EMISSION CHARACTERISTICS OF A TURBOCHARGED MULTI-CYLINDER MILLER CYCLE DIESEL ENGINE

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INTRODUCTION

In an effort to leave no stone unturned in the investigation of exhaust emissions characteristics in the various forms and versions of the compression ignition engine, the short compression-extended expansion concept "Miller" cycle diesel engine was investigated. The Miller cycle diesel engine was studied in the turbocharged form and also in the Low Heat Rejection (LHR) form by applying ceramic coating on the combustion chamber. The ceramic coated combustion chamber improved the performance of the conventional standard metal engine and thus was selected for the Miller cycle engine.

The extended expansion cycle in conjunction [2] with a short compression stroke is one of the few remaining engine concepts that is available for improving engine performance and reducing fuel consumption. The short compression stroke is achieved by: 1) closing the intake valve early in the cycle before BDC, or 2) by closing the intake stroke late after BDC. When the various engine breathing processes are considered such as emptying and filling, gas dynamics, the late intake valve closing displays some practical volumetric efficiency over the early intake valve closing. Better heat transfer is also achieved with late valve closing. These engines with extended expansion stroke and short compression stroke were known as the Atkinson Cycle and the later version as the Miller cycle [5].

The advantages of an extended expansion cycle are many and offer many ramifications for an improved engine cycle of the future. A phase 1 study of the Miller Cycle Advanced Military Engine resulted in the identification of a simple concept of closing the intake poppet valve late or early and pressurizing the intake air charge more to make up for the reduced inlet charge. Reduced specific fuel consumption and increased power output without increasing the peak cylinder pressure are some of the benefits [3]. The principle of operation is based on a low effective compression ratio and high expansion ratio. Because of the thermodynamic advantage of the Miller Cycle, the emissions such as NO_x are lowered.

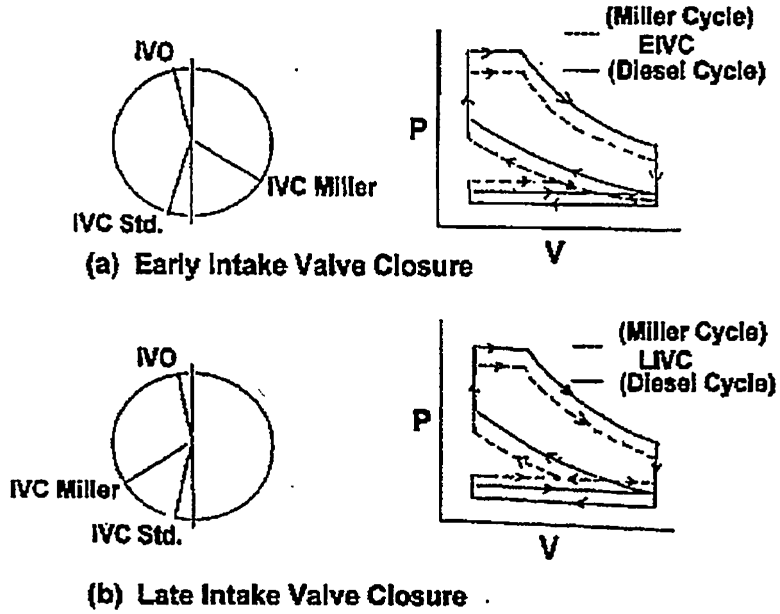
Finally, the incorporation of an insulated low heat rejection engine [4] with the Miller Cycle is shown to provide engine performance benefit nearly equal to the Miller Cycle alone. Application to military and commercial engines can be used to improve engine fuel efficiency, increase power output, improve durability, increase responsiveness, reduce heat rejection, and reduce the cost of power upgrading.

THE MILLER CYCLE

To illustrate the various aspects of the Miller Cycle engine [5], an early intake valve closing and a late intake valve closing cycle are shown. Figure 1(a) shows the valve timing diagram and a P-V diagram of the early intake valve closing cycle. Figure 1(b) shows the valve timing diagram and a P-V diagram of the late intake valve closure.

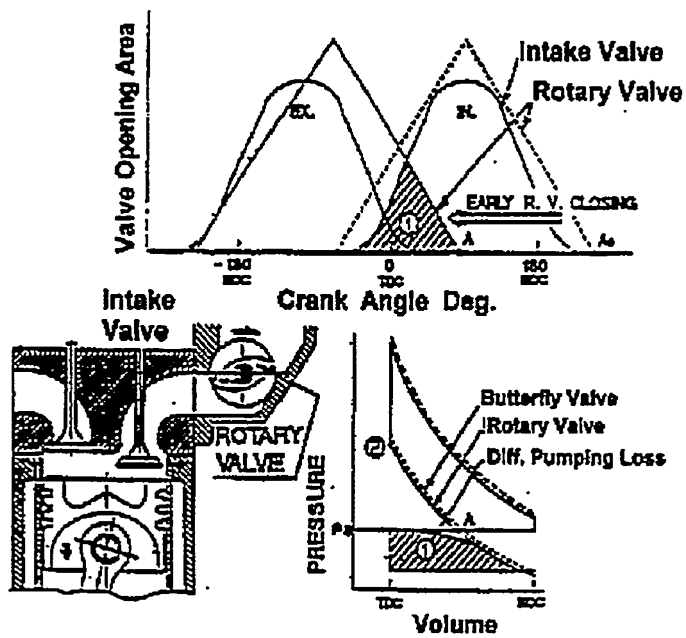
In both cases, the thermodynamics of the difference between the area below the expansion and compression curves is the network which is larger than the conventional engine. Conceptually and thermodynamically the early intake valve closure and the late intake valve closure are identical. The means to obtain a variable inlet valve closure will usually differ.

