V. OFF-HIGHWAY ENGINE EFFICIENCY R&D

V.1 Exhaust Aftertreatment and Low-Pressure Loop EGR Applied to an Off-Highway Engine

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Objectives

The 2006 objective of this project was to use the MTU 1-D diesel oxidation catalyst (DOC) model and the MTU 1-D 2-layer catalyzed particulate filter (CPF) model to predict the engine exhaust back-pressure, and the filtration and oxidation characteristics of the aftertreatment components as a function of engine loads, configurations and loading time. The loading experimental data was then used to characterize the performance of the DOC and CPF.

Accomplishments

- The MTU 1-D and 2-layer models have been enhanced and calibrated.
- The models predict the pressure drop across the DOC and CPF.
- The models estimate the amount of particulate matter (PM) entering the CPF, the amount oxidized and the amount exiting.

Future Direction

- The project is complete but the next step would be to apply the models to transient operation.

Introduction

An experimental and modeling study was conducted using emissions data measured from the exhaust of a John Deere 6.8 liter, turbocharged and after-cooled engine with a low-pressure loop exhaust gas recirculation (EGR) system which includes a DOC-CPF in the exhaust system. A series of experiments were conducted to evaluate the performance of the DOC, CPF and DOC+CPF configurations at various engine speeds and loads. Pressure drop across the devices, mass of PM deposited in the CPF at the end of loading, upstream and downstream gaseous and particulate emissions, and particle size distributions were measured at different times during the experiments to characterize the pressure drop and filtration efficiency of the DOC-CPF system at each engine load case as functions of loading time.

The project was divided into two tasks. Results from Task I focused on meeting the off-highway Tier 3 emission standards and were reported in 2004; results from Task II focused on meeting the Tier 4 emission standards with improved fuel economy and were reported in 2005. Finally in 2006 the results from the aftertreatment modeling studies are reported in this study.

Approach

The MTU 1-D DOC model was developed as part of this research [1] and is based on similar models available in references 2, 3, 4 and 5. This model uses a one-dimensional single channel representation of the DOC, as shown in Figure 1. The exhaust gas mixture flows through the DOC in a 2-phase flow (gas-phase and solid-phase), and all gaseous species reactions are considered to be occurring in the solid-phase, and at the local substrate wall temperature. The kinetics scheme considered in the model uses equations of the Langmuir-Hinshelwood form [4] for expressing the rates of chemical reactions. There are eight global one-step reactions available in the DOC model.

The detailed description of the MTU 1-D 2-layer CPF model developed as part of previous research at MTU is given in references 6 and 7, and is based on the

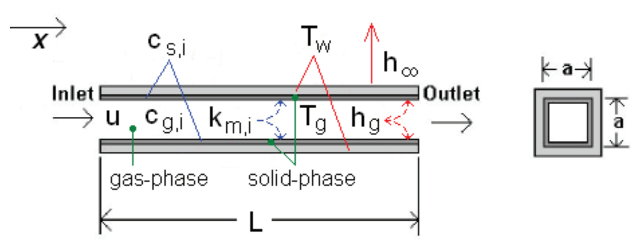

FIGURE 1. Schematic Representation of the Single Channel DOC

regeneration framework presented in reference 8, and the filtration process is based on the model presented in references 9 and 10. Figure 2 shows the representation of the CPF, which uses a single inlet channel, a substrate wall and a single outlet channel, with cross-sectional average values of velocity and exhaust temperature as input to represent all the CPF channels. The oxidation of PM deposited in the CPF takes place through two mechanisms – NO_2/temperature-assisted and thermal. The NO_2/temperature-assisted mechanism for PM oxidation occurs due to the inlet NO_2 as well as NO_2 produced as the exhaust gas mixture passes through the substrate wall. A description of the oxidation sub-model used in the CPF model is given in references 1, 6 and 7.

