FINAL REPORT

Marine Engine Testing and Emissions Laboratory (METEL)

Led by Maine Maritime Academy

Federal Grant Number: DTRT13-G-UTC43

Project Title:

Development of Medium Speed Engine Testing Laboratory

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1. Overview

One fundamental pillar of the marine industry is the use of diesel engines for propulsion and to establish the vessel's electrical grid. The extent that this critical piece of technology is used is under scrutiny due to upcoming MARPOL greenhouse gas emissions regulations, more specifically the mandate to reduce the sulfur content in the fuel used onboard to 0.5% mass by mass. The issue at hand is that heavy fuel oils, or bunkers, are used as a primary fuel source as it is a cheaper diesel derivate, but has a Sulphur content of approximately 3.5% mass by mass. [1] Maine Maritime Academy developed a research lab to enable both MMA and the marine industry to test and validate technologies, fuels, fuel additives, and lubrication oils to either increase the diesel engine's efficiency or reduce the overall emissions output. The engine lab features an instrumented Wartsila 6L20 medium speed engine, the required support systems, and a continuous emissions monitoring system.

2. Engine Room Development

2.1 Engine installation

As the intent of the METEL engine research lab was to emulate a marine industry style engine room, it was important to get a marine style generator set. One was located, a Wartsila 6L20, using a third party vendor, purchased, and transported to MMA. This particular engine is a good representation of generator sets found onboard marine vessels, as most vessels have two to three, if not more, generator sets to maintain the vessel's electrical grid. The Wartsila 6L20 purchased was rated for 1020kW at 900 RPM with a displacement of 8.8 L/cyl. [2]

Once the engine was selected final design considerations could be made for the support system. As this is a marine style engine, it requires a support system to reject the heat developed from combustion inside the engine through freshwater cooling loops. This engine has two freshwater heat rejection loops; the high temperature (HT) loop which services the engine's water jackets piston liners, and the low temperature (LT) loop that services the lubricating oil (LO) cooler and the intake air cooler, referred to as the charge air cooler (CAC). These freshwater loops were designed to be a closed loop cooling system to enable the use of corrosion inhibitors in the cooling water, therefore the need to keep both the HT and LT loops at a constant temperature was required. An open loop seawater cooling system was designed and installed for this purpose. METEL attained proper state environmental protection permitting to allow for the discharge of the seawater back into the harbor. An exhaust system was constructed to vent the exhaust gases outside of the engine space with a 25 dB noise reducing muffler and ports to allow for continuous sampling of the exhaust gases. METEL also attained air emissions permitting with state and federal environmental protection agencies to allow for the operation of the engine. A pressurized air starting system, consisting of an air compressor and receiver, was also designed and installed to provide the air supply for the air driven Bendix-drive starter for the engine. Figure 1 shows pictures of the seawater cooling and air starting system. In order to provide a constant and predetermined load on the engine, a resistive load bank was purchased. The benefit of a resistive load bank is the removal of reactive power losses due to impedance and induction losses, resulting in a power factor of less than 1.

Once the support systems and engine were installed in the engine room, an attempt was made to start the engine. The first start attempt was unsuccessful and upon closer inspection of the engine, it was determined that a number of factors required a rebuild of the engine. A engine repair technician from the engine manufacturer was contracted to aid METEL personnel in the rebuild and a number of students also volunteered to assist with the engine rebuild. One positive outcome of the engine rebuild was that not only did the students gain added experience with engine construction and maintenance, but METEL personnel learned many intricacies of this engine from the manufacturer representative. Figure 1 shows a number of pictures showing stages of the rebuild process and in total the following items in and on the engine were replaced, rebuilt or remanufactured:

Main bearings	Camshaft bearings	Piston big end and wrist pin bearings
Piston crowns	Piston liners	Fuel pumps
Fuel injectors	Heads and valves	Lubricating oil cooler
Charge air cooler	HT and LT thermostats	Lube Oil Thermostats

Figure 1: Wartsila Engine Rebuild photos

Once the rebuild was complete, the engine was successfully started. The engine was evaluated at a number of load settings to validate its ability to maintain a constant engine speed and load. During the initial validation, it was noted that the engine was not outputting the published rated power and at higher loads, the speed of the engine was fluctuating. An adjustment was required on the fuel rack, the method by which the engine's governor controls the amount of fuel injected to the individual engine cylinders. The adjustment of the rack corrected the fluctuating speed of the engine, but not the inability to reach the published engine rating. After referring the question to the engine repair technician, it was learned that because of the quality of the generator when it was manufactured and its current condition, the engine was derated. Figure 2 shows the medium speed engine as installed in the engine lab. Immediately in front of the engine, the control panel for the engine, the manual control of the load bank, and the fuel skid can be seen. Above the engine, the muffler and the heated exhaust sampling hoses and ports can be seen. Figure 3 shows a closer look at the fuel skid for the engine to the left and to the right shows the starting air compressor and the sea water cooling skid.