Another means of achieving variable inlet valve timing is to place another valve in series with the engine intake valve. Most notable of this type of valve timing is the K-Miller [1,2] Cycle in which a rotary valve is driven by the camshaft and is timed through a sliding mechanical helical gear set. This K-Miller concept has a dead volume



Two Methods of Obtaining Extended Expansion Cycle With
(a) Early Valve Closure and (b) Late Intake Valve Closure

Figure 1



Effect of Early R.V. Closing for Gas Engine

Figure 2

Engine Type	Miller 80				Standard (IVCT = 30)			
Load (%)	100	75	50	25	100	75	50	25
Exhaust Enthalpy (kW)	19.79	14.48	10.39	5.78	15.5	13	8.89	5.53
Air / Fuel Ratio	**21.6**	**23.08**	**24.9**	**28.73**	**29.5**	**34.6**	**41.5**	**50**
Compression Work	4.56	3.04	1.92	0.74	3.5	3.51	2.51	1.47
Turbine Work	8.51	5.65	3.54	1.33	7.3	6.4	4.28	2.45
Net Indicated Efficiency (%)	43.5	43.28	43	42.5	41.6	41.2	40.2	38.8
Peak Pressure (psi)	**2,220**	**1,741**	**1,360**	**887**	**2,340**	**2,150**	**1,710**	**1,310**
Fuel Input (kW)	81.6	63	48	30	64.8	55.2	40.2	27.6
ISFC (lb/HP-hr)	0.32	0.32	0.32	0.32	0.33	0.33	0.34	0.35
BSFC (lb/HP-hr)	**0.37**	**0.39**	**0.42**	**0.53**	**0.41**	**0.43**	**0.51**	**0.7**
Improvement in Indicated Efficiency (%)	4.54	5.13	6.99	9.42	-	-	-	-
Brake Power (kW)	30.6	22.37	15.7	7.85	21.7	17.5	10.9	5.46
Compression Ratio (GCR)	15	15	15	15	17.5	17.5	17.5	17.5
Effective CR (ECR)	10.3	10.3	10.3	10.3	16.72	16.7	16.7	16.72
Ratio of ECR to GCR	1.46	1.46	1.46	1.46	1.05	1.05	1.05	1.05
IMEP (kPa)	1714	1316	996.4	615.3	1302	1097	780	517.3
IMEP (psi)	248.6	190.9	144.5	89.24	188.9	159	113	75.02
Actual Boost Pressure Ratio	3.09	2.55	2.09	1.51	2.3	2.3	2.01	1.66

Figure 3: Performance of Miller Cycle, Standard

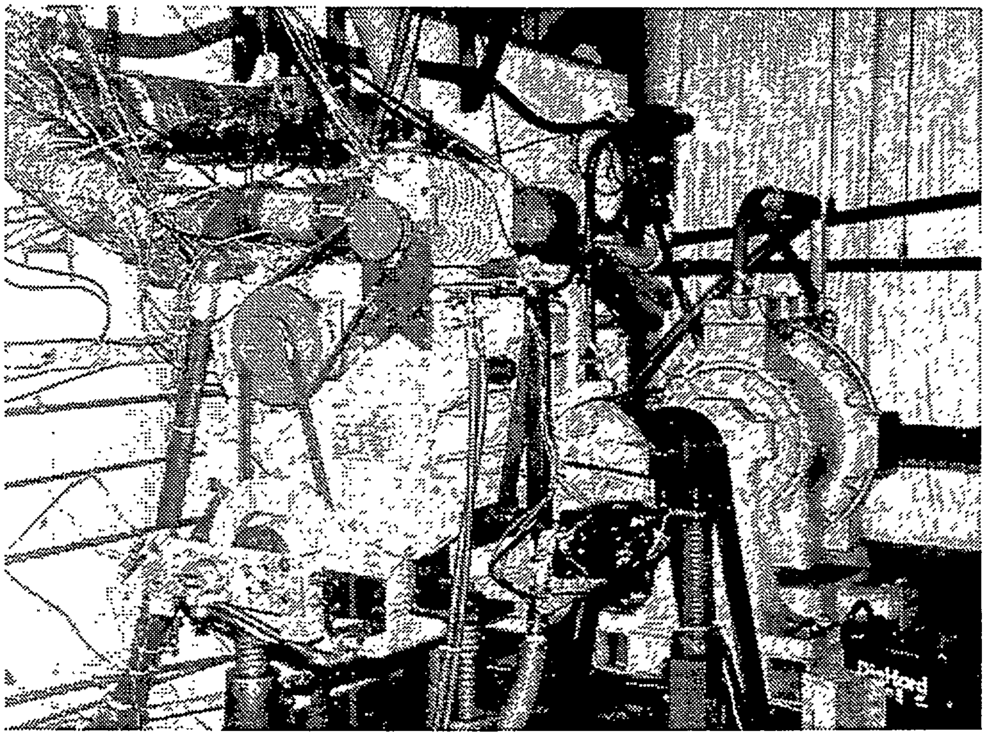
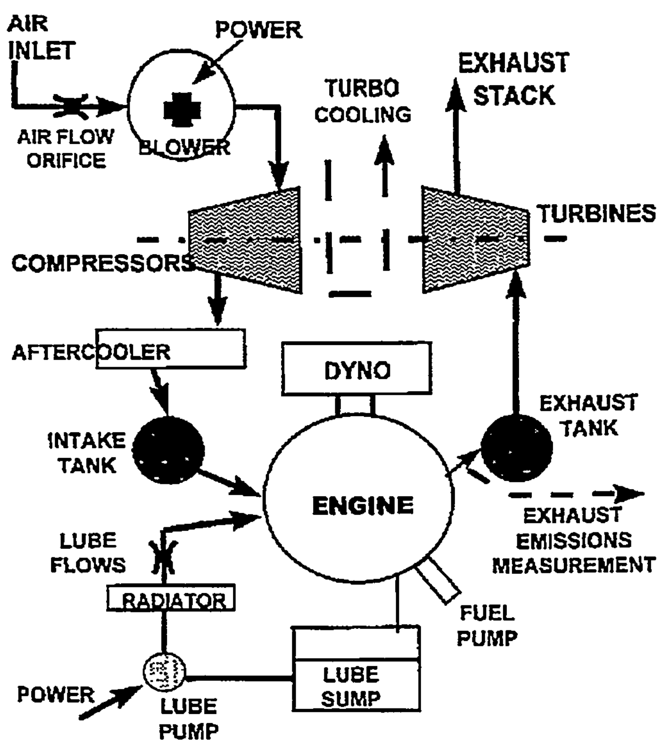