Results

Figure 3 shows a comparison of experimentally measured and model-predicted pressure drops obtained from the calibrated CPF model in the CPF configuration at the four engine load cases (25, 50, 75 and 100%) at 2,200 rpm, and Figure 4 shows a similar comparison for the four engine load cases in the DOC+CPF configuration at 2,200 rpm. A point-to-point comparison of pressure drop between experimental and model-predicted values showed a maximum variation of 0.85 kPa (in the 50% engine load case) in the CPF configuration and 0.80 kPa in the DOC+CPF configuration for the model-predicted values of ΔP. In the DOC+CPF configuration at 100% engine load case, a maximum variation of 1.22 kPa of the model-predicted ΔP from the experimental ΔP was observed, which is due to the CPF pressure drop model not being able to predict the highly transient variation in PM oxidation rates in the wall. Overall, good agreement of model-predicted CPF pressure drops was obtained in all cases, especially in the cake filtration regime.

Figure 5 and 6 show the mass balance curves from the calibrated CPF model outputs for the four

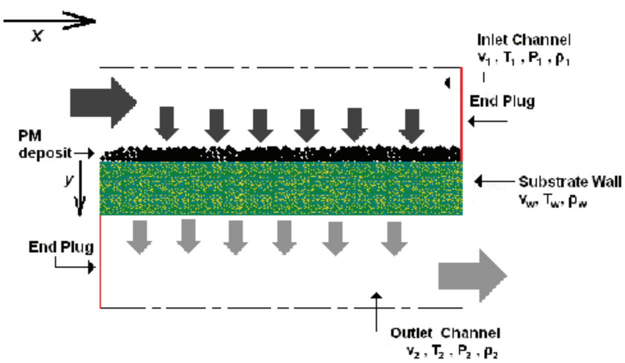

FIGURE 2. Schematic of Single Channel Representation used in CPF Model

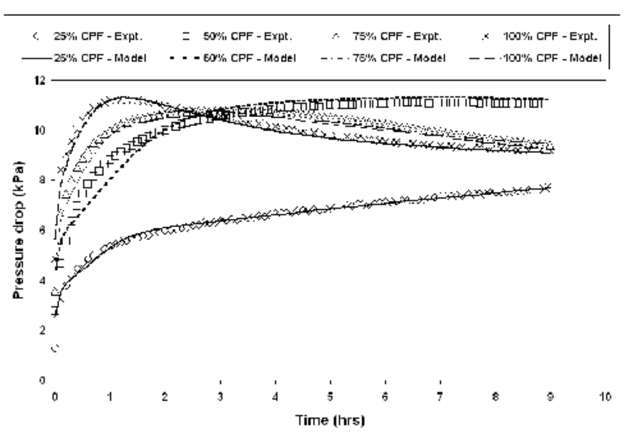

FIGURE 3. Comparison of experimental and model-predicted CPF pressure drop at various engine load cases in the CPF configuration at 2,200 rpm.

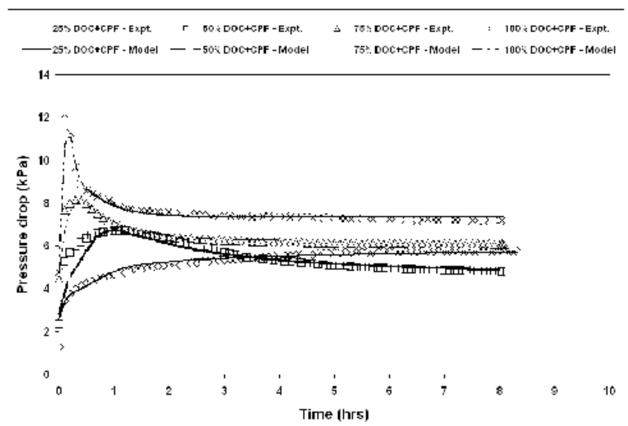

FIGURE 4. Comparison of experimental and model-predicted CPF pressure drop at various engine load cases in the DOC+CPF configuration at 2,200 rpm.