Figure 2: Medium Speed Engine Lab Completed

Figure 3: (left) Fuel Skid for engine operations (right) Seawater cooling and start air system

3. Instrumentation

3.1 CEMS

A Continuous Emissions Monitoring System (CEMS) developed at METEL was used extensively to conduct a variety of fuel, fuel additive, and lubricating oil tests in the medium speed engine lab. Figure 4 shows CEMS equipment integrated into the medium speed engine lab monitoring and control system. The CEMS consists of a Fourier Transform Infrared Spectrometer (FTIR) for measuring a variety of gaseous emissions including CO, total unburned hydrocarbons (THC), oxides of nitrogen (NOx), and a variety of hazardous air pollutants (HAPs). The CEMS is additionally equipped with a Scanning Electrical Mobility Spectrometer (SEMS) for measuring particulate matter (PM) size distribution, mass, and number concentration. Lastly, the CEMS includes gaseous and particulate sampling systems, which were developed at METEL to facilitate accurate and repeatable emissions measurements.

Figure 4: CEMS equipment integrated into the medium speed engine lab monitoring and control system.

3.2 Engine Monitoring and Control Instrumentation

Fuel mass flow supply and return was measured by Emerson Micro Motion coriolis flow meters with fuel viscosity monitored via Emerson Micro Motion Viscomaster viscosity meters. Three-phase generator voltage was measured via a Verivolt Entube TE voltmeter. Fluke i3000 flex current probes measured generator line current. The continuous voltage and current signals were used to calculate total generator power using the equation $\sqrt{3}V_{avg}I_{avg}$. A 1 MW discrete resistive load bank connected to the generator of the medium speed engine facilitated control of engine load. Intake air mass flow was measured by a Sierra 620s air flow meter. Intake air temperature and humidity were monitored with a Vaisala HMD112 temperature and humidity sensor. Intake air temperature repeatability of ±1°C is required when conducting industry standard fuel and lubrication oil tests and necessitated process control. Intake air temperature is controlled via two air-to-water heat exchangers installed in the engine air intake duct. The engine preheater skid is used as a continuous hot water source for intake air heating. Water from the low temperature (LT) freshwater engine cooling loop is used for intake air cooling. A 3-phase centrifugal water pump and variable frequency drive (VFD) mated to a standalone custom tuned PID controller regulates the cooling water pump speed and mass flow rate of cooling water through the heat exchanger. The intake air heater is operated at a fixed flow rate and water temperature of 40°C at all times. The intake air cooler provides the final intake air temperature control.

A variety of resistance temperature detectors (RTDs) monitored engine-operating temperatures including:

- Lubricating oil temperature
- Fuel oil temperature
- High temperature (HT) fresh water cooling inlet and outlet temperature

- Low temperature (LT) fresh water cooling inlet and outlet temperature
- Exhaust temperature for each cylinder
- Turbocharger exhaust temperature
- Charge air inlet and outlet temperature
- Generator winding temperature
- Front end and drive end bearing temperature

Fuel temperature repeatability of ±1°C is required when conducting industry standard fuel and lubrication oil tests and necessitated process control similar to intake air temperature. Fuel temperature is regulated via a 3-phase cooling water pump and variable frequency drive (VFD) controlled by a standalone custom tuned PID controller. Cooling water flow is drawn from the LT freshwater cooling loop.

A variety of pressure transducers monitored engine-operating pressure including:

- Lubricating oil pressure
- Fuel oil pressure
- HT fresh water cooling pressure
- LT fresh water cooling pressure
- Charge air pressure
- Start air pressure

Turbocharger and engine RPM were also monitored from factory transducers installed on the medium speed engine.

The medium speed engine was additionally equipped with instrumentation to conduct in-cylinder pressure measurements. Each cylinder (6 total) was monitored with an Optrand AutoPSI pressure transducer. Engine crank angle was measured with a US Digital HD25 industrial incremental encoder with 3600 cycles per revolution attached to the engine camshaft. The encoder serves to orient the in-cylinder pressure data to instantaneous crank angle or piston position. Pressure transducers are mounted on modified blow down petcocks, which are connected to the interior of each cylinder as shown in Figure 5.

Operability issues were experienced with the in cylinder pressure transducers which required significant attention. First, a cavity resonance interference was observed in pressure traces when mounting the in cylinder pressure transducers in a port with direct access to the cylinder interior. This resonance could only be remedied by mounting the transducers on the top of the blowdown petcocks downstream of the blowdown valve. The blowdown valve served to dampen the resonance interference, necessitating the blowdown valves is left open at all times during testing. This required a modification to the blowdown petcocks where a fitting was installed on top of the petcocks, downstream of the blowdown valve. The fittings were tapped to allow installation of the in-cylinder pressure transducers and a secondary blowdown valve to enable proper engine starting procedure. A second operability issue was experienced with the pressure transducers due to overheating and eventual failure. Overheating of the transducers was resolved by installation of a forced air cooling system. Air was introduced at high volume by a centrifugal blower pump through nozzles aimed at the transducers, reducing transducer temperatures to below failure limits.

Figure 5: In cylinder pressure transducer attached to blow down petcock.