Figure 4: Engine Test Set Up in the Laboratory With Supercharger and Miller Cycle Modifications.



Test Set Up for Engine Emissions Measurements
Figure 5

between the engine and the rotary intake valve which is detrimental from the thermodynamic standpoint. The K-Miller concept, P-V diagram and valve events are shown in Figure 2 [1].

The advantages of an extended expansion cycle are many, aside from more power and efficiency over the conventional powerplant. From the P-V and T-V diagrams it can be shown that the following advantages are present:

1. Lower compression temperature for lower cylinder component stress, fuel knock deterrent, i.e. natural gas, lower emission.
2. Lower peak pressures - advantageous from stress standpoint and engine sizing.
3. Lower exhaust pressure.
4. Lower compression work.
5. Greater expansion work.

CYCLE SIMULATION

Before starting on engine modification and testing, a cycle simulation of the Miller cycle and the standard engine was performed. Figure 3 shows a summary of the simulation. It compares the Miller cycle with 80 degrees aBDC intake valve closure at four load conditions of 100%, 75%, 50% and 25%. With a single stage equipped turbocharger, the Miller cycle at 75% and 100% load is running at Air/Fuel of 23.08 and 21.6, respectively. These Air/Fuel (A/F) conditions are too rich for optimum combustion and emissions.

SUPERCHARGER

A better turbocharger or two stage supercharger-turbocharger will be desirable. For this reason an EATON M112 Supercharger was selected in this study to boost the intake air and raise the A/F ratio.

This approach is undesirable because the supercharger will take engine shaft power and increase the brake specific fuel consumption (BSFC). However, the engine response will be excellent [1]. The M112 Supercharger is coupled to the engine crankshaft and operates at 13000 rpm maximum giving up to 35 KPa boost pressure. The power required is 30 Kw.

TEST SETUP

Figure 4 shows the laboratory setup of the 6.6 liter engine rated at 2600 rpm. The bore x stroke is 107 mm x 127 mm. The engine is equipped with an Eaton M112 supercharger with a 5.1 speed booster.

Figure 5 is a schematic of the test setup. The first stage intake pressure booster is the M112 supercharger. The first stage boosted air from the supercharger is fed into the turbocharger compressor and through an aftercooler to the intake tank and to the engine. Part of the engine exhaust is then measured for exhaust emissions. The remaining exhaust gases are released to the exhaust tank and turbocharger exhaust turbine before being released to the exhaust stack.

The single-cylinder engine test cell had an automated microcomputer-based data acquisition system for recording various engine data-temperatures, pressures, flow rates, engine speed, load, emissions, etc. In addition, a National Instruments 8 channel high speed microcomputer data acquisition system for on-line acquisition of cylinder pressure data was available. This system is capable of acquiring hundreds of thousands of engine cycles, averaging, analysis of cylinder pressure diagrams, and computation of heat release rates.

The laboratory also had emissions capabilities for the engine tests. In addition to the sample handling system, the emissions setup consists of the following analyzers:

- Beckman model 955 Chemiluminescent NOx analyzer
- Beckman model 400A FID Hydrocarbon analyzer
- Beckman model 870 NDIR CO analyzer
- Beckman model 8P70 NDIR CO_2 analyzer
- Beckman model 7003D Polarographic oxygen analyzer
- In Line Particulate Measuring System Developed at M.I.T.

The particulate matter measurements were obtained to simulate the atmospheric dilution process [6]. A mini-dilution funnel was patterned after development by M.I.T.

For smoke measurement, an AVL smoke filtering equipment was used. The mass fuel flow rate and laminar air flow rates were measured with the usual modern automotive laboratory equipment. A Kistler cylinder pressure indicator was used to determine peak pressures.

TEST RESULTS

Since presentation of all data for all loads and speeds was not possible within the context of this paper, a full 2600 rpm speed and 93% load conditions were presented. Some 25% load conditions are shown for comparison purposes only.

The factory performance curves of the original engine are shown in Figure 6. The tests were conducted on 93% load at various engine speeds (1600, 1800, 2000, 2200, 2400 and 2600 rpm). Some tests are shown for 25% load at various speeds. Figure 6 shows the points where tests were conducted.

Tests were conducted on the following engine builds:

- Standard metal engine (IVC @ 30 degrees aBDC)
- Standard Miller 100 (IVC @ 100 degrees aBDC)
- LHR Miller 100 (IVC @ 100 degrees aBDC) S/C OFF
- LHR Miller 100 (IVC @ 100 degrees aBDC) S/C ON
- Standard LHR Engine (IVC @ 30 degrees aBDC

#

Flexibility in testing engine builds was limited because once the thermal coating (LHR version) was applied, it was difficult to remove the thermal coatings to come back to the standard metal to check points.

