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ANALYSIS OF GASES EMISSIONS FROM BIODIESEL COMBUSTION IN A FIRE TUBE BOILER BY USING CFD MODELING

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Abstract

The utilization of biodiesel in boiler has a great benefit due to lower exhaust emissions. The combustion system tends to be simpler than compression ignition as performed in diesel engine. This study was carried out experimentally in a fire tube boiler, with heat input rate of 60.000 kCal/hr and 3 bars of pressure by using palm biodiesel as a fuel. The mixture was varied in 0, 10, 15 and 20% of biodiesel in blends with petroleum diesel (B0, B10, B15, and B20). The experimental research was validated with the CFD simulation by using ANSYS FLUENT CFD package. CFD analysis can provide a better understanding of the combustion process in boiler. The result shows that the use of biodiesel decreased the gases emission with the increasing value of biodiesel in blends. The lowest gases emissions are about 2,78 ppm (NO_2); 14,00 ppm (SO_2) and 7,65 % v/v (CO_2) which is found in the 20% of biodiesel in fuel (B20).

Keywords: biodiesel, CFD modeling, emission, fire tube boiler

I. INTRODUCTION

Nowadays, air pollution has shown a very poor condition. Air Pollution sources has come from any activity as industry, transportation, and residential. These activities contributed to produce several problems of air pollution. The increasing demand for energy supply also leads several environmental problems. Therefore, the environmental pollution and decreasing supply of fossil fuels are the key factors causing to find the alternative sources of energy. In order to meet the need for producing the clean air, Indonesian government declared the regulation no.41 year 1999 about the air pollution control. Meanwhile, the emissions of pollutant gases (NO_2, CO_2, and SO_2) from fossil fuel combustion have increased in recent years. The interests in the biofuels production are due to the high price of crude oil in recent years and efforts to reduce greenhouse gas emissions. One of several efforts for supporting the regulation and minimalizing the emissions of pollutant gases is the utilization of biodiesel as alternative energy.

Biodiesel is the alternative fuel which has a huge potential for switching the petroleum diesel. This is due to many properties of biodiesel which is similar to petroleum diesel. Generally, biodiesel utilization in any kind of engines is mixed with petroleum diesel. Compared to petroleum-based diesel, biodiesel is biodegradable, nontoxic and has a more favorable combustion emission profile, such as low emissions of carbon monoxide, particulate matter and unburned hydrocarbons [5]. Previous researchers [3] investigated that 20% or less of biodiesel blends with petroleum diesel is the optimum blend to produce the better effect of emissions reduction. The other researcher [7] also concluded that 20% or less of biodiesel blends with petroleum diesel did not require neither any special adjustments on engine operating conditions or modifications to the engine. However, they did not study the profile of pollutant gases concentration in the whole part of boiler during combustion process.

Simulation of combustion system in a boiler using computational fluid dynamics (CFD) modelling is still a challenging domain. The fundamentals research to understand the processes occurring in reactive flow systems have been studied. Several works are being carried out to develop computational methods suitable for coupling the many important aspects of chemistry and physics in a way that is efficient enough for solving boiler problems. The CFD modeling can provide a wide range of information for the design of boiler. The using of CFD modeling can reduce the cost of time-consuming experimental investigations. This research investigated the pollutant gases concentration profile from the combustion of petrodiesel and biodiesel fuel on fire tube boiler by using CFD modeling and experimental research. The chemical species concentrations (NO_2, CO_2, and SO_2) can be numerically predicted under different biodiesel blends condition.

II. CFD MODELING

In this study, the ANSYS FLUENT 16 was used to perform the simulation. The governing conservation equations of fluid flow represent the statement of the conservation laws of mass, momentum and energy. For reacting flows, the chemical species transport and mixing can be estimated by using species-transport equations.