3.3 Software

The medium speed engine lab monitoring and control software includes components to monitor and operate the CEMS, medium speed engine, and in-cylinder pressure measurement system.

3.3.1 CEMS

CEMS monitoring and control software was integrated into the larger medium speed engine lab monitoring and control system. The FTIR gas sampling and measurement portion of the CEMS control and monitoring software is shown in Figure 6.

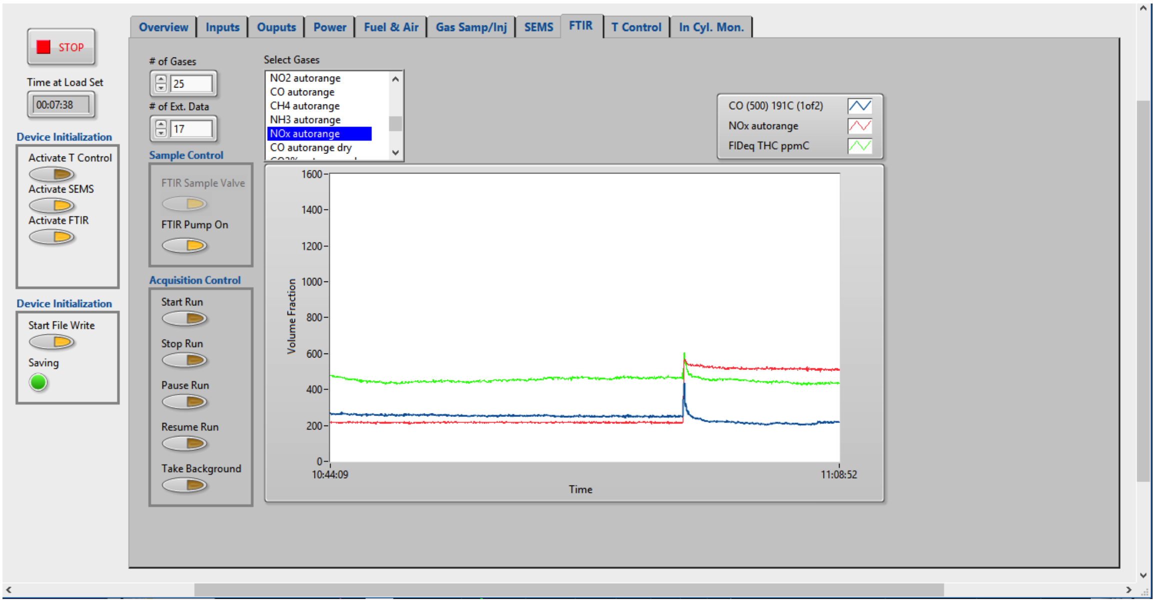

Figure 6: FTIR control tab integrated into engine monitoring software.

The SEMS PM sampling and measurement portion of the CEMS software is illustrated in Figure 7. Additional details of the CEMS software are provided in the CEMS project final report.

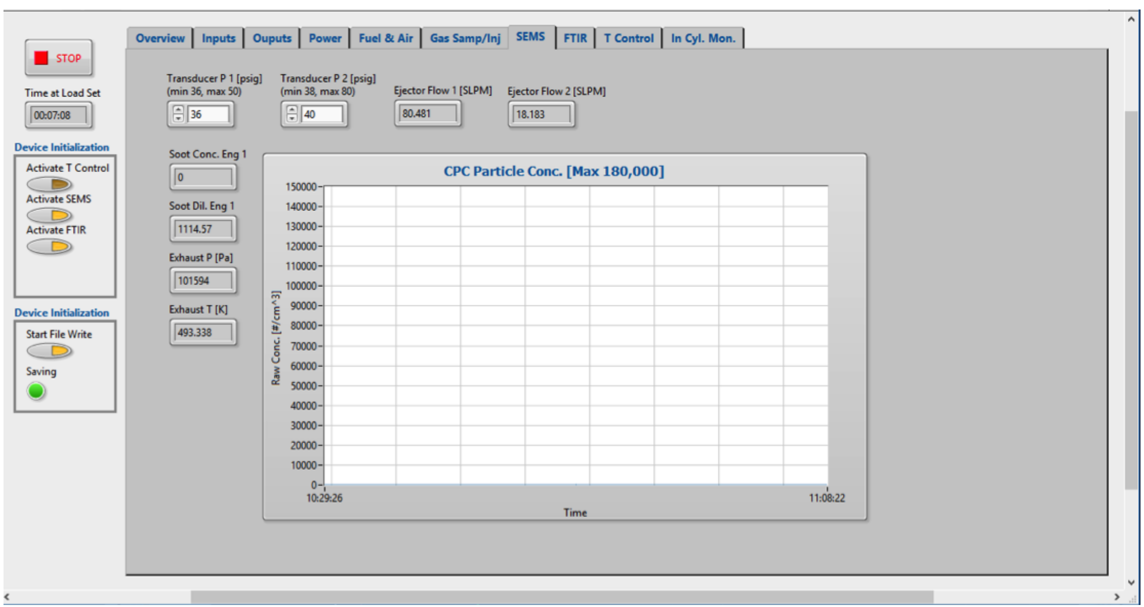

Figure 7: SEMS control tab integrated into engine monitoring software.

