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Technical Report:

PureFlow Diesel Fuel System – Test Data Analysis

Conducted for:

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Executive Summary

A PureFlow diesel fuel supply system provided power and efficiency improvements over stock diesel engine in laboratory testing. Air entrainment and cavitation were induced in the fuel system to simulate problems in field usage. These reduced power by 25% and fuel efficiency by 17%. The problems were completely rectified with the PureFlow device, restoring power and fuel efficiency to <u>greater than baseline levels</u>. These induced faults also degraded gaseous exhaust emissions of carbon monoxide, oxides of nitrogen, and unburned hydrocarbons. The PureFlow restored these values to baseline conditions.

An ISO 9000-certified independent engine test lab conducted the testing. The ISO 8178 test protocol was followed using the 8-mode off-road vehicle test cycle. Additionally, data from these test points were used to evaluate the PureFlow for other applications, including constant speed (generator set), locomotive, and marine test cycles. These different test cycles use varying weighting factors for each data point to simulate field conditions. The PureFlow provided approximately the same improvements in power and fuel efficiency under all these applications. Averaging of multiple test runs were used to prove that the results were statistically significant.

Product Description and Intended Market

According to the provided product literature, The PureFlow System is installed in the fuel supply line of a diesel engine. The system includes a fuel supply pump, fuel-water separator, air separator, fuel filtration, filter service indicator light, and other features. It is available in a range of sizes and is applicable, but not limited to diesel engines in trucks, tractors, boats, generators, marine, pumps, off-road equipment, and other applications.

Objective

The objectives of this project were twofold:

1. Monitor third party engine testing to insure proper test protocol is followed, and provide ongoing guidance to insure the PureFlow System was tested under conditions that will demonstrate its performance.

2. Analyze the test data to draw conclusions on performance and market applications. This exercise focused on determining the potential benefits of the PureFlow system.

Engine Testing – 3rd Party Laboratory

Third party engine testing was conducted by Olson EcoLogic Engine Testing Labs, LLC, Fullerton, CA. This is an ISO9001:2000 Registered lab, recognized by California Air Resources Board (CARB) and US Environmental Protection Agency (EPA). Principals in this laboratory have over 40 years experience in engine exhaust emission testing.

A Caterpillar 3045 direct injection diesel engine was tested in a steady state engine test cell at Olson. The engine had low operating hours and was in good condition. This 4-cylinder engine was rated at 90 hp @ 2400 rpm. It uses a rotary-type fuel injection pump that is very typical of engines in this class. The small size engine made testing economical. It is representative of a large class of diesels used in off-road equipment such as backhoes, stationary equipment such as generators and pumps, and other engine applications. We believe the engine and test cell setup was reasonable for this type of testing. If the test program were aimed at on-highway application, a different engine and test protocol would be more appropriate.

Why use an engine test cell instead of a vehicle or other application in the field? In general, laboratory testing is used to measure items that cannot be measured accurately in field use, or to control conditions so that specific tests can be made.

Lab testing, however, has its disadvantages. It represents "ideal" conditions that may not always directly compare to real world operations. For example, the lab fuel system will not undergo the same vibration environment as field operations. So if vehicle vibrations cause air entrainment not occurring in the lab, then the PureFlow system will not encounter the very problems it was designed to solve.

Therefore, the overall test program used the following logic:

A. Test the stock diesel fuel system to develop a baseline.

B. Add the PureFlow system to an otherwise unmodified engine to see if PureFlow changed this baseline.

C. Introduce a controlled "problem" for the PureFlow to solve. In the first case this was entrained air. The fuel system was modified to provide up to 10% air entrainment in diesel fuel, since 10% is often quoted in engine manufacturer's service literature. (The degree of entrained air was verified via fuel density testing done off-line before engine testing started.) Test the "problem" condition without the PureFlow to determine impact on baseline conditions.

D. Add the PureFlow to determine if the air entrainment "problem" is solved.

E. Test fuel line restriction or cavitation effect by removing the PureFlow and inducing a known restriction in the fuel supply line.

