Investigation of Electronically Controlled Steam Injection to Reduce NOx Emissions of DI Diesel Engine Running with Biodiesel

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Abstract: - Biofuels are seen as an alternative for diesel fuel owing to renewability, biodegradability and generating acceptable quality exhaust gases. The biggest penalty of biofuels is the increase in NOx emissions due to high level oxygen content. In this study, effects of electronically controlled water steam injection to the intake manifold of a single cylinder diesel engine to performance and emissions are investigated by experimentally, in order to control the high NOx emissions originated from biofuels. The biodiesel fuel, which is derived from canola oil by transesterification method, is blended with conventional diesel with mixing ratios of 10% by mass, for engine tests. In the experimental work, which is conducted in full load conditions, performance and emission changes are observed by injection of variable ratios of water steam (10%, 20%, 30%). Experimental results indicates that NOx emissions are decreased up to 22%, while engine torque and power increase up to 2,5% and break specific fuel consumption decrease up to 3%. Besides the progresses in the exhaust emissions and performance, there is an increase in the CO emissions, due to the cooling effect of the injected steam.

Key-Words: - Diesel engine, emission reduction, NOx emissions, biodiesel, steam injection

1 Introduction

Diesel engines are one of the primary sources of air pollution, in spite of being the major sources to provide the power demand in industry [1]. Diesel exhaust contains hundreds of chemicals in gaseous and particle phase. NOx and PM are the most considerable and hazardous ones in terms of human and environmental health [2].

One of the emission control methods for the purpose of reducing NOx emissions originated from diesel exhaust is the use of water. In this method, atomized water droplets reduce NOx emissions while absorbing some heat while vaporization which causes the peak combustion temperatures to lower [3,2]. Micro expositions of water droplets during the vaporization also provide a better atomization of fuel and improve combustion efficiency. Water injection in diesel engines can be implemented as emulsion of water and fuel, injection into the cylinder via fuel injector or a separate injector, or moistening of inlet air.

Many researches focusing on the effectiveness of water fuel emulsions on the reduction of NOx and other emissions can be found in literature [4,5,6]. On the other hand, water-fuel emulsion technique may cause an increase in other emissions [7,8], and reduce the thermal efficiency [9] meanwhile controlling NOx emissions. Furthermore, emulsion production and required modifications may rise the engine manufacturing and operation costs [3].

The other method of using water in purpose of reducing NOx emissions is injecting water into the cylinder directly. The major advantage of water injection technique is to allow the variation of water-fuel ratio according to engine parameters and it provides a better optimization in all operating conditions [10]. Although DWI technique provides a significant reduction on NOx emissions and a better combustion, as the water ratio in the mixture increase, sooth emissions may get worse and if injected water reaches cylinder wall, contamination of lubricating oil may bring a corrosion problem [11,12].

As the water can be injected into the engine directly, it can be used by moistening inlet air. In this method, various locations are possible to implement water injection including intake manifold, inlet or outlet of turbocharger compressor [3,13,14]. Inspite the achievements of this method,
some researchers reported that WI increase heat loses at cylinder wall and has a negative effect on engine global efficiency [3]. Diesel fuel can be considered as a non-renewable fuel and its sources may exhaust in near future[15]. Biofuels are seen as an alternative for diesel fuel owing to renewability, supply convenience and generating acceptable quality exhaust gases [16]. due to the reasons of either increasing need for alternative fuels, or international regulations taken into action by many governments, biofuels have become the subject of many researches [17,18,19]. The biggest penalty of biofuels is the increase in NOx emissions for the reason of high level oxygen content and shorter ignition delay [20]. Oxygen content of biofuels increases the NOx generation under the high temperatures during the combustion.

In this study, effects of electronically controlled water steam injection into the intake manifold of a single cylinder diesel engine to performance and emissions are investigated by experimentally, in order to control the high NOx emissions originated from biofuel use. To solve the problem associated with the corrosion in cylinder wall in case of water injection, thermodynamic condensation limit was determined numerically. Steam amount, which was injected in intake stroke, was determined as percentage of injected total fuel for each engine speed and load with the help of developed computer software.

2 Material and Method

2.1 Preparing Test Fuels

Methyl ester derived from corn oil is used in engine tests. Methyl ester was produced with transesterification method. Transesterification is the reaction of a fat or oil with an alcohol to form esters and glycerol. During the transesterification process, methyl alcohol in 99% purity was used in ratio of %20 by mass. As catalyst, KOH was used in ratio of 1% by mass.

The biodiesel fuel is blended with conventional diesel with mixing ratio of 10% by mass, for engine tests.

2.2 Experimental Set-Up

The effects of steam injection on the performance and emission characteristics are investigated during the test program using a single cylinder, four stroke, direct injection, water cooled, naturally-aspirated diesel engine running with different mixing ratios of biodiesel fuel. The experimental setup is shown in figure 1 and, specifications of the test engine used are given in table 1.