Figures 7 to 18 are presented to display the emissions and performance characteristics for primarily 2600 rpm and 93% engine load conditions. The figures are adequately labeled for identification. Some data at 25% load are shown for comparison purposes.

Figure 7 shows the performance and brake specific fuel consumption for a standard metal engine with IVC of 35 degrees aBDC. The standard Miller cycle with 80 degrees aBDC intake valve closure and LHR (low heat rejection) are all plotted against engine speed at 93% torque conditions. The LHR Miller 80 displayed consistently about 5% improvement in BSFC. Thus, all future Miller cycle builds were insulated (LHR) [7].

Figure 8 shows the same brake specific fuel consumption curves with LHR Miller 100 degrees. Again the LHR 100 S/c OFF displayed better BSFC than the standard engine.

Since all data of insulated (LHR) Miller becomes the focal point, the standard engine was also coated and shown as Standard LHR. Figure 9 shows the comparison of smoke between LHR Standard and LHR Miller 100. The standard engine with insulation (LHR) did better than the LHR Miller 100 with and without the supercharger.

The superior NO_x emissions characteristics are shown in Figure 10 at full load for the LHR Miller 100 with S/C on or off. This is to be expected as the compression temperature is lower for the Miller cycle because of its short compression stroke [5].

Figure 11 shows the NO_x emissions from the engine at 25% load. Both the LHR Miller 100 with S/C on and the Standard LHR were equal. The LHR Miller 100 is penalized for lack of air with the S/C off.

Figure 12 shows the full load HC emissions at full load. The LHR Miller 100 with and without S/C did better than the LHR Standard @ 93% load. At 25% load the HC from the LHR Miller 100 with S/C on is better than the LHR Standard. The LHR Miller 100 with S/C is the worst offender.

Regarding total particulate emissions, including absorbed organic at full load, Figure 14 shows comparable results. The best is the LHR standard engine and the worst is LHR Miller 100 with the S/C on. However, the particulates at 25% load show the LHR Miller 100 with S/C off is

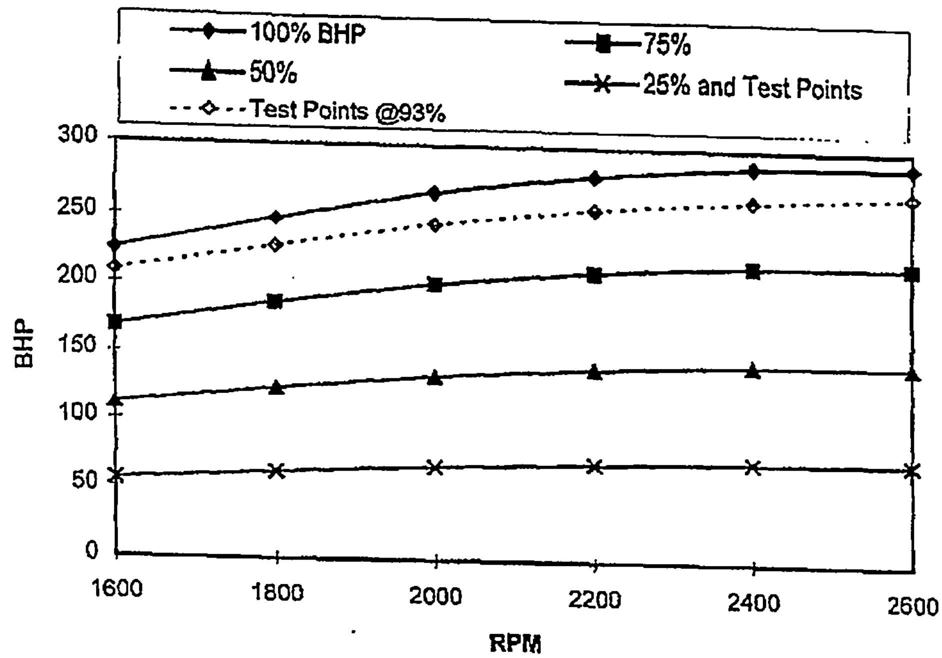


Figure 6. Brake Power vs. RPM

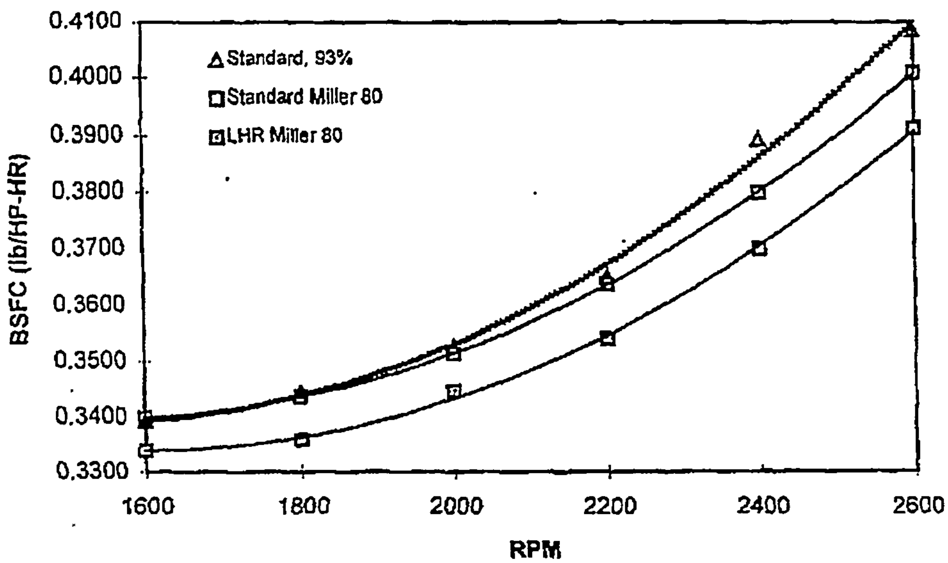


Figure 7. Comparison of BSFC Between Standard, Std Miller 80, and Insulated Miller 80 Engines at 93% Torque