The momentum conservation equation [1]:

$$\left(\frac{\partial}{\partial t}(\rho\vec{\upsilon}) + \nabla(\rho\vec{v}\vec{\upsilon})\right) = -\nabla p + \nabla.(\bar{\bar{T}}) + \rho\vec{g} + \bar{\bar{F}} \qquad (1)$$

Where:

$$\bar{\bar{T}} = \mu\left(\left[\nabla\vec{\upsilon} + \nabla\vec{\upsilon}^{T}\right] - \frac{2}{3}\nabla.\vec{v}I\right) \qquad (2)$$

The mass conservation equation [1]:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla.(\rho\vec{v}Y_i) = -\nabla.\vec{J}_i + R_i + S_i \qquad (3)$$

Where:

$$\vec{J}_i = -\left(\rho D_{i,m} + \frac{\mu_t}{S_{ct}}\right)\nabla Y_i \qquad (4)$$

$$\hat{R}_{i,r} = \Gamma(\upsilon''_{i,r} - \upsilon'_{i,r})\left(k_{f,r}\prod_{j=1}^{N}[C_{j,r}]^{(\eta'_{j,r}+\eta''_{j,r})}\right) \qquad (5)$$

$$\Gamma = \sum_{j}^{N}\gamma_{j,r}C_j \qquad (6)$$

The energy conservation equation [1]:

$$\frac{\partial}{\partial t}(\rho E) + \nabla.\left(\vec{v}(\rho E + p)\right) = \nabla.\left(k_{eff}\nabla T - \sum_j h_j\vec{J}_j + \left(\bar{\bar{T}}_{eff}.\vec{v}\right)\right) + S_h \qquad (7)$$

III. EXPERIMENTAL AND NUMERICAL PROCEDURE

A. Experimental Procedure

A fire tube cylindrical pilot plant boiler was used for investigating the effect of biodiesel blends on the emission of exhaust gas (NO_2, CO_2, and SO_2) during combustion process. The boiler was operated in a pressure of 3 bars and heat capacity of 60 000 kCal/h. The detailed specification of boiler was shown in table 1. On burner set, the arrangement of air supply was at a fan damper scale of 3.5. The biodiesel flow rate of 5 liter/h was used in the test. Various blending composition of biodiesel in petroleum diesel (B10, B15, and B20) was tested in the boiler experimentally. The stack flue gas was monitored with portable gas analyzer IMR 1400.

TABLE I. SPESIFICATION OF FIRE TUBE BOILER

TYPE	SB 60 MMT-Fire Tube
Pressure	4,5 Bar
Steam Capacity	60.000 k.cal/h
Temperature	150°C
Dimension	ID = 650mm, H=1425mm
Shell – Tube Plate	SS400-10 mm thick
Fire Tube	Seamless Boiler ST 35,8

B. Numerical Procedure

A schematic of the boiler consist of the inlet velocity of fuel, the inlet velocity of air (blue colors), the pressure outlet (red colors) and fluid zone (green colors). The geometry is shown in fig 1. The total structural mesh number is 1024. The simplification assumptions are summarized below:

- The process is steady-state
- The reaction is the irreversible.
- Instantaneous of vaporization of the biodiesel enters the boiler

All calculations were performed by using the commercial ANSYS FLUENT CFD package. A second order discretization scheme is used for all equations. The solution convergence is investigated by ensuring all residuals of the transport equations fall below a pre-determined threshold and no longer changing with iterations.

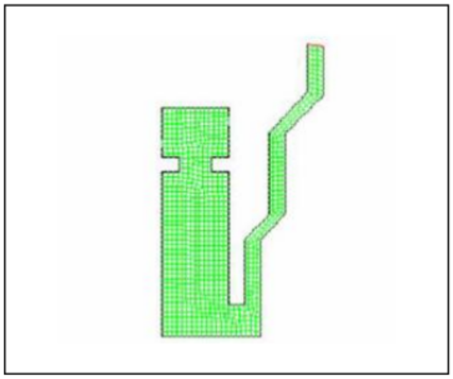

Fig 1. The geometry of the boiler (2-Dimension)

IV. Results And Discussions

The effect of biodiesel composition on the formation of pollutant gases during combustion process experimentally and CFD simulation was shown in figure 2, 3 and 4 respectively.

