CONTROL OF DIESEL ENGINE EMISSIONS BY DILUTE OXIDIZER INJECTION

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ABSTRACT

The current diesel engine power systems have progressed to the point where significant reduction in emissions or fuel consumption are at the limit of the state of the art with the present fuels. It is proposed that overall system weight, power or efficiency must be traded to achieve reduced exhaust emission levels.

Emission control through the injection of dilute oxidizers are explored to minimize the formation of noxious gases, emission of unburned hydrocarbons and soot in internal combustion diesel cycle engines. Relevant literature detailing the attempts to control exhaust emissions by altering the intake charge are reviewed and utilized as the foundation for the current study. Steady flow type combustion simulations utilizing low concentration hydrogen peroxide with available air in varying ratios are presented for trend comparison to experimental data developed during this investigation.

The empirical portion of the study focused on the adaptation of proposed dilute hydrogen peroxide injection to a standard four cylinder marine diesel engine. The main thrust evaluated the impact of oxidizer injection on an aging engine without significant modifications to the existing auxiliary equipment. A simple spray apparatus delivered the dilute hydrogen peroxide to the air intake stream to minimize the alterations to the existing system.

Water injection was performed as an experimental control for comparison to reference literature and to normalize the results obtained from the injection of the 5% and 10% concentration hydrogen peroxide. The injection of both concentrations of hydrogen peroxide showed an improvement relative to water injection for unburned hydrocarbon and oxides of nitrogen emissions. The improvements relative to water was greater with the higher concentration of hydrogen peroxide.

INTRODUCTION

The purpose of this study was to evaluate the effects of low concentration hydrogen peroxide (H₂O₂) injection into the inlet air stream of a diesel engine on exhaust emissions. The potential effects were initially evaluated by analytical methods using chemical equilibrium computer simulations of a steady state combustion process and finally through experimental results. While the steady state combustion simulations do not account for chemical kinetic effects, they were used as an indicator of the trends to be expected from the empirical portion of the investigation. The investigation was initiated with a literature search of pertinent studies which were used to develop a set of control experiments to validate the test configuration.

REVIEW OF CURRENT PAPERS

Numerous attempts have been made to reduce the emissions of diesel engines and understand the mechanism of the emission formation process. The diesel combustion process is highly unsteady and is an extremely difficult process to model even with the most sophisticated analytical tools. In this study careful attention has been placed on the notion that to change the exhaust emission, one must change the constituents in the intake charge.

Plee (1982) et al suggest a simple correlation technique for predicting the NOx in diesel engines by comparison to steady-spray flame analysis. The intake charge was varied by the introduction of O₂, N₂, Ar, exhaust gas and heated air into
CHEMICAL EQUILIBRIUM

The NOx emissions for two different engines were evaluated over a range of speeds and maximum continuous engine load with the relative NOx formation found to be independent of engine speed and combustion chamber geometry. The data derived from the testing indicated a direct correlation of NOx formation to the flame temperature of the combustion process. The NOx reductions did reach a minimum value at 2125 K with N2 injection at which point the combustion process had deteriorated to the point where excessive ignition delay with high carbon monoxide (CO) and unburned hydrocarbons (HC) were detected.

Greeves (1977) et al evaluated the effects of water injection on diesel exhaust emissions using various injection methods. Three methods were studied; direct cylinder injection, injection into the air inlet stream and fuel emulsification techniques. The results were similar to Plee (1982) et al; however, the NOx reduction was again reported to be achieved at the expense of increased ignition delay, smoke, CO and unburned HC. This study shows the sensitivity of exhaust emissions to the constituents of the intake charge. The technique which produced the least ignition delay was injection of water into the intake air stream.

Jiang (1990) et al evaluated the effects of alcohol injection with the intake air stream. The apparent correlation of NOx to temperature was again observed with the increase in CO and unburned HC. The control for the experiments was water injection into the air inlet stream. By evaluating the ratio of NOx reduction with alcohol to that with water injection versus combustion temperature, significant differences were noted with the alcohol.

The alcohol injection again resulted in lower NOx levels at the expense of increased CO and HC emissions. The approach transferred high temperature diesel fuel combustion to the lower net flame temperature associated with the combination of diesel and alcohol. The net result enforced the temperature dependency of NOx formation in the combustion process beyond the lower flame temperature limit identified by Plee (1982) et al. The resulting increase in measured HC emissions was also lower than that observed for water injection.

It is proposed that NOx emissions can be controlled and HC emissions maintained at or near constant by injection of a dilute oxidizer to provide the necessary flame temperature suppression to avoid NOx formation and allowing the combustion process to continue to completion in the oxidizer rich zones by the liberation of free oxygen as heat is transferred to the oxidizer droplets. The aforementioned attempts to control the exhaust emissions neglected measures to ensure complete combustion and therefore resulted in the measured increases in CO and HC.