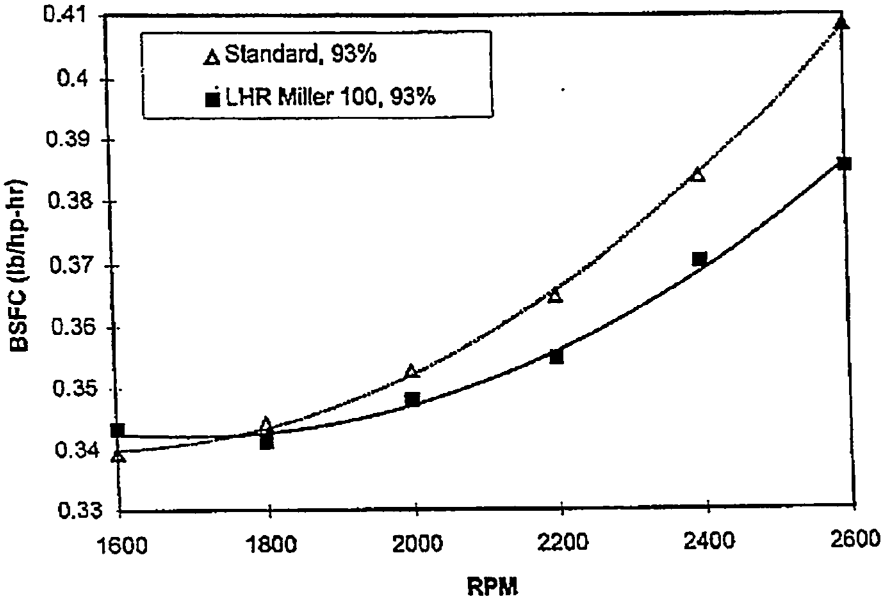


Figure 8. Comparison of BSFC Between Standard and LHR Miller 100 Engines at 93% Torque

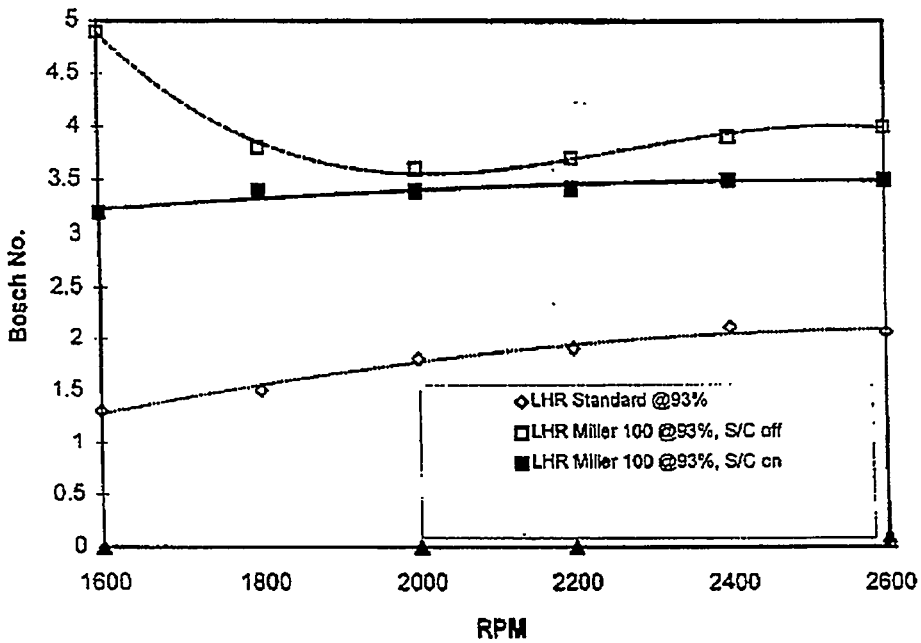


Figure 9. Comparison of Smoke Between LHR Standard and LHR Miller 100 at 93% and 25% Torque

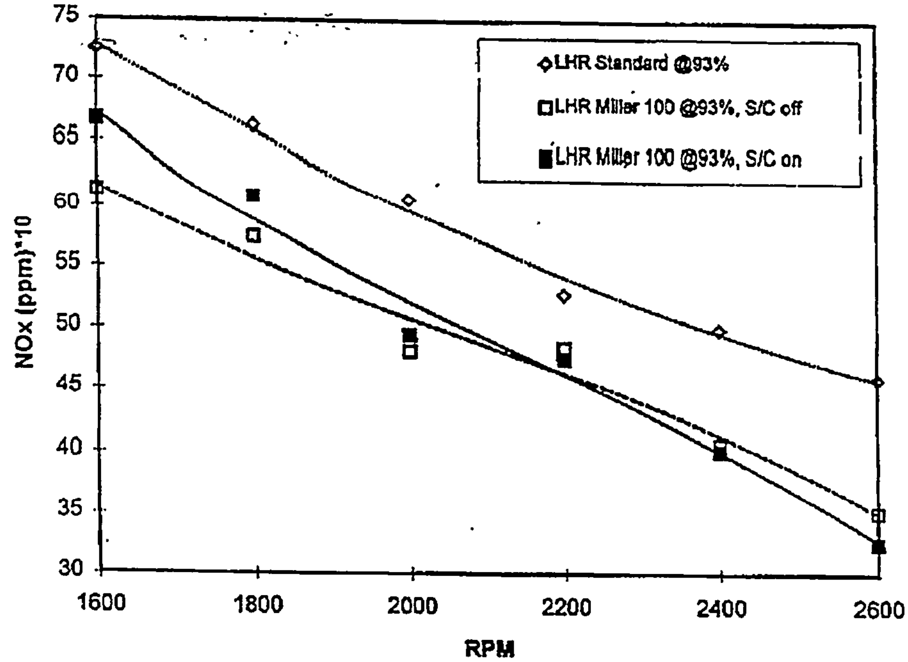


Figure 10. Comparison of NOx Between LHR Standard and LHR Miller 100 Engines at 93% Torque

best. The LHR Miller 100 with S/C on is the worst. The LHR Standard takes the middle road. These results are plotted in Figure 15.