F. Add the PureFlow to determine if the cavitation "problem" is solved.

The above outline letters indicate each test scenario, and these are used for the rest of this report. (Baseline = A, PureFlow only = B, 10% Air = C, etc.)

Variability in Performance and Data

Engine testing would be greatly simplified if the engine ran exactly the same each time it was tested under specified conditions. Unfortunately this is not the case. There is a natural variability in internal combustion engine performance (power, fuel efficiency, emissions, etc.) even when test conditions are seemingly identical. The reasons for this variability are not completely known. Some theories include mechanical items such as piston ring rotation, differential thermal expansion of parts, induced vibrations in the engine block structure, variations in airflow distributions, and a variety of other theories. Other factors include chemical variability, such as minute changes in mixture formation or combustion rates.

To illustrate this concept, consider rifle marksmanship. Each bullet exiting a rifle fired from a stationary rest will not follow the exact same path. Holes in the downrange target will have a natural dispersion, even under identical conditions. Even the world's most accurate rifle and ammunition combination exhibits some variability, such that each successive bullet fired makes it own hole in the target. Note that a rifle is a simple form of "one-cycle engine" with a "disposable" piston (the bullet). Any additional hardware (such as a "real" engine) only adds opportunity for further complication and variability

Regardless of the causes, variability in engine performance increases the difficulty in making meaningful comparisons and conclusions. These are compounded (or confounded?) by inaccuracies in the test instrumentation and measurement techniques. For example, it is fruitless to try to determine a +/- 2% engine change if the instrumentation or test technique has a ± 5% measurement accuracy or repeatability.

How is this solved? Statistical analysis through averaging multiple data points increases the confidence in results. Where the number of tests allowed, similar data points were averaged, and these averages were compared. Several of the included charts indicate "error bars", graphically denoting a specified variability.

Test Cycles

A standardized test cycle was used for the PureFlow comparison. This test cycle and protocol are part of the International Organization for Standardization (ISO) ISO 8178 test cycle. As described on the Dieselnet website (www.dieselnet.com):

> “The ISO 8178 is an international standard designed for a number of non-road engine applications. It is used for emission certification and/or type approval in many countries worldwide, including the USA, European Union and Japan. Depending on the legislation, the cycle can be defined by reference to the ISO 8178 standard, or else by specifying a test cycle equivalent to ISO 8178 in the national legislation (as it is the case with the U.S. EPA regulations).
>
> The ISO 8178 is actually a collection of many steady-state test cycles (type C1, C2, D1, etc.) designed for different classes of engines and equipment. Each of these cycles represents a sequence of several steady-state modes with different weighting factors.”

The ISO 8178 cycle includes testing at three different engine speeds: rated power, torque peak speed, and idle. At each speed, testing is then done at discrete load points, representing 100, 75, 50 25, and 10% of the maximum power available at that speed. The different test cycles then apply weighting factors to each data point. The sum of these weighted values is then meant to be representative of those applications.

For example, the test cycle for railway locomotives includes a 60% weighting for idle, since locomotives spend approximately this time idling in real life. For engine-driven electrical generators, the testing is only done at the single operating speed of the generator, and then weighting factors are biased toward primary operating conditions.

PureFlow testing was done with the ISO8178 Type C1, 8-mode cycle intended for off-road vehicles. However, since this test encompasses test points used by other applications, further analysis and comparison is possible. We were able to compare operation for the constant speed Type D1 test (generators, etc.), Type F Locomotive Test, and Type E2 marine application test from this same data set.

Off-Road, 8-Mode

The 8-mode test runs at Olson Ecologic Labs were used to collect data for other applications as shown below. Our analysis in this report is from the data provided by Olson Labs. While monitoring the testing, we collected other data during the runs to provide confidence in engine and test cell operation and calibration of instrumentation. Confident that this was being done correctly, we used only the supplied data since it includes correction factors and compilations not available through our manual data collection. Our analysis is no better than the data provided, however we feel this is data valid the purposes of this comparison.