![Fig.1. Experimental set-up](image)

<table>
<thead>
<tr>
<th>Table 1. Engine specification</th>
</tr>
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<tbody>
<tr>
<td>Engine Type</td>
</tr>
<tr>
<td>Bore [mm]</td>
</tr>
<tr>
<td>Stroke [mm]</td>
</tr>
<tr>
<td>Cylinder Number</td>
</tr>
<tr>
<td>Stroke Volume [cm³]</td>
</tr>
<tr>
<td>Power, 1500 rpm, [kW]</td>
</tr>
<tr>
<td>Injection pressure [bar]</td>
</tr>
<tr>
<td>Injection timing [Crank Angle]</td>
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<tr>
<td>Compression ratio</td>
</tr>
<tr>
<td>Maximum speed [rpm]</td>
</tr>
<tr>
<td>Cooling</td>
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<tr>
<td>Injection</td>
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Engine torque was measured by anBaturalp-Taylan brand hydraulic dynamometer. All emission measurements during these tests were made using MRU Delta 1600 L model exhaust gas analyzer. A steam injection system was used for injection of steam through the inlet manifold of the engine. The injected steam amount was controlled by a programmable ECU. The steam injection system was located just behind to the inlet valve, to ensure the injection timing in the inlet stroke.
Steam was injected at 133.5°C and 3 bars conditions, which is the saturation point of water, via coil winding injector. Throttling by injector, pressured and heated water which is in the form of saturated liquid becomes superheated steam thus the corrosion problem caused by condensation is prevented.

Engine tests was performed under full load conditions and at variable engine speeds. During the tests, injection timing has been maintained at 35° before top dead centre. Tests have been carried out for steam injection in three different ratios including 10%, 20% and 30% by mass of injected total fuel to determine the optimum steam ratio, and obtained results are compared to biodiesel blends and conventional diesel fuel results.

3 Results and Discussion

The effects of steam injection on diesel engine running with biodiesel are investigated in this study. Obtained experimental results are given below in comparison with standard diesel fuel results.

3.1 NOx emission

NOx emissions are resulted from high temperatures in cylinder during the combustion. Biodiesel fuels increase the combustion temperature and NOx emissions due to the approximately 10% oxygen content. Figure 2 shows the in-cylinder temperatures for the various steam ratios and engine speeds in the use of 10% biodiesel blend by mass (B10).

Fig. 2. Temperatures for different steam ratios

Lowering effect of the steam injection on the in-cylinder temperatures, which increase with the use of biodiesel blend, can be seen in fig.2.

Fig. 3. NOx emissions for B10 and B10+S10

Fig. 3. shows the NOx reduction with the use of steam injection and fig.4 shows the percentage of change of NOx emissions regarding to standard diesel fuel values.

Fig. 4. Percentage of change of NOx emissions

It can be seen from the figures that biodiesel blend increase the NOx emissions due to the high oxygen content. Steam injection reduced the emission levels under the standard diesel fuel values. NOx emission values decrease at all engine speeds and all steam ratios. Maximum reduction on NOx emissions regarding to standard diesel fuel values is 22% at 1200 rpm with 10% biodiesel blend and 10% steam injection (10B+10S). The lowest NOx level found as 462 ppm at 2400 rpm engine speed with 10% biodiesel blend and 10% steam injection. 10% steam amount is seen as
optimum level for all engine speeds in term of NOx emission.

3.2 CO Emissions

![Fig.5. CO emission levels for different steam ratios](image1)

Fig.5 gives the CO emissions for steam injection in variable ratios. It is shown from the figure that steam injection has a negative effect on CO emissions. The main reason of the CO formation in combustion is poor oxygen level or low combustion temperature. The cooling effect of the steam injection increase CO levels, while reducing NOx emissions.

3.3 Engine Torque and Power

![Fig.6. Engine torque levels for different steam ratios](image2)

Fig.6 gives the experimental results of engine torque with steam injection. Engine torque levels increase with the 10% steam injection, besides the increase in the steam amount make an adverse effect on engine torque. Maximum torque level is observed at 1600 rpm with 10% biodiesel blend and 10% steam injection. The highest change on the engine torque regarding to standard diesel fuel values is approximately 2.5% at 1200 rpm with 10% biodiesel blend and 10% steam injection.

![Fig.7. Engine power levels for different steam ratios](image3)

The effect of steam injection on engine power is shown in fig.7. the engine power results are in parallel with engine torque results. The highest change on the engine power regarding to standard diesel fuel values is approximately 2,5% at 1200 rpm with 10% biodiesel blend and 10% steam injection.

3.4 Brake Specific Fuel Consumption

![Fig.8. BSFC levels for different steam ratios](image4)
Fig. 8 gives the effects of steam injection on brake specific fuel consumption (BSFC). Steam injection of 10% provides some decreases in BSFC in many engine speeds. Higher steam levels make a negative effect on BSFC. As injected steam amount increase, BSFC levels increase, too.

Maximum reduction on BSFC is 3% at 1200 rpm with 10% biodiesel blend and 10% steam injection.

4 Conclusion

Experimental investigation of the effects of steam injection to a single cylinder biodiesel fueled diesel engine to performance and emissions has been presented, in this study.

Experimental results show that, steam injection significantly reduces NOx emissions up to 22%, which was increased with biodiesel blend. The cooling effect of steam injection lowers in-cylinder peak temperatures and provides lower NOx emission values. On the other hand, these lower temperatures make an adverse effect on CO emissions and cause an increase in CO levels at all engine speeds.

It is also found that, steam injection increase the engine torque and power up to 2.5%. Brake specific fuel consumption can be reduced up to 3% with 30% steam injection.

10% seems as optimum steam injection ratio in terms of NOx reduction, engine torque, engine power and BSFC, for diesel engine running with 10% biodiesel blend.

On the whole, steam injection method has a considerable potential to reduce NOx emission for on-road vehicles, heavy duty diesels and marine diesel engines without a loss in performance. However, the method still needs some improvements for application to the real engines.

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