3.3.2 Engine Monitoring

Figure 8 illustrates the dedicated engine monitor and alarm screen built for the medium speed engine lab. The monitor provides an overview and time histories of various important engine operational parameters including:

- Lubricating oil temperature

- Fuel oil temperature
- HT and LT cooling water inlet and outlet temperatures
- Exhaust temperatures for all six cylinders
- Charge air inlet and outlet temperature
- Generator winding temperature
- Lubricating oil pressure
- Fuel oil pressure
- HT and LT cooling water pressure
- Charge air pressure
- Start air pressure
- Turbocharger and engine RPM

Twenty-three alarms were developed for critical out of specification engine operational parameters. Alarms are reported to the alarm message window for observation when triggered. The alarms include:

- Low lubricating oil level
- Low lubricating oil pressure
- High lubricating oil temperature
- High lubricating oil filter differential pressure
- Fuel leak
- Low fuel pressure
- Fuel viscosity out of range on fuel supply or return
- High charge air temperature
- Low LT or HT cooling water pressure
- High HT water temperature
- Engine speed over range
- Low start air pressure
- Control air low pressure
- High cylinder exhaust temperature for all six cylinders
- High turbocharger exhaust temperature
- Tachometer/power alarm

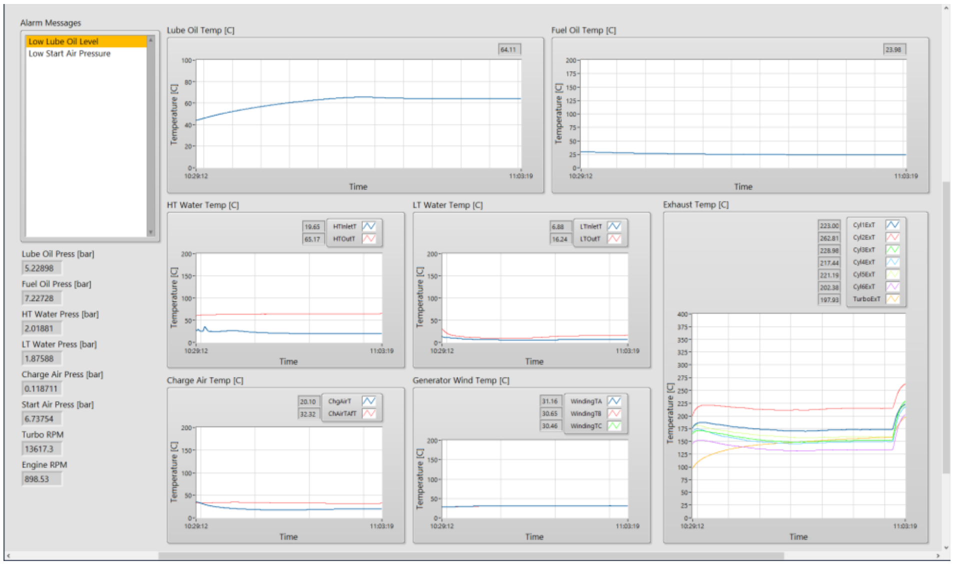

Figure 8: Dedicated engine monitoring and alarm screen for important operational parameters.

Additional monitoring and control of the medium speed engine is conducted on the primary data acquisition and control program. Figure 9 shows the engine load monitoring and control window. Generator power, 3-phase RMS generator current and voltage, and engine RPM are displayed. Engine loading is controlled manually using load step buttons, which remotely switch individual relays on a 1MW discrete resistive load bank mated to the engines generator. Engine loading can also be automated by selecting the "Auto Test" button. With an automated test enabled, the software steps load up or down in accordance with one of several load cycles used for testing. Buttons are also included for stopping an automated test, or stopping and dumping load in a controlled manner in the event of emergency. All engine and emissions data can be saved manually or automatically as part of an automated test sequence.