The diesel baseline testing (Scenario A) included three separate test runs. Individual data points were weighted per the test protocol. These were then averaged to provide a comparison for future tests. Test documentation showed scenario B had 2 test runs, C had 3, and D had 2. Fuel cavitation testing (Scenarios E & F) had only one run each.

Engine Original Equipment Manufacturers (OEMs) report through their service literature that up to 10% air can be entrained in diesel fuel in field service. This is due to fuel tank agitation and other circumstances in some fuel delivery systems (which includes the fuel return line back to the storage tank.) Since data was not available to indicate the exact amount of entrainment in a particular application or usage, the lab simulation was designed to provide an “abundant” entrainment level for comparison. Off-line testing using fuel density measurements indicated that approximately 10% air entrainment was achieved.

The analysis included determination of fuel efficiency or fuel economy, as is often expressed in terms of “miles-per-gallon”, horsepower-hours per gallon, or some other standard. These provide an indication of the work done divided by the energy supplied, i.e., “10 miles traveled per each gallon consumed”, or 10 mpg. Unfortunately, miles-per-gallon does not have meaning for road machines or generators. Instead, fuel economy is normally discussed as “brake thermal efficiency” in most technical circles. This is simply a “generic” description of work output per energy input. It does not have specified dimensions, and therefore can be used to compare performance across a wide range of engine applications.

A diesel engine provides approximately 33% brake thermal efficiency, as each gallon of diesel fuel produces 1/3 gallon of useful work, while 1/3 of the provided energy is wasted out the radiator plus one third is wasted out the exhaust pipe.

We considered using other metrics to describe fuel economy for the various applications, but none is as universal as “brake thermal efficiency”; or “fuel efficiency” as subsequently used in this report.

Scenario A is the diesel baseline testing. An average of three runs, using the cycle weighted data, provided an output power of 45.68 Hp. Scenario B, air entrainment, reduced this power by 25% to 34.37 HP. By adding the PureFlow system, the power was fully restored to 45.69 HP. Figure 1 shows this graphically.

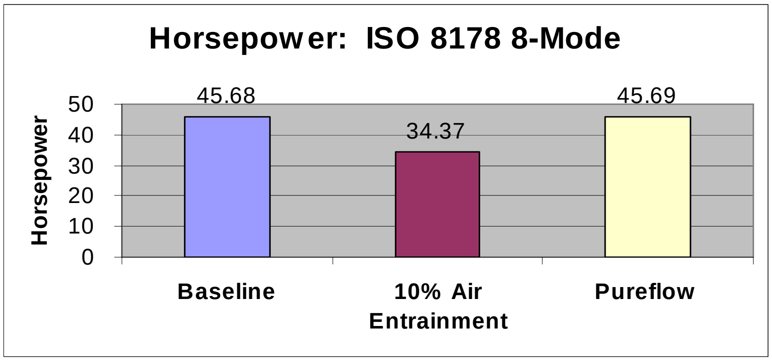

Figure 1. Horsepower for Baseline, 10% Air Entrainment, and PureFlow.

Fuel economy testing provided similar results, shown in Fig. 2. The average Brake Thermal Efficiency (BTE) was 28.8%. This means that of all the energy supplied to the engine by the fuel, 28.8% of this returned in the form of useful work, the remaining 71.2% was wasted to the atmosphere via the radiator, exhaust, and direct radiation). Air entrainment reduced this to 23.9% BTE, a reduction of 17%. Again, the PureFlow device fully restored performance to baseline conditions, raising thermal efficiency to 29.2%.