Table 1: Average Baseline Testing Conditions

<table>
<thead>
<tr>
<th>RPM</th>
<th>Power</th>
<th>Air Flow (kg/hr)</th>
<th>Fuel Flow (kg/hr)</th>
<th>Phi</th>
<th>Pcyll (Psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1300</td>
<td>5 HP</td>
<td>67.61</td>
<td>1.26</td>
<td>0.27</td>
<td>425</td>
</tr>
<tr>
<td>1800</td>
<td>10 HP</td>
<td>93.60</td>
<td>2.26</td>
<td>0.35</td>
<td>550</td>
</tr>
<tr>
<td>2200</td>
<td>15 HP</td>
<td>114.4</td>
<td>3.45</td>
<td>0.43</td>
<td>650</td>
</tr>
</tbody>
</table>

The PEP code was used primarily as a trend indicator and was not intended to develop absolute predictions of the test results. The exhaust products were evaluated from the combustion chamber results of the output data. The Gibbs steady state free energy minimization routines of the PEP code do not accurately predict unburned hydrocarbon emission levels. This is primarily due to assumptions of constant pressure combustion and no cylinder wall or piston combustion quenching effects associated with the kinetic portion of the combustion process.

Figures 1 and 2 summarize the initial chemical analysis which represents the comparison of the mean combustion temperature and normalized NOx emission prediction (NOx / NOxsd) for water, 5% and 10% H2O2 injection versus diluent to fuel ratio (volume ratio) for plateau 2. NOxsd is NOx emission prediction without the addition of water or H2O2. The inverse temperature dependency of the NOx emissions as predicted by PEP are similar to the results obtained in the reference literature.
EMPIRICAL STUDIES

Empirical studies were performed using a four cylinder Westerbeke 30 marine diesel engine connected to a combination water / friction brake dynamometer. The 91 cubic inch displacement engine has a 2.875 inch bore, 3.5 inch stroke with a 23:1 compression ratio and provides a maximum continuous output of 25 horsepower (HP) at 2500 revolutions per minute (RPM). The fuel injection system was left at the factory settings for the entire test series. The goal was to evaluate the overall trends of the combustion process and exhaust products while maintaining a constant injection timing.

The liquid injection was accomplished though direct injection into the air inlet manifold. A 4 inch diameter extension tube 12 inches in length was substituted for the air filter assembly. An oil burner fuel injection nozzle was positioned in the center of the induction pipe in an attempt to maximize the atomization of the injection fluid. Flow control was accomplished by pressurizing the liquid storage tank with air and adjusting the pressure regulator until the desired flow was achieved. The flow rate was measured using an in-line flow meter.

The instrumentation used for the experiments consisted of turbine flow meters to measure liquid flow rates, an engine dynamometer, HC and NOx analyzers to measure the exhaust characteristics, thermocouples for the exhaust temperature measurement and a magnetic sensor for engine speed in revolutions per minute (RPM). Data acquisition for the entire test series was conducted at 10Hz sample rate for 4 seconds at each plateau to yield a total of 40 samples recorded for each channel.

The three testing power levels were chosen from the manufacturer recommended propeller loading curve. The primary objective of this study was to evaluate the injection system as close to practical implementation conditions as possible. This differed from the reference literature which typically used the maximum continuous power curve associated with the test engines. Since the testing was conducted with a seasoned engine it would not have been advisable to exceed the recommended propeller loading curve.

Numerous baseline measurements of the engine were planned for the purpose of normalizing the data from the injection of the various liquids and for establishing the deviation or expected errors in measurement. Water was chosen as a control case study for the experiments since there was an abundance of data from the reference literature for comparison. Water injection would also serve as a benchmark to compare the relative performance of the H2O2 injection on the unburned HC and NOx exhaust emissions.

Baseline tests were to be conducted before, after and periodically during each of the test series. A test series was defined as completing one set of data by varying the volume ratio of injection liquid to fuel flow from 0.25 to 1.25 in 0.25 increments at each of the three power levels for a total of 15 discrete test plateaus. A test series was repeated a minimum of 3 times to ensure repeatability of the measurements.

Once the basic test configuration was validated by establishing the baseline measurement deviation, water injection, then 5% and 10% concentration H2O2 was injected for analysis and comparison to the reference literature. The data was normalized by dividing the measured exhaust emissions by the median baseline exhaust values.

RESULTS

Water injection was evaluated as a control for the experiments and for comparison to the results obtained in the reference literature. Adjustments were made as necessary to the throttle to maintain baseline speed and power levels during each test series. The results were used for a direct comparison to the baseline data previously obtained. The diluent to fuel ratio (volume ratio) was varied from 0.25 to 1.25. Similarly, the 5% and 10% H2O2 data was acquired. Figures 3 through 5 show the
results normalized with the baseline median values for HC, NO\textsubscript{x} and fuel flow for plateau 2.

**Figure 3: Plateau 2 Normalized Water Injection Results**

Data reduction was used to validate the test configuration by comparison to the water injection results from the reference literature. The normalized HC results for water injection presented in figure 3 may appear highly variable, they fall within the results noted by Greeves (1977) et al. Water injection results were also used to normalize the 5% and 10% H\textsubscript{2}O\textsubscript{2} injection data.