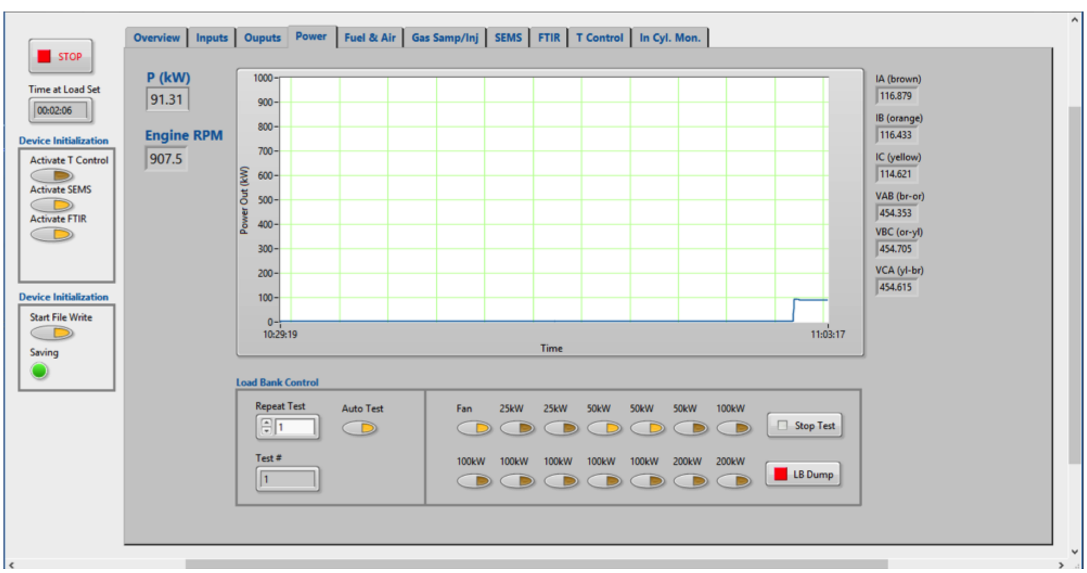

Figure 9: Engine load monitoring and control window.

Proper process control of intake air temperature and fuel oil temperature within ±1°C is critical during fuel and lubricating oil testing. Thus a fuel and air monitoring window was created, dedicated to displaying time histories of intake air temperature, humidity, and flow along with fuel flow and fuel viscosity. The fuel and air monitoring window is shown in Figure 10.

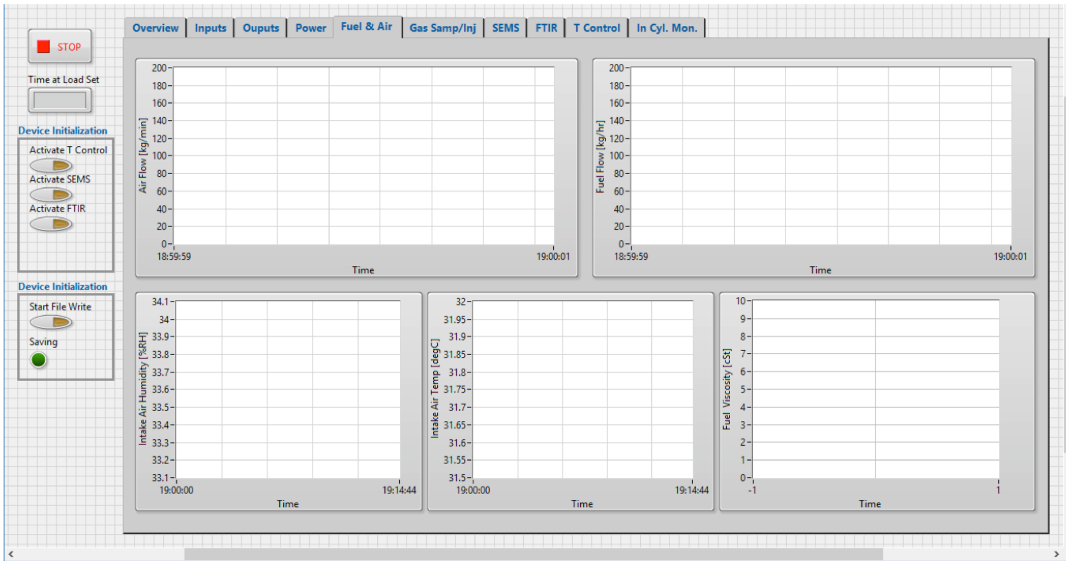

Figure 10: Medium speed engine intake air and fuel monitoring window.

A separate dedicated computer is used to monitor and collect in-cylinder pressure data on all six cylinders of the medium speed diesel engine. A separate computer was used to ensure robustness of data acquisition due to occasional errors in encoder data from generator EMF interference. Encoder pulses are used as a hardware timer to collect pressure data synchronized to engine crank angle (and instantaneous cylinder volume). Figure 11 illustrates the in-cylinder pressure monitoring program where pressure vs. crank angle and pressure-volume (PV) diagrams are displayed for each cylinder averaged over a user selectable number of cycles. The “ICM On” button enables continuous monitoring of cycle averaged in-cylinder pressure. The software additionally allows for manual or automated collection and storage of pressure traces by activating the “Write ICM” button on the program window. The “Write ICM” button saves one cycle averaged set of in-cylinder pressure data to the computer hard drive. In the event of automated testing where in-cylinder pressure data is collected, a hardware trigger is passed between the primary data acquisition program and in-cylinder pressure program to synchronize data acquisition. Future improvements to this software include continuous heat release and combustion analysis for each cylinder.