In order to understand what is going on in the engine, it would be useful to know what the Air/Fuel ratio going into the engine is. Also the CO_2 out of the exhaust can indicate the completeness of combustion. For this purpose Figure 16 shows the full load Air/Fuel ratio for the various engines' tests. Figure 17 shows the comparison of CO_2 in the exhaust between LHR Std and LHR Miller 100 engines with and without S/C. Figure 17 is for 25% load and Figure 18 is for 93% load.

CONCLUSIONS

A conventional contemporary turbocharged diesel engine was converted to a late intake valve closure and extended expansion Miller Cycle turbocharged engine. A two-stage supercharger-turbocharger air handling system was employed. The supercharger could be used or cut out in the system. The exhaust emissions were measured to determine the emissions characteristics from a turbocharged Miller cycle diesel engine. The following can be concluded from the data presented:

1. The LHR Miller 100 offers superior BSFC over the LHR Standard engine.
2. LHR Standard engine has demonstrated better smoke characteristics than the LHR Miller 100 engines.
3. The LHR Miller 100 shows better lower NO_x emissions than the LHR Standard engine.
4. The LHR Miller 100 with supercharger offers lower HC emissions than the LHR Standard engine at all speeds and load conditions.
5. Total particulate matter, which includes absorbed organics at 93%, load is lowest for the LHR Standard engine. However, at 25% load, the LHR Miller 100 demonstrates lower particulates than the LHR Standard engine.
6. At 93% load, the air/fuel ratio is too low for good combustion at 1600-1800-2010 engine rpm

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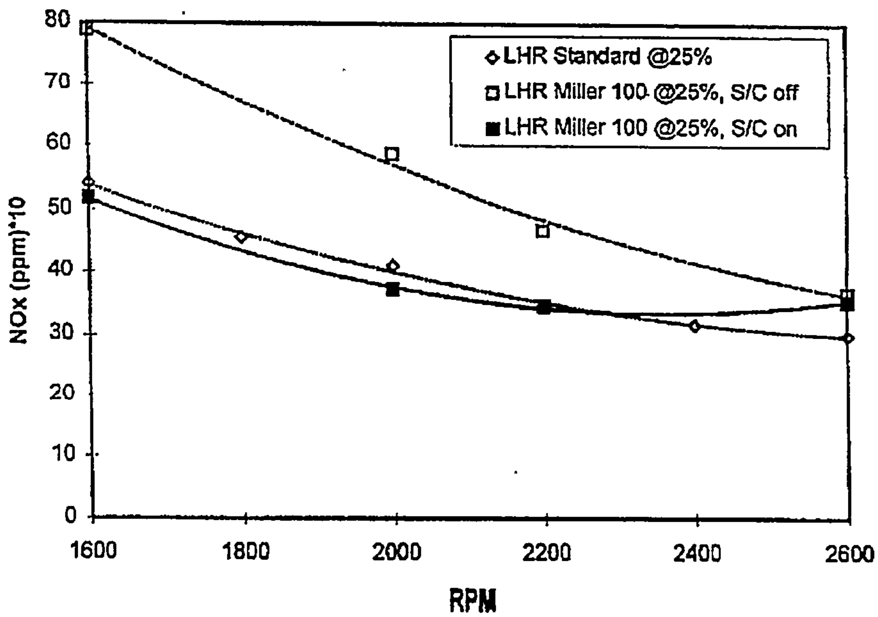

Figure 11. Comparison of NOx Between LHR Standard and LHR Miller 100 Engines at 25% Torque

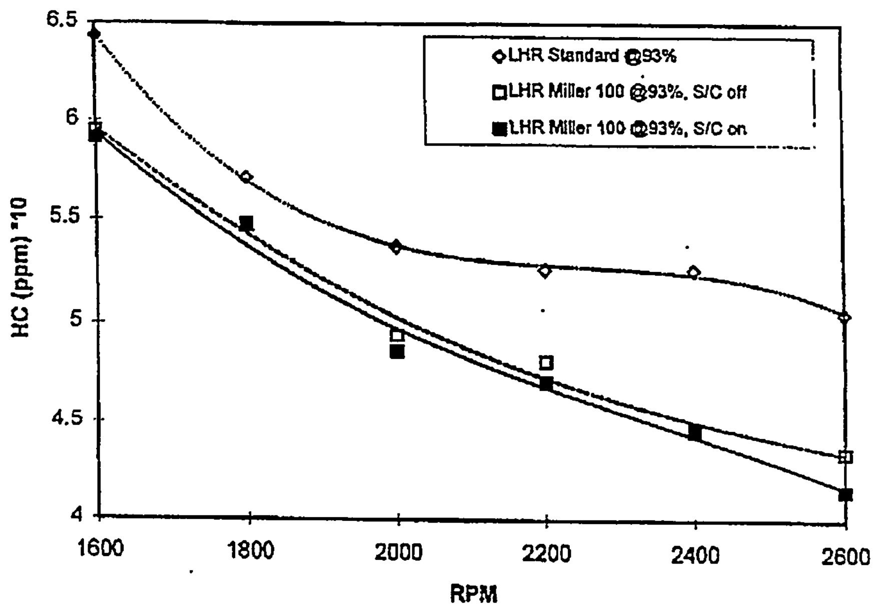

Figure 12. Comparison of HC Emission Between LHR Standard and LHR Miller 100 Engines at 93% Torque

