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

Novia Novia  
Chemical Engineering Department  
Faculty of Engineering, University of Sriwijaya  
Indonesia  
noviasumardi@yahoo.com

Tri Kurnia Dewi  
Chemical Engineering Department  
Faculty of Engineering, University of Sriwijaya  
Indonesia  
tkdewi@yahoo.com

Winny Andalia  
Postgraduate Student, Chemical Engineering Department  
Faculty of Engineering, University of Sriwijaya  
Indonesia

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 (NO₃), 14.00 ppm (SO₂) and 7.65 % v/v (CO₂) 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 (NO₃, CO₂, and SO₂) 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\textsubscript{2}, CO\textsubscript{2}, and SO\textsubscript{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]:

\[
\left( \frac{\partial}{\partial t} (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) \right) = -\nabla p + \nabla \cdot (\tau) + \rho \mathbf{g} + \mathbf{F}
\]

(1)

Where:

\[
\overline{\tau} = \mu \left( \nabla \mathbf{u} + \nabla \mathbf{u}^T \right) - \frac{2}{3} \nabla \left( \mathbf{\bar{v}} \cdot \mathbf{\bar{v}} \right)
\]

(2)

The mass conservation equation [1]:

\[
\frac{\partial}{\partial t} (\rho Y_i) + \nabla \cdot (\rho \mathbf{u} Y_i) = -\nabla \cdot \mathbf{J}_i + R_i + S_i
\]

(3)

Where:

\[
\mathbf{J}_i = \left( \rho D_{ij} + \frac{\rho H_i}{S_{ij}} \right) \nabla Y_i
\]

(4)

\[
\mathbf{R}_i = \Gamma \left( \mathbf{D}_{i}^{\text{chem}} - \mathbf{D}_{i}^{\text{chem}} \right) \left( k_{ij} \mathbf{C}_j^{\text{chem}} \right)
\]

(5)

\[
\Gamma = \sum_j \gamma_{ij} \mathbf{C}_j
\]

(6)

The energy conservation equation [1]:

\[
\frac{\partial}{\partial t} (\rho E) + \nabla \cdot (\rho \mathbf{u} E + p) = \nabla \cdot \mathbf{q} + \left( k_{\text{eff}} \nabla T - \sum_j \lambda_j \mathbf{J}_j \right) + \mathbf{S}_h
\]

(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\textsubscript{2}, CO\textsubscript{2}, and SO\textsubscript{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>
<thead>
<tr>
<th>TABLE I. SPECIFICATION OF FIRE TUBE BOILER</th>
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<tbody>
<tr>
<td>TYPE</td>
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<tr>
<td>Pressure</td>
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<tr>
<td>Steam Capacity</td>
</tr>
<tr>
<td>Temperature</td>
</tr>
<tr>
<td>Dimension</td>
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<tr>
<td>Shell – Tube Plate</td>
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<tr>
<td>Fire Tube</td>
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</tbody>
</table>

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.
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.

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\(_2\)O 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.

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.
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.

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$_2$S). 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.

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.
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 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 (NO2); 14.00 ppm (SO2) and 7.65 % v/v (CO2) 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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