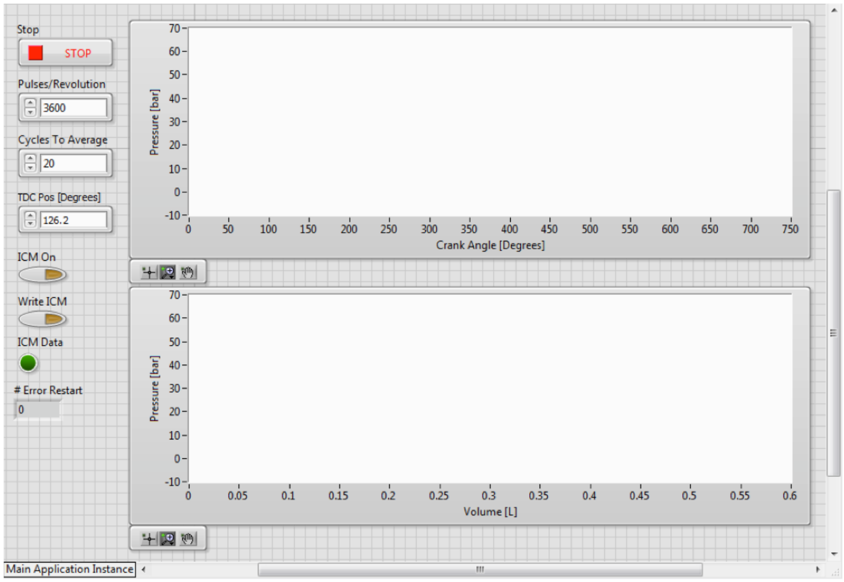

Figure 11: In-cylinder pressure monitoring window displaying pressure vs. crank angle and pressure vs. volume diagrams.

4. Results/Improvements

As a result from the engine rebuild and the implementation of the continuous emissions monitoring system, the development of the medium speed engine lab is a success. Figures 12 and 13 show an example of both the in-cylinder pressure monitoring system in operation and plots of exhaust emissions as they vary with load. As can be seen, real time monitoring of the performance of, and both gaseous and particulate emissions from, the engine has been achieved. Since the engine was put online, a number of research projects have been furthered by this engine, including the continuous emissions monitoring development, the glycerin emulsion fuel project, and a number of external industrial research and development. METEL has successfully completed three testing contracts to date and has two additional industrial testing contracts to complete this year. This medium speed lab has proven to be a unique independent fuel and lubricating oil testing and evaluation site world-wide and has been identified as such by contract clients.

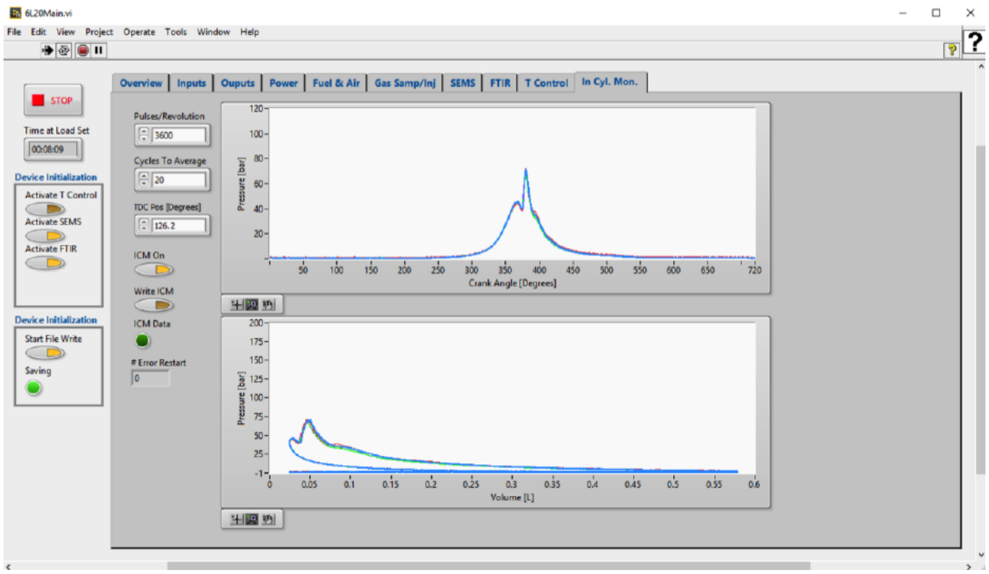

Figure 12: An example of the In-cylinder pressure monitoring in operation

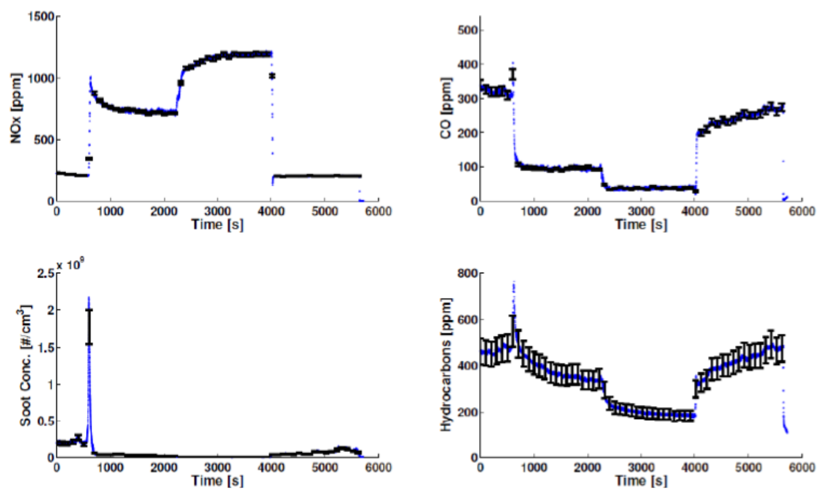

Figure 13: An example of the emissions results from the operation of the engine under differing loads