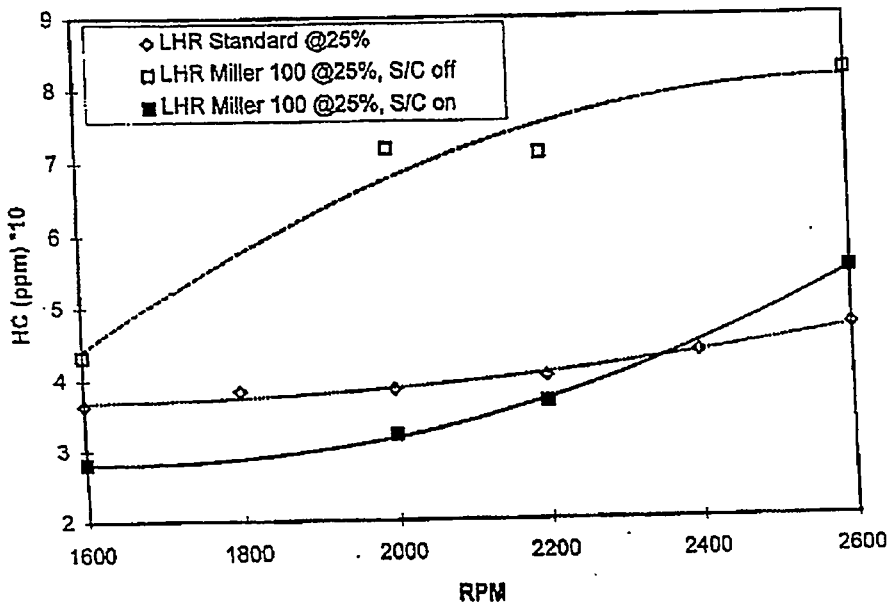

Figure 13. Comparison of HC Emission Between LHR Standard and LHR Miller 100 Engines at 25% Torque

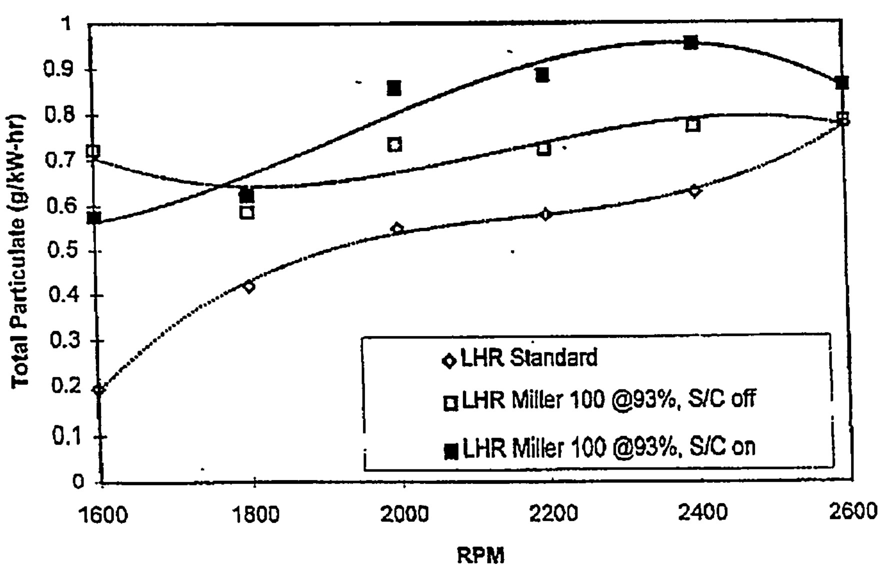

Figure 14. Comparison of Total Particulate (includes absorbed organic) Between LHR Standard and LHR Miller 100 Engines at 93% Torque

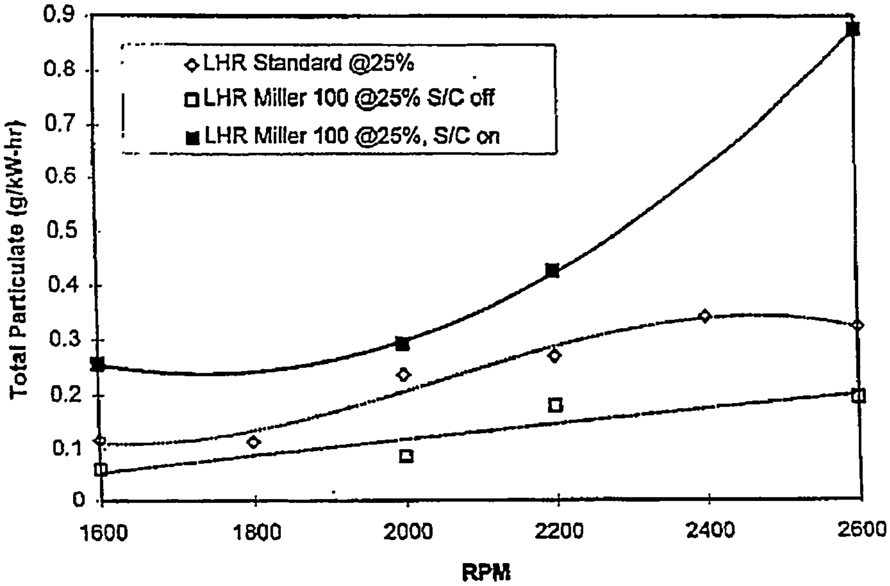

Figure 15. Comparison of Total Particulate (includes absorbed organic) Between LHR Standard and LHR Miller 100 Engines at 25% Torque