A. *Effect of Biodiesel Composition on the formation of NO_2 gas emissions*

A comparison of NO_2 gas emissions between experimental and CFD modeling can be seen in fig 2. Interestingly, this graph has shown that NO_2 formation decreased significantly with the increasing of biodiesel composition in its blending fuel. The reduction of NO_2 content was caused by the decreasing of temperature in the combustion room [2]. The other study [3] compared biodiesel from palm oil and diesel oil to be tested in a fire tube boiler with the same operating condition. Their result showed that NO_2 emissions is 10,27 % lower than diesel oil. This is due to palm oil characteristics leads the sorter ignition delay and the lower combustion temperature. On the other hand, previous researches [6, 8] found that the addition of biodiesel in the fuel increased NO_2 content of exhaust gasses.

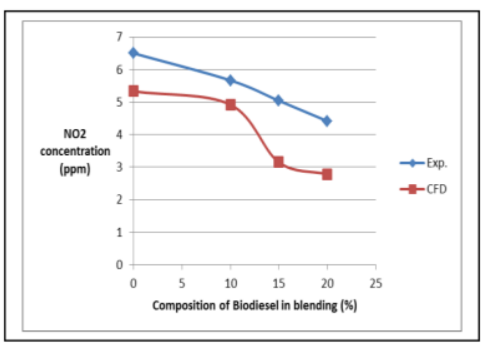

Fig 2. Effect of Biodiesel Composition on the formation of NO_2 gas emissions by Combustion Experimentally and CFD Modeling

B. *Effect of Biodiesel Composition on the formation of SO_2 gas emissions*

Fig 3 illustrates SO_2 gas emissions were tested in a fire tube boiler experimentally and CFD simulation. We can see from the figure that the lowest SO_2 concentration was found at the biodiesel composition of 15% (B15) which is about 14 ppm. Furthermore, the highest concentration of SO_2 experimentally is about 31 ppm. From CFD modeling result, it has been shown that the higher composition of biodiesel in the fuel leads the lower concentration of SO_2. The CFD modeling described that the lowest concentration of SO_2 is about 12,6 ppm at the biodiesel composition of 20%. The other author [3] also tested the gas emissions in the boiler. Their result showed that the emission change of 32% found at the 20% of biodiesel in fuel. The lower reacted air caused the reducing of CO_2 and H_2O products so the reaction heat and temperature decreased significantly. Previous researcher [4] investigated the gas emissions in the stack gas by using Continuous Emission Monitoring System (CEMS). Their result showed the reduction of SO_2 emissions compare to diesel oil.

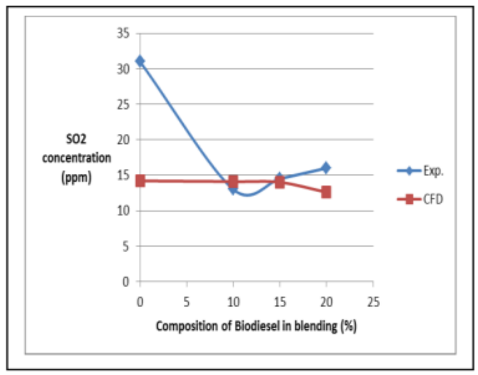

Fig 3. Effect of Biodiesel Composition on the formation of SO_2 gas emissions by Combustion Experimentally and CFD Modeling

C. *Effect of Biodiesel Composition on the Formation of CO_2 Content*

It has been observed that CO_2 concentration increased slowly with the addition of biodiesel in fuel (fig 4). Range of CO_2 concentration is about 7,43 to 7,65 % (v/v). CFD modeling data describe that concentration of CO_2 significant decreased with the raising of biodiesel composition. The lowest value of CO_2 concentration in CFD modeling is about 1,64 % (v/v). The other study [3] used biodiesel from palm oil and tested in a fire tube boiler with the same operating condition. Their result showed that CO_2 emissions are higher compare to diesel oil. The numerical results indicate that the predicted generation of CO_2 is consistent with the data measured.

