common methods used were sampling or direct measurement, mass balance, and engineering calculation (fuel analysis and emission factors). The method used depends on available data, available resources, and the degree of accuracy requirement. In general, direct measurement is the most accurate for characterizing and quantifying the emissions.[3]

Emission factors developed from measurements for a specific process may sometimes be used to estimate emissions at other sites. Ideally, the emissions estimates are based upon factors compiled through extensive fields testing and are related to the fuel type, the boiler type and size, and the method of firing. Although the use of emission factors based on the above parameters can yield an accurate first approximation of on-site boiler emissions, these factors do not reflect individual boiler operating practices or equipment conditions, both of which have a major influence on emission rates.

From fuel and stack emission data, the emission factors specific will be generated to boiler operations. The emission factors are stated as the amount of a concerned pollutant emitted per unit mass of fuel burned (gr pollutant/kg fuel). The primary information necessary to develop emission factors in the standardized units. Emission factors are commonly provided as an emission rate (e.g., lb pollutants/lb fuel combusted) and also provided above the fuel heat input rate (e.g., lb pollutants/MMBtu). Minnesota Pollution Control Agency[19] has already released a database of emission factor of biodiesel combustion in boilers, as well Miller (2008) concluded in a study[18] as presented in Table I.

IV. EXPERIMENTAL AND ENGINEERING CALCULATIONS

A. Direct measurement

A fire tube cylindrical pilot plant boiler was used in the study to perform the emission effect of biodiesel combustion. As shown in Fig. 1, the boiler was operated in a pressure of 3 bars and heat capacity of 60 000 kCal/h, the detailed specification is listed in Table II. On burner set, the arrangement of air supply was maintained in fan damper scale of f 4.0–4.6. The biodiesel used in the test was palm methyl ester and stack flue gas was monitored with portable gas analyzer IMR 1400.

The characterization of biodiesel was conducted following the American Society for Testing and Materials (ASTM) and European Standards (EN) methods, and the analysis of fatty acid components contained in palm biodiesel was conducted by gas chromatography Hewlett Packard (HP) series with capillary column Innowax Agilent with a Flame Ionization Detector (FID) and split injector, using nitrogen as the carrier gas.

B. Calculating emission factors using Environmental Protection Agency (EPA) Method 19

Emission factors developed from pollutant concentration data, with considering oxygen percentage in the gas stream, and F factors (Fd) for oil type of fuel (2.65×10^{-7} dscm/J or 9.190 dscf/MMBtu). The formulation is

$$EF_x = (C_d * F_d)\left[\frac{20.9}{20.9 - \%O_2}\right], \tag{1}$$

where EF_x is the emission factor in lb/MMBtu of pollutant x, Cd is the pollutant concentration (lb/dscf), and Fd is the F factor at standard condition 20 °C and 760 mmHg = 9190 dscf/MMBtu (oil fuel)—ASTM Method D 388-77.[9]

TABLE I. Emission factor database for biodiesel combustion.

Version	Fuel	Type of boilers	Biodiesel raw materials	Emission factors (lb/MMBtu)			
				CO	CO_2	NO_x	SO_2
MPC[a]	B100	Utility boiler	Soy/rapeseed	0.055		0.109	0
	BXX		Soy/rapeseed	0.170		0.300	1.60
Miller[b]	B100	Fire tube boiler 3×10^6 Btu/h	Soy based	2.85×10^{-3}	142	1.11×10^{-1}	4.62×10^{-3}
	B100		Animal-based	3.14×10^{-3}	139	1.14×10^{-1}	3.15×10^{-3}
	Diesel oil no. 2		…	1.73×10^{-3}	168	9.92×10^{-2}	3.07×10^{-2}

[a]Minnesota Pollution Control Agency (Ref. 19).
[b]US EPA by Miller (Ref. 18).

FIG. 1. The fire tube boiler.

An emission factor relating emissions to the heat input rate for the boiler is expressed as

$$EF_x = \frac{E_x}{H_{in}} \tag{2}$$

and

$$H_{in} = \frac{Q_f . HHV}{10^6}, \tag{3}$$

where H_{in} is the heat input rate in MMBtu/h, HHV is the higher heating value in Btu/lb, Q_f is the mass fuel flow rate (lb/h), E_x is the emission of pollutant x in lb/h, EF_x is the emission factor of pollutant x in lb/MMBtu.

V. RESULT AND DISCUSSION

A. Trend in emission reductions

Biodiesel and its blends were tested in the boiler with a variety of blending compositions, at 10%, 20%, 30%, and 100% biodiesel in diesel oil, later labeled as B10, B20, B30, and

TABLE II. Experiment boiler specifications.