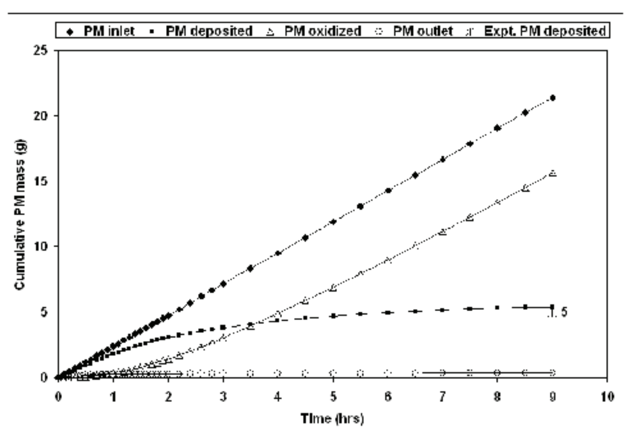

FIGURE 5. Particulate mass balance curves obtained from the calibrated CPF model at 100% engine load case in the CPF configuration at 2,200 rpm.

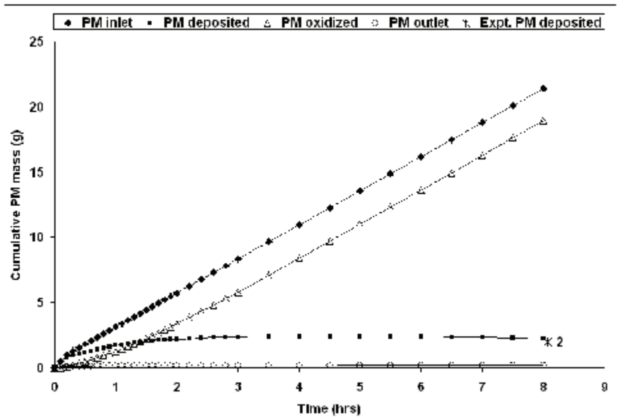

FIGURE 6. Particulate mass balance curves obtained from the calibrated CPF model at 100% engine load case in the DOC+CPF configuration at 2,200 rpm.

engine load cases studied. The experimental PM mass deposited in the CPF at the end of loading are also shown, labeled by their numeric values in *grams*. 'PM inlet' curves for each engine load case were linear since the CPF inlet PM concentrations and volumetric flow rates for the CPF model were considered to be the load-average values. 'PM deposited' for each engine load case shows the cumulative values, and was the sum of PM deposited in the PM cake layer as well as the substrate wall, although the majority of PM mass deposited was in the PM cake layer. Similarly, 'PM oxidized' curves also were the sums of PM mass oxidized in the PM cake layer and substrate wall. 'PM outlet' curves show the cumulative PM mass that had exited the CPF till the particular loading time since start of loading simulation. For both Figures 5 and 6 the PM deposited agreed well with the total PM mass measured in the CPF. Note that the DOC+CPF configuration had significantly higher PM oxidized due to the higher concentration of NO_2 in the exhaust.

Conclusions

- The MTU models accurately predicted the pressure drop across both the DOC and the DOC+CPF aftertreatment for various engine speeds and loads under steady-state operation.
- The MTU models also accurately predicted the amount of mass deposited and oxidized in the CPF as a function of time.
- The next step would be to apply transient operation to the MTU models to determine if they can be used to predict when an active regeneration would be required.

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FY 2006 Publications/Presentations

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V.2 Electrically Coupled Exhaust Energy Recovery System Using a Series Power Turbine Approach

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Objectives

The overall objective of this project is to demonstrate the technical benefits of electrically coupled turbo compounding. Specific objectives for 2006 included:

- Develop hardware and software suitable for vehicle demonstrations.
- Confirm compatibility of the technology with Tier 3 emissions regulations.
- Demonstrate performance characteristics on the dyno and in vehicles.

