CONSEIL INTERNATIONAL
DES MACHINES A COMBUSTION

INTERNATIONAL COUNCIL
ON COMBUSTION ENGINES

PAPER NO.: 253

Experimental Experience Gained with a Long-Stroke Medium-Speed Diesel Research engine using Two Stage Turbo Charging and Extreme Miller Cycle.

Mathias Fiedler, FMC Fiedler-Motoren GmbH, Germany
Hugo Fiedler, FMC Fiedler Motoren GmbH, Germany
Peter Boy, Flensburg University of Aplied Sciences, Germany

Abstract: The objective of the paper is to present experimental results gained from a long-stroke medium speed diesel engine. The study is carried out on the 3-cylinder long-stroke FMC 4524 research engine located at Flensburg University of Applied Sciences in cooperation with ABB Turbo Systems, Baden. Based on a IMO II Layout of the engine featuring • High stroke / bore ratio of s/d = 450mm/240mm = 1,875, • optimized mechanical efficiency based on crankshaft design acc. to classification rules, • combustion chamber design optimized for high compression ratio (=17.8), • 2 stage High Pressure Injection System with variable injection pressure, • Single Stage Turbo Charging, • and standard Inlet Valve Timing, Two Stage Turbo Charging and Miller Cycle Inlet Valve Timing were applied in several steps. In parallel modifications to the exhaust gas system were applied to improve part load and startup performance. Also variations of exhaust gas valve timing and injection characteristics were executed. The project is primarily aimed at reduction of CO_2- and PM-Emissions in the envelope of IMO III exhaust gas regulations for non ECAs. In an intermediate development step Inlet Valve Timing was moved to 42°CA before BDC (Miller 42) and 50°CA before BDC (Miller 50). The first results of Miller 42 showed a reduction of fuel consumption to 168 g/kWh, meaning a CO_2-Emission reduction of app. 6% based on the values of the base engine. PM-Emissions stayed constant on the low level of the base engine. In opposition to the expected trend Nitric Oxide Emissions could be reduced by 20% down to about 8g/kWh. Further development steps will include tests with more extreme Miller-Configurations up 60°CA before BDC. Additionally, pilot-application of other means for emission control like EGR and Fuel-Water emulsion are planned to evaluate further emission reduction potential aiming at emission regulations for ECAs.

INTRODUCTION

With IMO Tier II Emission regulations already in force and IMO Tier III emission limits announced for 2016, diesel engine development is focused on solutions for the upcoming challenges.

Not only Nitrogen Oxide and Sulfur Dioxide-emissions must be reduced, but also Carbon Dioxide- and Particulate Matter emissions need to be kept in mind. And last, but not least, space requirements, reliability, plant maintenance and cost of ownership must be considered.

While SO_2-emissions can only be handled with exhaust gas after treatment or fuel specifications, there are a variety of measures to reduce NO_x-emissions.

Exhaust gas after treatment with a SCR-Catalyst and Particulate-Filter is a possible solution, as long as limited applicability for HFO-operation and extensive investment in hardware and operation costs are accepted.

On the other hand, there are engine internal or engine related methods influencing the thermodynamic process to achieve reduced exhaust emissions, among them

- Optimized engine dimensions,
- Optimized injection parameter,
- Valve timing,
- Turbo charging,
- Exhaust gas recirculation,
- Water direct injection,
- Humid air system or
- Fuel-water-emulsion.

Test Facility

To verify the potential of a number of these measures a test program was carried out on the FMC 4524 research engine located at Flensburg University of Applied Sciences in cooperation with ABB Turbo Systems, Baden and Institute for Ship Research, Flensburg.

Originally designed to examine the influence of large bore-stroke ratios, the engine geometry also allows implementing high compression ratios up to 1:19 without compromising combustion chamber shape. Engine base data are shown in Table 1.

Furthermore, the engine is equipped with a high performance 2-stage injection system.

FMC 4524 - Engine Parameter		
bore	[mm]	240
stroke	[mm]	450
s/d	[-]	1,875
speed	[rpm]	600 (720)
NOx-Limit Tier II	[g/kWh]	10,10
NOx-Limit Tier III ECA	[g/kWh]	2,50
BMEP	[bar]	24 (26)
Compression ratio	[-]	(12)…17,8…(19)
cylinder peak pressure	[bar]	220 bar
number of cylinders	[-]	3 (6)
Turbocharging	ABB Turbo Systems	
Injection System	FMC 2-stage system	

Table 1: Engine base data

Designed as a hybrid between Common Rail- and Cam Operated Injection System a (first stage) pressure pump feeds a constant pressure into the second stage plunger pump. The first stage pressure is also applied to the backside of the injector needle. The cam operated plunger pump imposes a pressure wave on the lower side of the injector needle and opens the needle as known from conventional injection systems (Figure 1).

Due to the high back pressure on the injector needle the opening pressure is increased to 1300bar, while the closing pressure is increased to 800bar at 500bar first stage pressure.

This leads to optimized spray formation over the complete injection. Areas of low injection pressure at start and end of injection known from conventional injection systems and some Common Rail applications are eliminated.