Type	Steam boiler/SB 60
Type	SB 60 MMT-fire tube
Model	Cylinder vertical
Steam capacity	60.000 kCal/h
Working pressure	3 bar
Temperature	150 °C
Burner size	3
Operating hours	Average (6 h/day × 300 day/yr)
Manufacturing year	2008

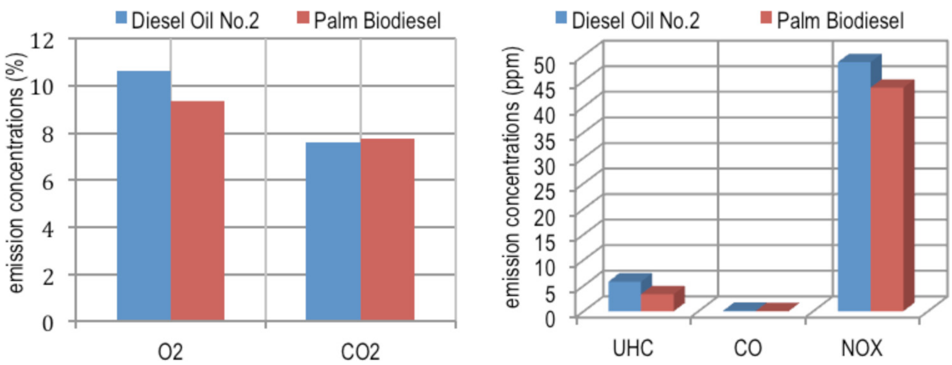

FIG. 2. Emission concentration of palm biodiesel vs petroleum diesel oil in boiler.

B100. The exhaust emissions were measured on the boiler's stack. The comparison of emission concentration of palm biodiesel and petroleum diesel oil combustion in boiler is presented in Figure 2. The utilization of palm biodiesel in the boiler clearly showed a lower performance in gaseous emissions compared to diesel oil.

The previous tests in boiler using biodiesel from various feed stocks, such as soybean, animal oil,[18] rubber seed[21] showed some differences in trend of emission reduction due to the different physical properties of the fuel blends related to different feedstock of biodiesel. It is associated to the higher viscosity, higher density, lower heating value, and higher cetane number carried by palm biodiesel used in the test.

The highest emission reduction is shown in CO and un-burnt hydrocarbons (UHC). Emission of CO_2 is slightly higher than petroleum diesel oil, while O_2 in flue gas of boiler fuelled with palm biodiesel was reduced. Figure 3 showed the changes in emissions of CO, NOx, unburnt hydrocarbon which it decreased by the increase of biodiesel contents in the fuel blends. It is associated with the better combustion performance that promoted by higher cetane number, heat of combustion and oxygen content in palm biodiesel. The condition correlates to the increase of CO_2 emissions by the increase of biodiesel. It can be affected by the changes in combustion performance due to the air supply arrangement in the boiler burner. The performance of NOx emission in gaseous surprisingly showed a reduction at 10.27% compared to petroleum diesel oil. It is strongly caused by the shorter ignition delay and lower combustion temperature.

B. Fuel analysis of palm biodiesel

The properties of the various individual fatty esters caused by different feedstock, which comprise biodiesel, determine the overall properties[6] it included when it blends to fossil fuel.

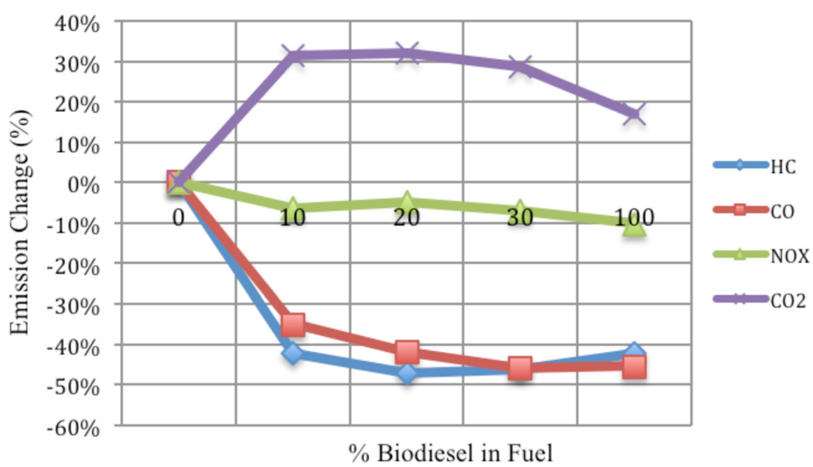

FIG. 3. Emission changes in fire tube boiler using palm biodiesel.

TABLE III. Fuel properties of petroleum diesel and palm biodiesel.