Accomplishments

- Through component optimization and turbo system matching, performance goals of 20% power growth and a 10% increase in fuel economy have been demonstrated at Tier 3 emissions levels.
- A compact 50 kW flywheel mounted motor/generator system was developed and tested. System efficiencies of over 95% in the key operating areas for off-highway equipment were demonstrated.
- A Deere 8530 tractor has been built and tested with a complete turbo compounding system. Power recirculation and system compatibility has been successfully demonstrated. The tractor is ready for fuel economy and productivity testing on the test track and field.
- A Deere 9L engine has been installed in an International 8600 truck and tested at the National Renewable Energy Laboratory (NREL). Results showed mileage equivalent to the base M11 truck engine. Turbo compounding hardware including a high power hybrid transmission and battery pack have been designed, built and tested. This equipment is now being installed into the truck and will be retested at NREL in early 2007.
- A variable geometry power turbine was developed and tested. The ability to increase part load system output by 50% was demonstrated. Fuel economy improvements were limited to less than 2%.
- Based on successful demonstration of concept demonstrator hardware, a second generation system has been designed. A more automotive-style turbo generator has been designed that uses higher rotor speeds with a revised speed control algorithm to improve system efficiency.

Future Directions

- Test vehicles under realistic operating cycles to document real world benefits in both fuel economy and vehicle productivity. This includes both tractor and truck evaluations.
- Develop second generation hardware with improved performance and greater commercialization potential. Updated turbo machinery will be critical here, particularly development of a turbocharger system that will provide high efficiency and adequate surge margin.
- Define optimal system architecture and power splits for Tier 4 emissions compatibility. Emphasis will be on aftertreatment and exhaust gas recirculation (EGR) plumbing.
- Increase scope of application of turbo compounding by evaluating performance enhancements in both larger and smaller engine platforms. Start with modeling to define potential and adapt existing hardware to demonstrate if advantages justify.

Introduction

The objective of this project is to characterize fuel economy and power growth benefits of electrically coupled turbo compounding, a waste exhaust heat recovery technology. This technology is becoming viable due to the commercialization of cost-effective high efficiency electrical components and controls, and because of increased emphasis on fuel economy. Bare engine and in-vehicle testing are being employed to develop valid performance assessments of the concept. Integrating the technology with emissions-driven engine changes to synergistically optimize system performance is a key requirement for successful implementation.

Approach

High power steady-state duty cycles glean maximum benefit from turbo compounding due to the greater time averaged energy availability compared to lighter duty cycles. Agricultural tractors fit this definition as do many on-highway trucks. A Deere 9.0L Tier 3 engine was selected as a demonstration platform since this engine is in a power class that fits both large agricultural tractors and on-highway Class 8 trucks. Special turbo compounding hardware including a high performance single stage high pressure ratio turbocharger, a high efficiency turbo generator, and a compact and efficient flywheel motor generator were designed, analyzed, built, and tested. Engine performance characteristics using this experimental hardware were compared to baseline engine performance. Performance development work completed in FY 2006 was focused on comparisons at Tier 3 emissions levels, while efforts are continuing to define optimal architecture for Tier 4.

Although bare engine performance provides an acceptable measure of the potential benefit offered by turbo compounding, it is ultimately necessary to apply the hardware to vehicles that can be evaluated under typical duty cycles to assure the benefits translate to real world fuel savings. This is due to different levels of benefit over the operating envelope, as well as potential transient effects. Vehicle testing is also useful in defining challenges that must be addressed in order to allow successful commercialization. Two vehicles were built to evaluate fuel economy benefits. A large 8530 Deere row crop tractor was upgraded to provide an additional 50 kW of power to the ground. The additional power was provided by the turbo compounding system. A 50 kW motor generator system was also integrated into the tractor drive train to couple the turbo generator output back into the tractor drive train. The base tractor was upgraded in order to be able to deliver the added power to the ground. This was done by stretching the wheelbase and applying significantly larger experimental tires.