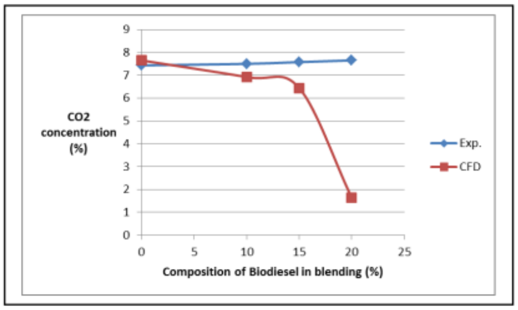

Fig 4. Effect of Biodiesel Composition on the formation of CO_2 content

D. Profile of Pollutant Gases Emissions in the Boiler

Based on experimental and CFD modeling data's were established that the optimum condition of biodiesel composition obtained at the 20% of biodiesel in fuel (B20). The results of application of the CFD model showed the profile of pollutant gases (NO_2, CO_2, and SO_2) as described in fig 5, 6 and 7.

CFD is helpful in minimizing NO_2 emissions using optimization. But NO_2 emission modeling is one of the most challenging tasks in CFD-based combustion modeling. The main reasons are the large number of species and radicals in low concentrations involved in the nitrogen chemistry and their sensitivity to temperature and turbulent motion of the flow. Fig 5 describes the concentration distribution of NO_2 during combustion process of 20% of biodiesel (B20). The concentration of NO_2 at the gas stack is about 2,78 ppm. These numerical results were very consistent with the experimental results. Evaluation of the NO_2 emission from the boiler is carried out using a post-processing approach. The CFD model solves a transport equation for NO_2 concentration integrated with velocity, turbulence, temperature and chemical species that are already established by the flow solver. The model computes the thermal and prompt emissions of NO_2. NO_2 is formed by the oxidation of atmospheric nitrogen present in the combustion air. The Prompt NO_2 is produced by fast reactions at the flame front, and affects to the specific combustion environment such as in the low-temperature and the fuel-rich conditions.

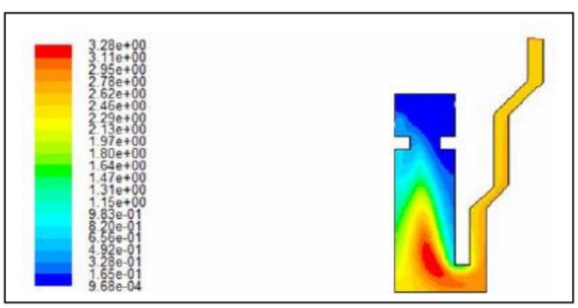

Fig 5. The profile of NO_2 concentration (ppm) in the boiler for 20% of biodiesel in fuel (B20)

It has been illustrated in fig 6 that the SO_2 concentration at the gas stack is about 14,00 ppm. SO_2 production is modeled as the oxidation of reduced sulfur gases (i.e. H_2S). Due to burning of fuel the sulfur is oxidized primarily to sulfur dioxide. Primarily during combustion of fuel in boiler the chances of formation of these gases are very thin. The sub-models of sulfur emissions are added to main CFD model to know the emissions. In the case shown on the figure, the formation of SO_2 occurs in the boiler when the kinetics, stoichiometry, and mixing rates are favorable. SO_2 did not undertake further reaction, and the concentration is decreased slowly by dilution as the gases move up to the stack.