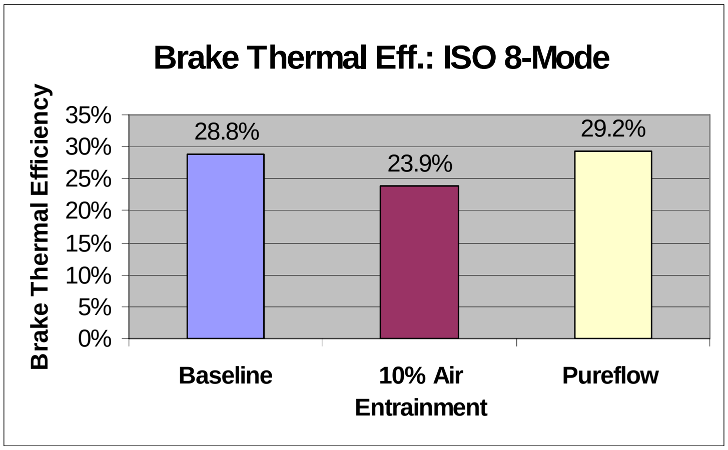

Figure 2. Brake Thermal Efficiency for Baseline, 10% Air Entrainment, and PureFlow, 8-Mode test.

EMMISSIONS IMPACT OF PUREFLOW SYSTEM:

Air entrainment increased all components of gaseous emissions, including carbon monoxide (CO), oxides of nitrogen (NO_x), and unburned total hydrocarbons (THC). The increases ranged from 25-100% in terms of gm/bhp-hr, as seen in Fig. 3. Often, there is a tradeoff between these emission components. The fact that all three were significantly worsened indicates a serious disruption in the combustion event. Notably, the PureFlow system restored all three components to essentially baseline conditions.

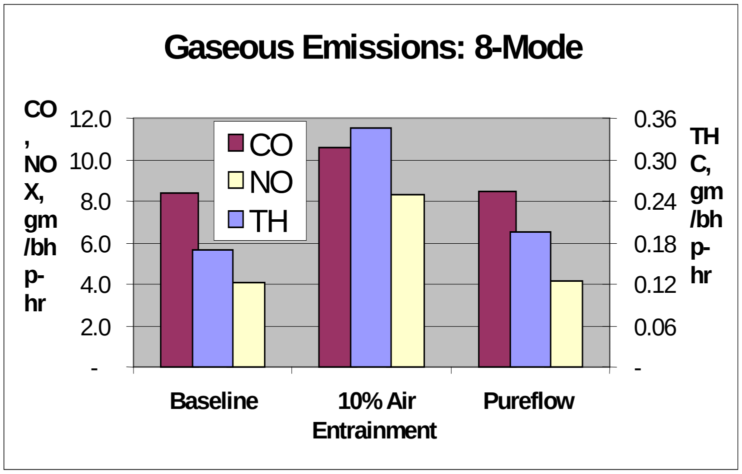

Figure 3. Gaseous Exhaust Emissions for Baseline, 10% Air Entrainment, and PureFlow, 8-Mode test.

Fuel cavitation testing, simulated by a fuel line restriction, provided similar results to that of air entrainment. There was a 23% loss in power accompanied by a 6% loss in fuel efficiency, as is illustrated in Figs. 4-5. The PureFlow system restored baseline values.

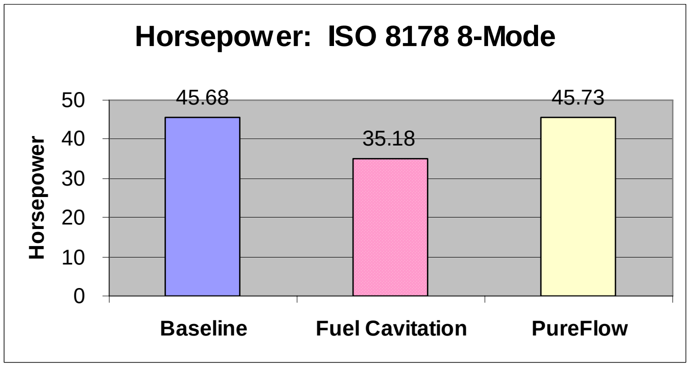

Figure 4. Horsepower for Baseline, Fuel Cavitation and PureFlow, 8-Mode test.