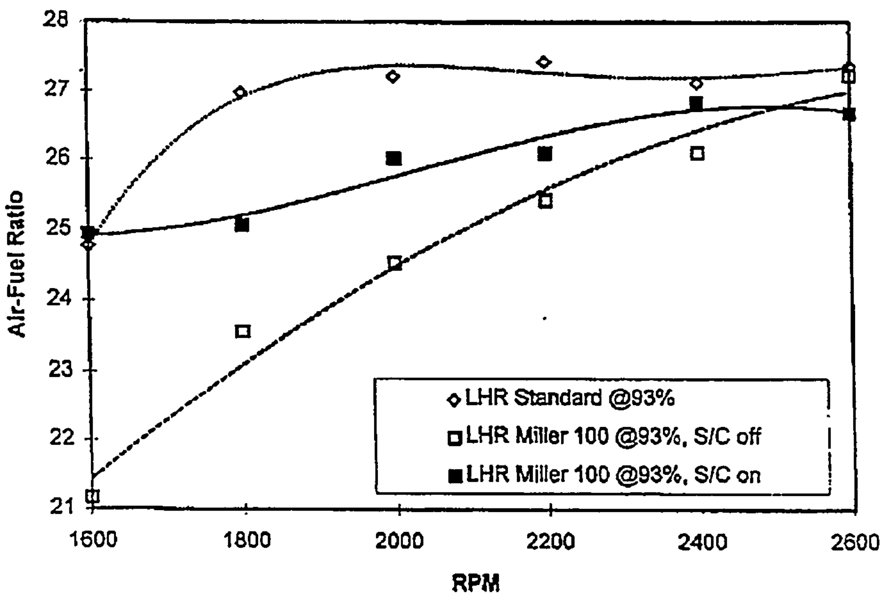

Figure 16. Comparison of Air-Fuel Ratio Between LHR Standard and LHR Miller 100 Engines at 93% Torque

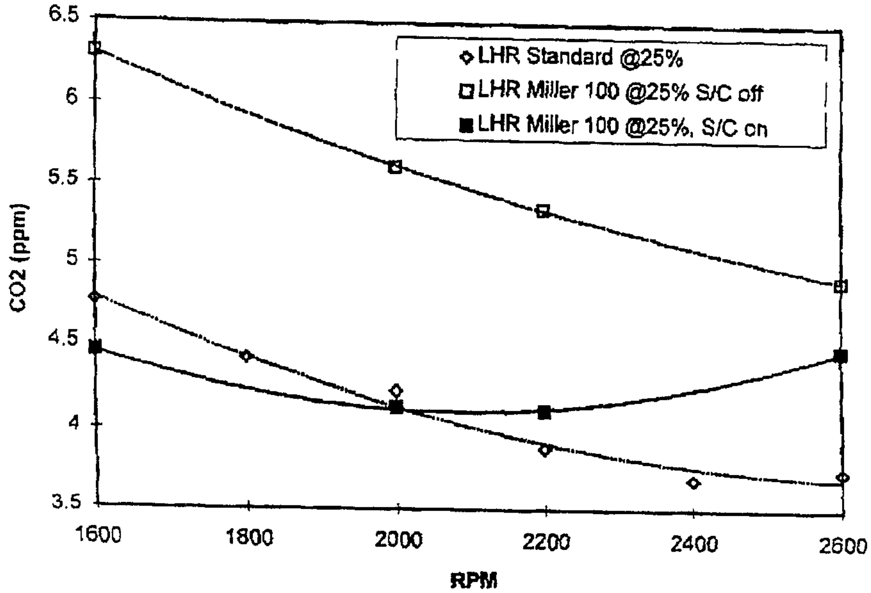

Figure 17. Comparison of CO2 Emission Between LHR Standard and LHR Miller 100 Engines at 25% Torque

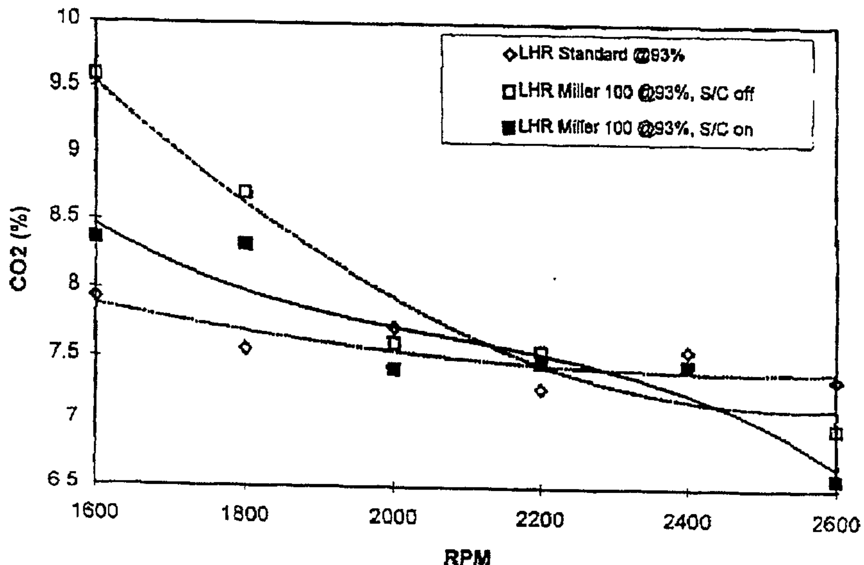

Figure 18. Comparison of CO2 Emission Between LHR Standard and LHR Miller 100 Engines at 93% Torque