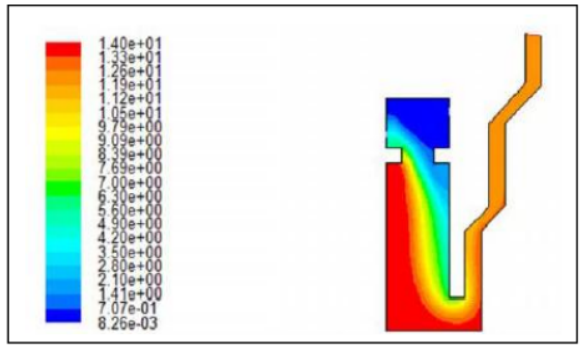

Fig 6. The profile of SO_2 concentration (ppm) in the boiler for 20% of biodiesel in fuel (B20)

From fig 7, we can see that the contours of CO_2 concentration at the outlet of gas stack has been predicted about 7.65% (v/v). Higher CO_2 concentrations are observed in the middle of combustion room. The CO_2 concentrations become lower in the gas stack area. The CO_2 emission depends on the fuel composition and combustion temperature. It is one of most important greenhouse gas that received the greatest attention in terms of emission control. CFD is used to study its behavior while combustion of fuel in the boiler.

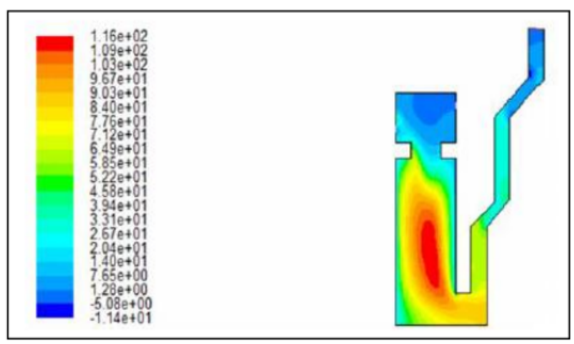

Fig 7. The profile of CO_2 concentration (ppm) in the boiler for 20% of biodiesel in fuel (B20)

E. Temperature Profile of Combustion

Fig 8 presents the temperature profile of combustion in the boiler for 20% of biodiesel blends. The temperature field presents two zones: the first one is located in the combustion area; the second is located in the boiler stack. The highest temperature is shown in the center of the boiler chamber. Due to the nature of diffusion combustion of the boiler, the maximum temperature value is achieved along the the centre of boiler which is about 2080 K. Fig 8 also indicates that the temperature decreased significantly with the increasing of stack length. The lowest temperature of the boiler stack is about 1900 K.

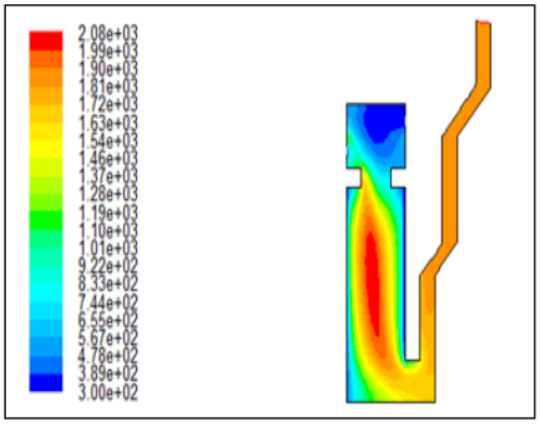

Fig 8. The temperature profile of combustion (K) in the boiler for 20% of biodiesel in fuel (B20)

V. Conclusion

Based on experimental and CFD simulation data's, it was concluded that the utilization of biodiesel has the advantage for industrial boiler since it can reduce the gases emissions compare to petroleum diesel oil. The numerical models were found to give reasonable agreement with the experimental data. The emission of pollutant gases decreased with the increasing of biodiesel content in the blends. CFD Simulation results show that the lowest gases emissions are about 2,78 ppm (NO_2); 14,00 ppm (SO_2) and 7,65 % v/v (CO_2) which is found in the 20% of biodiesel in fuel (B20). The lowest temperature of the boiler stack is about 1900 K.

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