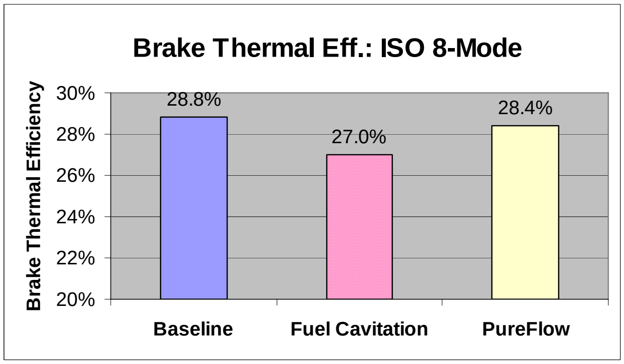

Figure 5. BTE for Baseline, Fuel Cavitation and PureFlow, 8-Mode test.

CO, NOx, and THC gaseous exhaust emissions were degraded by cavitation as seen in Fig. 6. The PureFlow system restored these values to near baseline conditions.

What about exhaust particulate matter emissions (PM)? Lack of data for the baseline and wide variability in recorded results under otherwise similar conditions precludes any definitive analysis of PM.

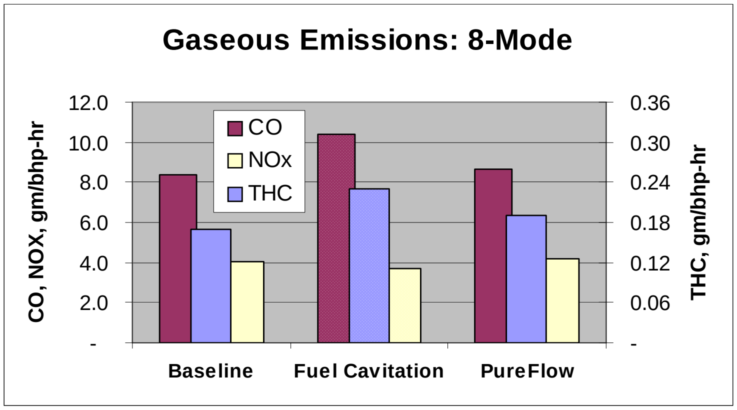

Figure 6. Gaseous Exhaust Emissions for Baseline, Fuel Cavitation, and PureFlow, 8-mode test.

ELECTRICAL GENERATOR TEST CYCLE

The ISO 8178 Type D1 test cycle is designed for engine genset and other constant speed applications. This test includes three load points, 100%, 75%, and 50% load, all at rated speed. These are weighted 0.3, 0.5, and 0.2, respectively. This is indicative of a heavily loaded genset as might be used for electrical grid connection or for dedicated operation at higher loads. Usually this test is done at the synchronous engine speed for the generator, typically 1800-rpm for diesel of this class. The actual speed tested was 2400 rpm, but this should be reasonably representative of combustion at the lower speed.

The PureFlow test indicated increased power, and fuel economy (brake thermal efficiency) under all scenarios. The data also indicated that the PureFlow system provides increases in power and thermal efficiency above the diesel baseline. These results are shown in Figure 7.

Thermal efficiency for genset operation is shown in Fig. 8. This graph includes error bars of +/- 2% to indicate the significance of efficiency improvements.

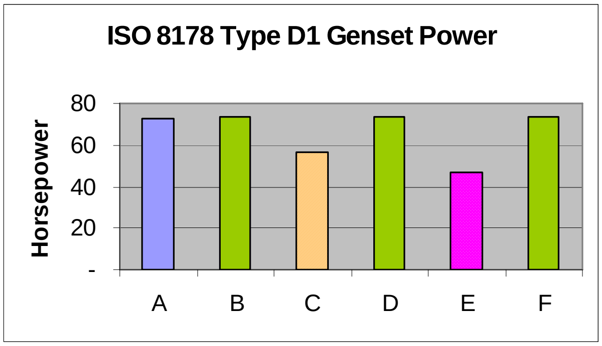

Figure 7. Horsepower for all scenarios, Genset D1 cycle. (Green bars = PF online.)