In order to explore broader application of the technology, a Deere 9L engine was installed into an 8600 International truck. Baseline testing of the truck was required since this engine has not been applied to truck applications before. Testing was completed at NREL, showing the same fuel economy as the original truck engine. Hardware to add the complete turbo compounding system including an electric hybrid transmission and electrical energy storage system were also designed and built. Vehicle testing with the turbo compounding system is scheduled to be completed in early FY 2007.

Results

Output characteristics of a 50 kW electrically coupled turbo compounding system applied to a Deere 275 kW 9L diesel engine are shown in Figure 1. The engine meets Tier 3 off-highway standards. Results show output power from the turbo compounding system being reasonably linear with load and speed with maximum contribution at rated speed. The fuel economy plot in Figure 2 shows the benefits compared to a baseline non-turbo compounded engine over the speed range.

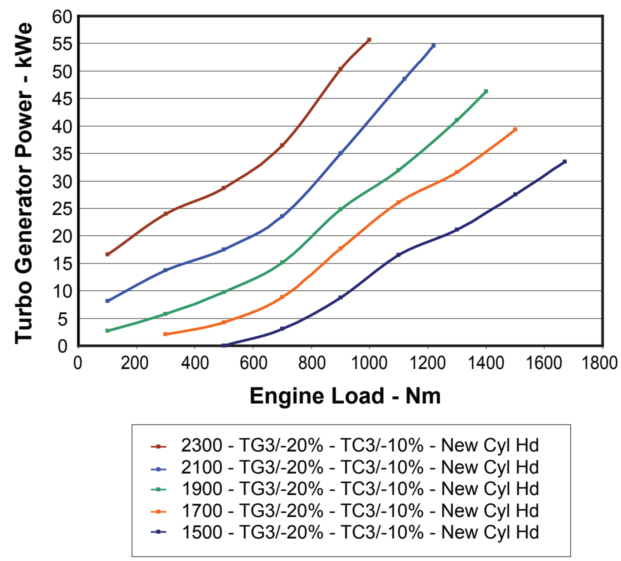

FIGURE 1. Typical System Output Characteristics

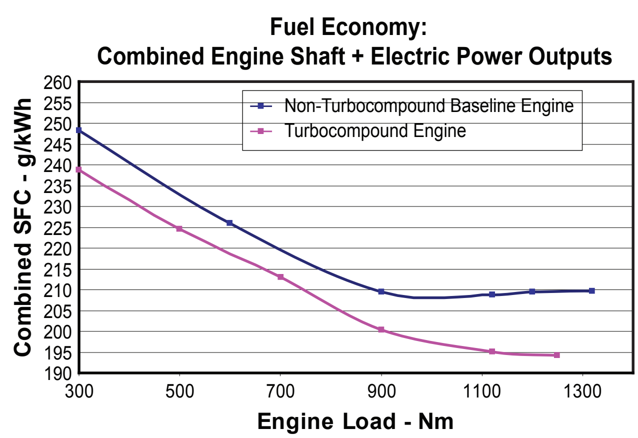

FIGURE 2. Specific Fuel Consumption (SFC) Characteristics at 2,100 RPM

Figure 3 shows a photo of the hardware as it was tested in the dyno. A variable geometry power turbine was developed and tested in an effort to extract more power at light loads common in many applications. An increase in output of 60% was demonstrated at the design point with modest improvements is overall fuel economy. Figure 4 shows the brake specific fuel consumption at 1,900 RPM.