Standard curve fitting routines were applied to the data acquired and used to develop graphical trend indicators. The equations for the best fit curves were used to compile emission trends for equivalent injection volume ratios. The 5% and 10% H\textsubscript{2}O\textsubscript{2} trend results were divided by the water injection trend results to develop the performance comparison relative to water for each plateau. The results of the data reduction are presented in figures 6 through 9. Error bars were not included in the trend indicator plots for clarity (but must be considered for absolute values).

The NO\textsubscript{x} emission reduction results of all the testing were compared to predicted reductions in addition to the performance comparison relative to water injection. The trends are shown in figures 10 through 12. Since the PEP code does not take into account chemical kinetics, it does not predict the presence of unburned HC and the comparison with experimental results was omitted.
Figure 7: Comparison Of 5% H₂O₂ To Water Injection NOₓ Emissions

Figure 8: Comparison Of 10% H₂O₂ To Water Injection HC Emissions

Figure 9: Comparison Of 10% H₂O₂ To Water Injection NOₓ Emissions

Figure 10: Plateau 2 Water Injection NOₓ Reduction Comparison To Predicted

Figure 11: Plateau 2 5% H₂O₂ Injection NOₓ Reduction Comparison To Predicted
CONCLUSIONS AND RECOMMENDATIONS

In general, the injection of dilute hydrogen peroxide resulted in an improvement over water injection with respect to NO\(_x\) emissions and reduced the magnitude of unburned HC emissions relative to water injection. The trend indicators revealed an expected exhaust emission power dependency due to the peak cylinder pressure differences for each power level. At lower power levels, the combustion process is more easily quenched due to the low cylinder pressure, equivalence ratio and low mean cylinder temperature. As the power levels are increased, the associated increase in the mean cylinder pressure, equivalence ratio and mean cylinder temperature improves the combustion process.

The injection of the various fluids has a minimal effect on the fuel consumption of the engine (typically less than 5% increase). This is encouraging from an implementation point of view in that the fuel cost would remain constant with an add on water or oxidizer injection system. The reference literature indicates improvements in the fuel consumption at low volume ratio injection flow rates. The fuel consumption at very low volume ratio injection flow rates were not evaluated during this investigation due to limitations in injection flow measurement equipment. Exploration of the 0.1 to 0.25 volume ratio injection flow rates with dilute hydrogen peroxide is recommended for future studies.

Comparison of the experimental results to predicted values indicates that injection of \(\text{H}_2\text{O}_2\) has a marked effect on the chemical kinetics of the combustion process. Emissions with water injection exceed predicted levels and the \(\text{H}_2\text{O}_2\) injection shows improvement over predicted NO\(_x\) levels as the concentration is increased. For example, at an injection volume ratio of 1, the NO\(_x\) emissions were 90% and 80% of water for 5% and 10% \(\text{H}_2\text{O}_2\) injection respectively. The increased available oxygen in the form of \(\text{H}_2\text{O}_2\) in the combustion zone along with the necessary diluent water to reduce the flame temperature appears to stabilize the combustion relative to the baseline or water injection combustion process. The combustion kinetics improvement is similar to that experienced with low volume flow rates of water injection which reduces NO\(_x\) and HC emissions with lower fuel flow rates.

The large variations in HC emissions observed while injecting the various fluids may have been due to the various cylinders receiving different quantities of the diluent liquid. This is largely due to the longer intake manifold runner length for the outer two cylinders. Since the entire injection stream was not atomized, the injection fluid “puddle” in the intake manifold. This is a systemic problem which is evident in all inlet manifold injection applications due to the geometry of existing engines. The net effect would be to occasionally distribute more liquid to the center two cylinders and less to the outer two. This causes the inner two cylinders at times to produce much more unburned HC than the outer two because of the increased volume ratio of injection fluid.

It is recommended that the next logical step in reducing exhaust emissions is to minimize the dependency of the system on available in cylinder air for combustion. This can be accomplished by the use of a fuel oxidizer emulsion. By doing so, the classic center rich and perimeter lean combustion of the diesel cycle can also be minimized. By injection of a stoichiometric propellant emulsion, the compressed air would act mainly as an initiator for the emulsion. The temperature of the combustion process can be controlled more precisely by the amount of water dilution of the oxidizer and minimize the formation of NO\(_x\). The emulsion will also eliminate the fuel rich core which contributes to the levels of unburned HC emissions.

The injection of a stoichiometric emulsion can lead to combustion behavior similar to steady flow type combustion chambers. The resulting stabilized combustion process may remain steady at much lower temperatures. Further testing in steady flow combustion chambers and diesel engines is recommended to evaluate the low limit combustion temperature with stoichiometric fuel / oxidizer emulsions.

As a cautionary note, it is imperative that the pumping system be qualified in a remote controlled test cell with the proposed emulsion to verify detonation of the fuel / oxidizer will not occur in the pump. Navy experience indicates 50% total water content and above of the emulsion as minimizes the potential for fuel detonation in the pump. Hydroxyl Ammonium Nitrate (HAN) is another candidate oxidizer which has excellent storage and emulsion pumping characteristics for the emulsion studies.

REFERENCES