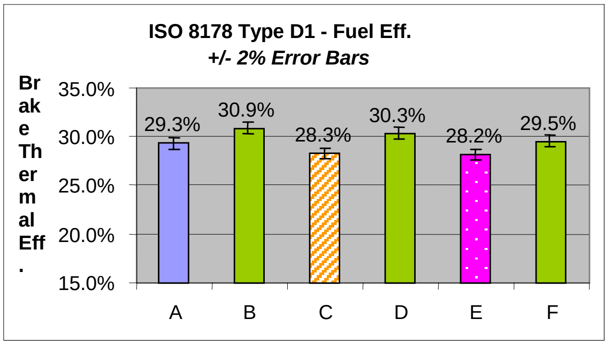

Figure 8. BTE for all scenarios, Genset D1 cycle. (Green bars = PF online.)

LOCOMOTIVE TEST CYCLE

Railway locomotives are compared using the ISO 8178 Type F test cycle. This uses weighting factors of 0.25 @ full power, 0.15 @ half load (torque speed), and 0.6 @ idle. Therefore this cycle tends to compare engines primarily under light load operations. Although clearly this is not a locomotive engine, the results should give some indication of performance improvements if further locomotive engine tests are performed.

Weighted cycle power and thermal efficiency with the PureFlow system is higher under all test scenarios, as shown in Figs. 9 and 10. Note the error bars are +/- 5% for Fig. 10. It is also interesting to note that this test cycle is weighted more toward light load operation, with 60% weighting of the idle point. However the results are quite similar to the genset and marine E2 cycle (below) with weighting toward the higher loads. The implied conclusion is that the PureFlow system provided improvement under all engine operating conditions, not just at high fuel flow rates.

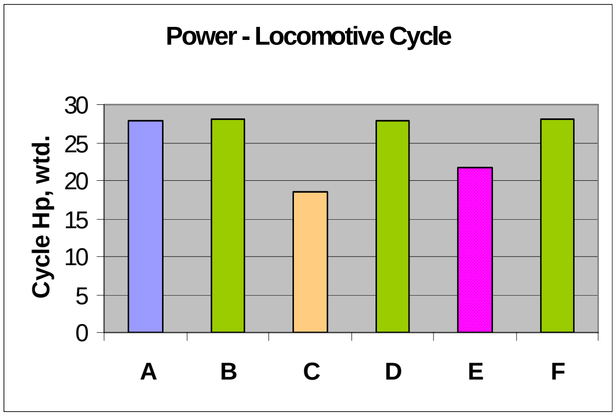

Figure 9. Horsepower for all scenarios, Locomotive Type F cycle. (Green bars = PF online.)

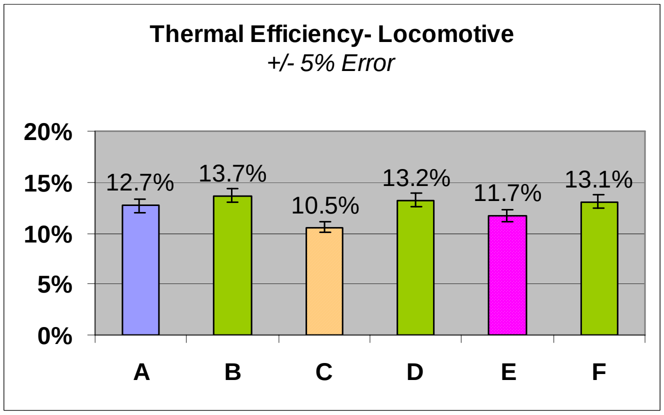

Figure10. BTE for all scenarios, Locomotive Type F cycle. (Green bars = PF online.)

MARINE APPLICATION TEST CYCLE

The ISO 8178 Type E 2 compares selected marine applications. This test cycle is for rated speed only and uses weighting factors of 0.10 @ full power, 0.50 @ 75% load, 0.15 @ 50% load, and 0.10 @25% load. Thus, this cycle is for heavily loaded applications at fixed speed, as is the case in marine operations. There are other marine test cycles available, but the specified test points were not run during this program.

The results were similar to all other test cycles: PureFlow completely rectified induced problems of air entrainment and cavitation, bringing power and fuel efficiency to slightly above baseline conditions. Figures 11 & 12 show power and BTE under the marine E2 test cycle. The results are similar in direction and magnitude to other test cycles.