5. Impact on Commercial R&D in the Marine Transportation Sector

Workforce Development Impact

The MSEL has been an invaluable asset to the current merchant mariners and to the training of future merchant mariners. The MSEL has been used for a number of internal research and development projects, such as the glycerin emulsion fuel development, but also for external industrial research and development. METEL, using the MSEL, has been involved in the testing and evaluation of new heavy fuel replacement blends and new lubricating oil composition blends. The heavy fuel replacement project has the goal of developing a new heavy fuel replacement with a similar fiscal benefit as traditional heavy fuel but would meet the upcoming MARPOL requirement on Sulfur content. The lubricating oil project aims to increase the overall efficiency of the engine by reducing the internal friction of the engine, leading to a reduction in fuel consumption, thereby reducing the total emissions output of the engine. As quoted from the client, the results garnered from the METEL testing directly influenced the development direction for both the heavy fuel replacement and the lubricating oil chemical composition, leading to further improvements.

The MSEL has been a critical component in the development of new lecture and lab exercise material for courses offered at MMA, as well as a direct influence on students by employment or volunteer work during maintenance and testing procedures. Using the operating plant, the control systems, the data acquisition systems, and the emissions monitoring system, the following courses and labs were improved or created using case studies, data, systems drawings, and procedures. In the table shown below, the impact on a number of selected courses at MMA as well as the approximate number of students affected.

Course	MSEL Impact
MSE Capstone	Staff mentored students on their design projects involving the MSEL (12 students)
MET Capstone	Staff mentored students on their design projects involving the MSEL (5 students)
Air Pollutions and Emissions Testing	Data was used to develop lecture material and lab exercises (4 students)
Biofuels: Production and Use	METEL equipment and data used to develop new lab materials (8 students)
Thermal Fluids Lab	Engine performance data used to develop new lab exercises (100 students)
Thermodynamics 2	Cylinder combustion pressure trace data used for lecture material (75 students)
Diesels 1 and 2	MSEL used as a case study for operational considerations, engine system demonstrations and tours, and procedure development (150 students)
Fundamentals of Engineering	MSEL served as piping tracing example for students in lieu of training ship (120 students)
Power Equipment Lab	Performance data, equipment, and safety procedures used to improve lab exercises (150 students)
Technical Communications	Engine performance data used by students to develop technical reports and MSEL procedures used as examples (10 students)
Electrical Power 1 and 2	MSEL used as a case study for generator wiring, pump wiring, sensor placement and electrical measurements (250 students)
Automation and Controls	MSEL used as a case study for control methodologies, sensor placement, and measurements employed by the lab (120 students)
Maintenance	MSEL supplemented available mentoring resources for the ship’s maintenance by showing students proper engine maintenance procedures by having them participate in normal routine maintenance exercises (50 students)

Outside of Coursework	The MSEL employed 6 students and had approximately 40 additional student volunteers during the engine rebuild and testing procedures

Impact on Maritime Research; Present and Future

The MSEL has already made contributions through the DOT UTC projects to maritime fuel development including oxygenated fuels and biofuels through several projects. Through work with commercial oil companies MSEL has worked on advanced marine heavy fuels and advanced marine engine lube oil development. Over the last 2 years MSEL has completed about $200k of test contract work with another $200k planned to be completed by the end of 2019.

The trajectory of industry testing R&D contract is growing quickly as the MSEL is one of the few independent marine engine test labs in the world capable of high fidelity performance and emissions testing on a marine engine using marine fuels. In this sense the MSEL has become as world class facility and a national R&D asset for future maritime engine research. With the emphasis on meeting emissions requirement in the near future the MSEL is strategically poised to provide significant industrial R&D support and the current trajectory of funding in this area will likely require and expansion of the lab to meet industry demand. To meet this demand there are plans underway to expand METEL into a newly acquired port facility in Bucksport Maine(figure 14). The current plans are to replicate the MSEL engine test cell with new engines located in Bucksport. Such capacity would allow us to expand into long term durability testing of lube oils and fuels which is near the final stages of commercialization of the developed technologies.

Figure 14: Mill at Bucksport Maine; Future home of MMA Maritime training center and possible expansion location for METEL.

Currently, METEL has a $M cooperative agreement with MARAD to conduct research on engine emissions. The procurement of this funding was a direct result of the DOT UTC funded MSEL project. This funding is directed toward using the METEL facilities to conduct research on fuels and fuel distributions strategies to reduce and possibly eliminate diesel emissions pathways for soot and other emission gases. The lab is currently building a highly instrumented benchtop fuel combustor for fundamental research on marine fuels. In additions the lab has added a state of the art Gas Chromatograph Mass Spectrometer (GCMS) (funded by NSF). This instrument provides the lab with high fidelity combustion emissions characterization. Coupled with the MSEL, METELs fuel chemistry lab and fuel emulsion production equipment provides the capability to study combustions science on fuels, then fabricate promising in large quantity run the on a large diesel engine, thus validating the fuel performance in a commercial engine and providing feedback for continued development of the fuel.