Vehicle testing is needed to accurately characterize fuel economy benefits. A complete turbo compounding system was applied to a John Deere 8530 tractor. The machine is shown operating at high load on the power take-off dyno in Figure 5. The tractor is now ready for test track evaluation. Figure 6 shows the Deere 9L engine in the 8600 International truck. The truck was tested at NREL to define baseline fuel economy. Test results matched the baseline engine in the truck at 5.44 MPG on the West Virginia test cycle. Figure 7 shows the truck on the chassis dyno. The truck is now being rebuilt with turbo compounding hardware and is planned to undergo testing some time after March 2007.

Tier 4 emissions significantly impact the benefit of turbo compounding. Higher EGR rates rob the power turbine of flow with high-pressure loop EGR architectures. Flow restrictions due to diesel particulate filters are multiplied by the turbine pressure ratios, and

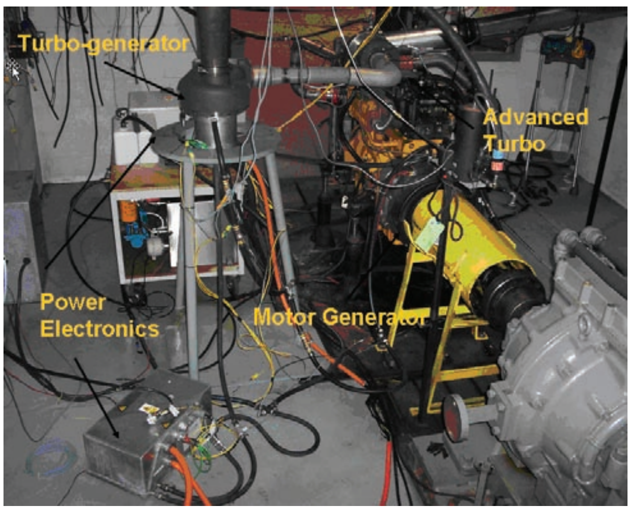

FIGURE 3. Electric Turbo Compounding System Hardware – Dyno Installation

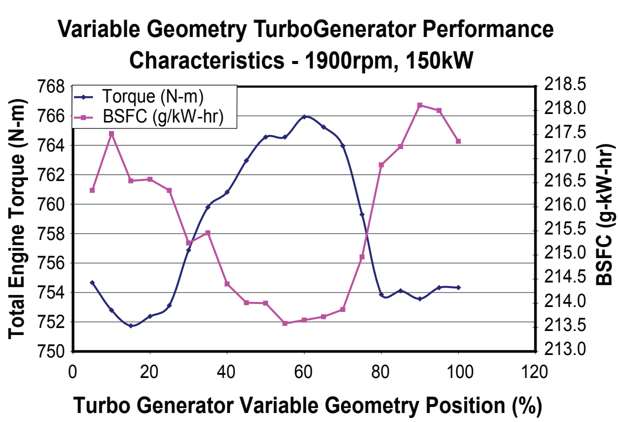

FIGURE 4. Performance of Variable Geometry Power Turbine

FIGURE 5. Turbo Compounded 8530 Tractor on Dyno

FIGURE 6. View of Truck Showing Deere 9L Engine in 8600 International Truck

FIGURE 7. Truck Running on NREL Chassis Dyno

this can significantly reduce the allowable pressure ratio and system output. Fuel economy with low-pressure loop EGR has been shown to be 3% better than with high-pressure loop and heat rejection is also significantly lower. Power growth with low-pressure loop EGR is also substantially greater. Turbo compounding eliminates the need for a variable geometry turbocharger, significantly reducing system complexity and cost.

Conclusions

Electric turbo compounding can deliver fuel economy benefits of 10% and provide power growth capability of 20% or more at Tier 3 emissions levels.

Turbo compounding is compatible with Tier 4 emissions regulations, but additional work is required to define optimal system architecture and performance. This is the subject of FY 2007 work that will address not only emissions, but also development of truly automotive hardware. Low-pressure loop EGR provides significant benefit, but also presents technical challenges.

System integration and performance has been demonstrated. Hardware has been shown to be reliable, and controls have proven manageable.