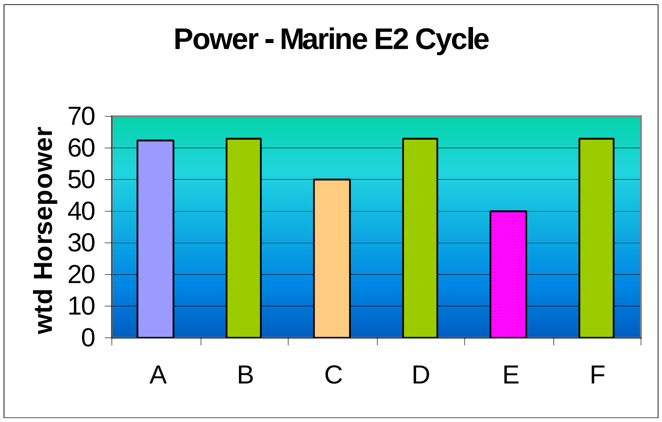

Figure 11. Horsepower for all scenarios, Marine Type E2 cycle. (Green bars = PF online.)

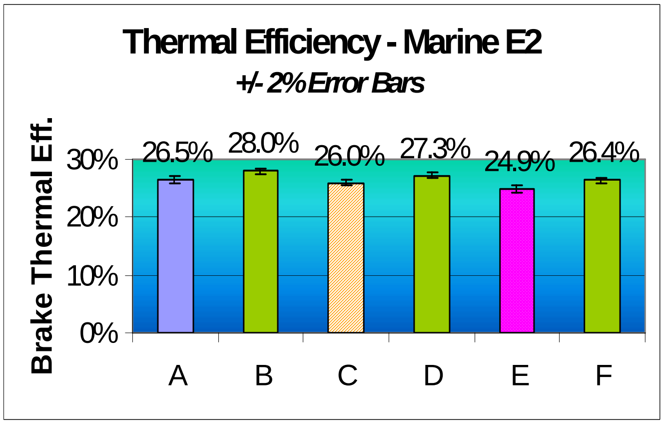

Figure 12. BTE for all scenarios, Marine Type E2 cycle. (Green bars = PF online.)

SUMMARY AND CONCLUSIONS

- The ISO 8178 test protocol appears to be a reasonable means to compare PureFlow performance for a range of non-road applications in a reasonable and economic manner.
- This test series is meant for off-road engines. On-highway engines may benefit from a different test protocol (such as the on-highway transient test) and a diesel engine intended for this application.
- There were no direct faults or errors observed in engine setup or test operation that would obscure or skew the test results.
- The PureFlow system did no harm to the diesel performance in any scenario.

- The PureFlow system simultaneously improves power and fuel efficiency in all test scenarios. Gaseous exhaust emissions are at least the same and often better with the PureFlow.
- Air entrainment in diesel fuel of up to 10% has a negative impact on power, fuel economy, and emissions. Testing indicates a power loss of 25% and a fuel economy loss of 17% in 8-mode testing.
- The PureFlow system completely restores lost power and fuel efficiency due to air entrainment. Gaseous exhaust emissions are also restored to baseline levels.
- Fuel line cavitation as tested hurts power by 23%, fuel efficiency by 6%, while negatively impacting exhaust emissions.
- The PureFlow System restores power and efficiency losses from cavitation, and brings exhaust emissions in line with original levels.
- ISO test cycles for off-highway, generator, locomotive, and marine all indicate the same results, trends, and magnitudes. This is true even as some cycles emphasize high load operation and some emphasize light load operations. The results are statistically significant.
- There is nothing in this data set to indicate that performance or efficiency would be harmed by using PureFlow in a “real world” environment.
- Long-term impacts of the PureFlow were not determined during this test. There is nothing observed in this data set to indicate this would be a problem.

Closure

This project was conducted under contract from PureFlow Technologies, Inc. For further information contact the author, Shannon Vinyard, Vinyard Technology Company, Inc., 200 E. Mill St., Hartford, AL 36344, ph 334-588-6644, fax 334-588-6602, svinyard@vinyardtech.com

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