For future research using the MSEL, the US DOT Maritime Administration (MARAD) is in the process of securing funding to sustain applied research programs at state maritime academies, to provide significant funded for these institutions to develop and sustain high quality applied maritime research programs for which METEL was used as a prime example of the type of research they are planning to fund. The impact of the METEL lab on the nature and structure of this funding as significant and if this funding comes to fruition will have a large impact on maritime research nationwide. The MARAD research thrust areas for this funding include, Vessel Emissions, autonomous vessel research, efficiency improvements, maritime safety and workforce development. METEL facilities are capable of making significant contributions in all of these areas. Such funding would provide a key resources to ensure the long term sustainability of METEL and other labs at state maritime for the next five years.

To meet the demands of the issues of the maritime industry, with MARADs guidance on priorities METEL is developing a planning document to expand its research capabilities to meet this call and is working with industry to evolve the research program. Planned expansions underway include:

- Vessel Emissions: Continuing our work on diesel engine emissions reductions as well as conducting R&D and testing for major oil companies, shipping companies and entrepreneurial startups in the maritime field.

- Marine Automation and Autonomous Vessels
  This is a major new development in the maritime industry and a significant new research area for METEL. METEL is partnering with industry stakeholders such as the American Bureau of Shipping (ABS) as well as commercial shipyards and entrepreneurial companies working in this area. The medium speed diesel lab is a highly instrumented and automated "ship" engine room that can be enhanced to become a live simulator of an autonomous ship Diesel generator set. This allows METEL to conduct practical R&D on autonomous ship technology by providing

developers a platform to prove out technologies, protocols and control strategies on a live engine. METEL plans to use the engine lab as a testing platform to investigate and develop autonomous vessel technology. This is a pressing topic in the maritime industry as technology advances to a level that makes autonomous operation of vessels, both commercial and military attractive. The Navy has recently announced an interest in research projects of this nature. [3]. METEL plans to pursue involvement in the US NAVY Autonomous ship development effort.

- Workforce Development: Continuing on the type of efforts previously described as well as development of professional mariner training programs for our continuing education division, which provides Coast Guard certifications for professional maritime officers.

- Maritime Safety: Implementation of maritime safety training and protocol development of the maritime industry. MMA has begun as substantive campaign to develop world class maritime safety training. Since the MSEL is a vessel engine room on land, it can be used as a training facility for maritime safety for engine room operations.

- Vessel Efficiency Improvement: METEL has already been conducting industry contracted R&D on improved lube oils which we have demonstrated significant efficiency improvement. The company involved in this effort stated that the results of the testing at METEL have made a significant contribution to the company development of these fuels and future testing efforts are underway at METEL. This is just one practical example of METELs demonstrated capability to contribute applied research results to this area.

6. Conclusions

Discussed was the development of the Medium speed Diesel lab at the Marine Engine Testing and Emissions Laboratory at Maine Maritime Academy. The key accomplishments of this project are summarized as:

- Development and implementation of a medium speed diesel generator set up as a marine engine room on land. The facility is a world class marine Diesel engine laboratory with state of the art performance and emissions measurement capabilities. The engine is capable of running a wide variety of diesel fuels and blends up to 700 cStokes in viscosity.

- R&D results using the MSEL in the areas of lube oils and advanced fuels and development of future fuels including Emulsion fuel blends. Over $1M in secured research contracts (beyond DOT UTC funding) for future marine engine emissions research(MARAD)

- Successful support of industrial R&D test contracts ($200k to date w/ another $200k planned for 2019.

- Enhancement of marine engineering training on Diesel engines using MSEL adding the capability of training on advanced control and emissions systems
- Provided a model for successful applied maritime research at a state maritime academy to guide other similar institution in the development future plans to implement research programs.

The MSEL facility has also become a platform for future maritime R&D and workforce development in the following areas:

- Autonomous Ship R&D and smart engine room technology: The MSEL is planned to upgrade its automation to become a live simulator of an autonomous ship engine room for development of autonomous ship technology.
- Continued advanced fuels and emissions reductions technologies
- Expansion of engine test facilities to meet industrial R&D testing demands including engine technology development and long term durability testing.
- Expanding the workforce development training utilizing the MSEL in the areas of continuing education/professional mariner certification, autonomous engine room operation and maritime safety training and protocol development.

In final remarks the development of the MSEL has far exceeded the original intent of the laboratory development project and become a unique national asset for the advancement of marine engine R&D, industrial support and workforce development. The MSEL has set up Maine Maritime Academy with a research asset which is beginning to address some of the large global issues facing the maritime industry, the nation and the world including energy security, global emissions and improvements in the economic efficiency of global shipping.

7. References

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