Parameters	Unit	Petroleum diesel (oil no. 2)[a]	Palm biodiesel[b]
Density@ 40 °C	kg/m^3	823	894.8
Kinematic viscosity @40 °C	cSt	4.0	4.524
Calorific value	MJ/lb	46.8	40.135
Flash point	°C	98.0	184.0
Sulfur content	wt. %	0.10	0.001
Carbon residue	wt. %	0.14	0.17
Cetane number		53	75.2
Carbon content	%	84.15	76.30
Hydrogen content	%	12.67	11.75
Oxygen content	%	2.93	12.10

[a]Data from PERTAMINA and compilation from Refs. 6 and 20.
[b]Using ASTM methods.

Palm biodiesel has a higher viscosity, density, flash point, and oxygen content compared to most of the other biodiesel feedstocks. As presented in Table III, the palm biodiesel has a cetane number reached 42% higher than petroleum diesel. Fuel with a higher cetane number will shorten the ignition delay time at a lower temperature thereby potentially lowering NOx emissions. The heat of combustion will increase along with the length of fuel constituent molecular chains.[14] The dominance of saturated molecules in biodiesel allowed it to easily oxidized and performing a better combustion process.

However, the amount of chemical energy released during combustion changed due to the different chemical structure. The heating value of biodiesel is normally less than mineral diesel due to the fuel-bound oxygen, It means that an engine running on biodiesel will output less energy per unit mass of fuel used.[4] The fuel analysis introduced to estimate pollutant emissions, which involves determining carbon, sulfur, oxygen, and hydrogen contents of fuel combusted and applying that to the amount of fuel burned to get the pollutant emissions.

The higher viscosity of biodiesel is related to the longer the fatty acids hydrocarbon chain in the molecules. Compared to other biodiesel feedstock, palm oil is dominated by unsaturated fatty acid groups and straight-chain single bonds.

The alkyl ester structure and chain position in the molecules determine some physical properties of the fuel such as cetane number, viscosity, heating value, cold flow, and oxidative stability.[24] As presented in Table IV, the analysis of palm biodiesel composition showed that the fatty acid content consists of C16 (palmitic) and C18:1 (oleic), which means that the long hydrocarbon chains dominated the structure of palm biodiesel molecules rather than branched chain.

C. Emission factors of palm biodiesel combustion

By using engineering calculation method developed by US EPA, the emission factor of palm biodiesel combustion in fire tube boiler in this study was defined in Table V. Since there

TABLE IV. Palm biodiesel composition.

Components	Contents (wt. %)
Lower-C14	1.21
C16 (palmitic)	56.10
C18 (stearic)	5.24
C18-1 (oleic)	30.46
C18-2 (linoleic)	6.59
C20	0.39

TABLE V. Emission factor for palm biodiesel combustion in fire tube boiler.

Fuel	Emission factors (lb/MMBtu)			
	O_2	CO_2	CO	NO_X
Diesel oil	1.343×10^{-2}	0.1322	1.1234×10^{-4}	3.1660×10^{-3}
B10	1.538×10^{-2}	0.2669	1.1168×10^{-4}	4.5456×10^{-3}
B20	1.688×10^{-2}	0.2640	9.8417×10^{-5}	4.5449×10^{-3}
B30	1.601×10^{-2}	0.2406	8.5555×10^{-5}	4.1607×10^{-3}
B100	1.766×10^{-2}	0.2307	9.1255×10^{-5}	4.2338×10^{-3}

are differences in the tendency of emission reduction, the data resulted from the test cannot be directly used as a database in order to estimate the emission factor of biodiesel combustion in a boiler. It is important to consider the boiler type, capacity, age of boiler utilization, and other combustion performance parameters, such as air to fuel ratio, fuel injection system, burner design, etc.

The difference in the value of the emission factor of petroleum diesel oil combustion in the boiler than the existing database[13,18,19] indicates that the combustion operating conditions, equipment configuration, and performance of the engine very likely affect to the quantification of emissions, other than considering the properties of the fuel.

VI. CONCLUSION

The utilization of biodiesel is undoubtedly potential for industrial boiler due to its favorable benefit on emission reductions compared to petroleum diesel oil. The utilization of palm biodiesel in fire tube boiler then becomes more potential to promote a better combustion due to its properties such as higher cetane number, heat of combustions, and oxygen contents.

Emission factors of biodiesel combustion in boilers, which are presented by previous studies, cannot be used directly as a reference, because it is derived from a series of tests on different sources of biodiesel and different types of boilers. In addition, the properties of fuels introduced by its molecular chain structures and different operating conditions affected the trend of emission factors. The emission factors of palm biodiesel combustion in fire tube boilers showed similar trends with the change of emissions of CO, NOx, and CO_2. The emission factors of CO and NOx decreased with the increase of biodiesel content in the blends, while emission factors of CO_2 tend to increase.

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