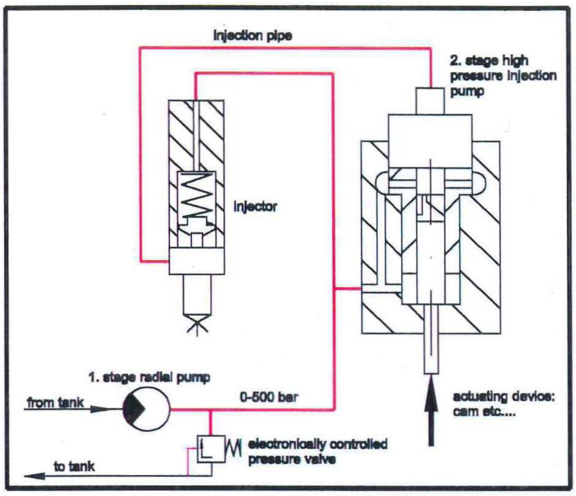

Figure 1: Two stage injection system

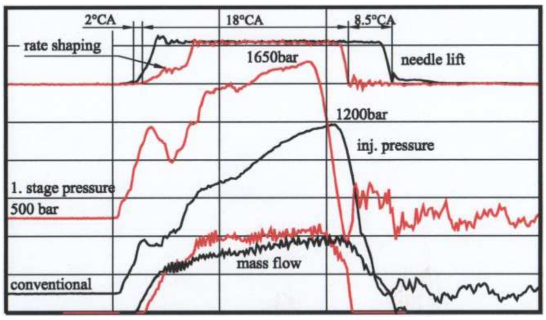

Figure 2: Influence of First stage pressure on line pressure, needle lift and mass flow

Figure 2 shows the influence of first stage pressure on injection pressure, needle lift and mass flow measured on an injection test rig equipped with rate tube. At high first stage pressures a delayed, slow needle movement can be observed, which was due to the high closing force on the needle. This led effectively to rate shaping and smooth start of combustion (Figure 3).

Additionally, the higher injection rate and duration results in increased heat release rate, shortened combustion duration and improved thermodynamic efficiency.

Test Approach

Based on optimized geometrical and thermodynamic conditions of the base engine Two Stage Turbo Charging and Miller Cycle Inlet Valve Timing were applied in several steps, the main objective being reduction of CO_2- and PM-emissions under IMO Tier II / Tier III non ECA conditions.

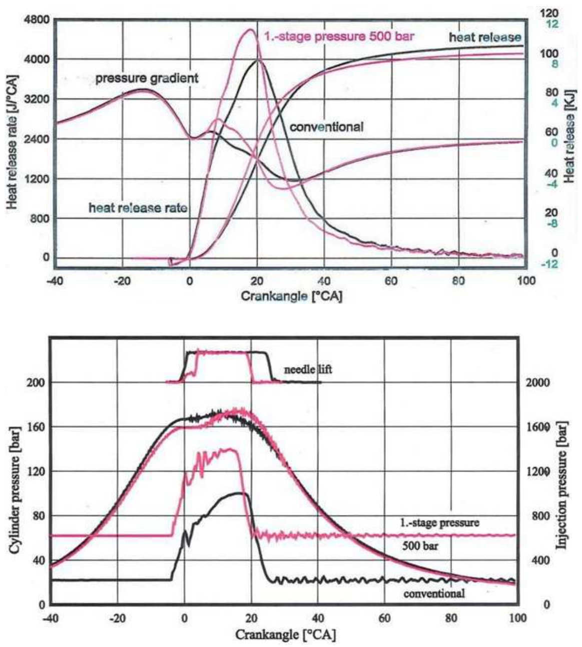

Figure 3: Influence of first stage pressure on injection and combustion characteristic

A second objective of the project is NO_x reduction as far as possible below IMO Tier II limits, to provide an optimized starting point for additional measures like EGR or Fuel-Water-Emulsion, targeting IMO Tier III ECA emission levels.

MAIN PART

Single Stage Turbocharging and Miller Cycle

The scope of research is based on our studies on the FMC 4524 engine performed as part of the CLEAN I joint research project (1995-1998).

Starting from the original fuel consumption optimized engine configuration (A) with standard timing, high injection intensity and subsequently high NO_x-emissions, by far exceeding IMO Tier I limits, two different strategies to meet Tier II regulations were found:

Engine Configuration	Inlet Valve Closing	Turbocharger Configuration	First stage Injection pressure
A	+35°	1-stage	500 bar
B	+35°	1-stage	50-200 bar
C	-40°	1-stage mod.	500 bar

Table 2 : Clean I Engine Configurations

- Standard Timing with reduced injection intensity (engine configuration B), using a first stage injection pressure performance map.
- Miller Cycle with IVC 40°CA b. BDC, single stage turbocharging and high injection intensity (engine configuration C). Turbocharger specifications adapted to higher required pressure ratio and air flow.

Engine Configuration	E2-Cycle						BSFC min	
	NOx		BSFC		PM			
	g/kWh	Δ%	g/kWh	Δ%	mg/m³	Δ%	g/kWh	Δ%
A	14,0	-	175	-	0,06	-	173	-
B	10,1	-28	186	6	0,16	196	184	7
C	9,3	-34	174	-1	0,03	-38	172	-1

Table 3: Clean I Test Results

In both cases IMO Tier II NO_x limits could be fulfilled (Table 3). In configuration B IMO Tier II were fulfilled to the cost of higher fuel consumption and nearly doubled particulate emissions. Using Miller-Timing, the fuel consumption was slightly better and PM-emissions could be reduced by about 40%. Detailed test results are shown in Figure 4.

Switching to Miller cycle NO_x-emissions are reduced by around 40%, paired with significant BSFC and PM-emission improvements at high loads. At part load below 50% both BSFC and PM-emission are slightly higher compared to the base specification (A) as a result of insufficient charger layout at part load operation.

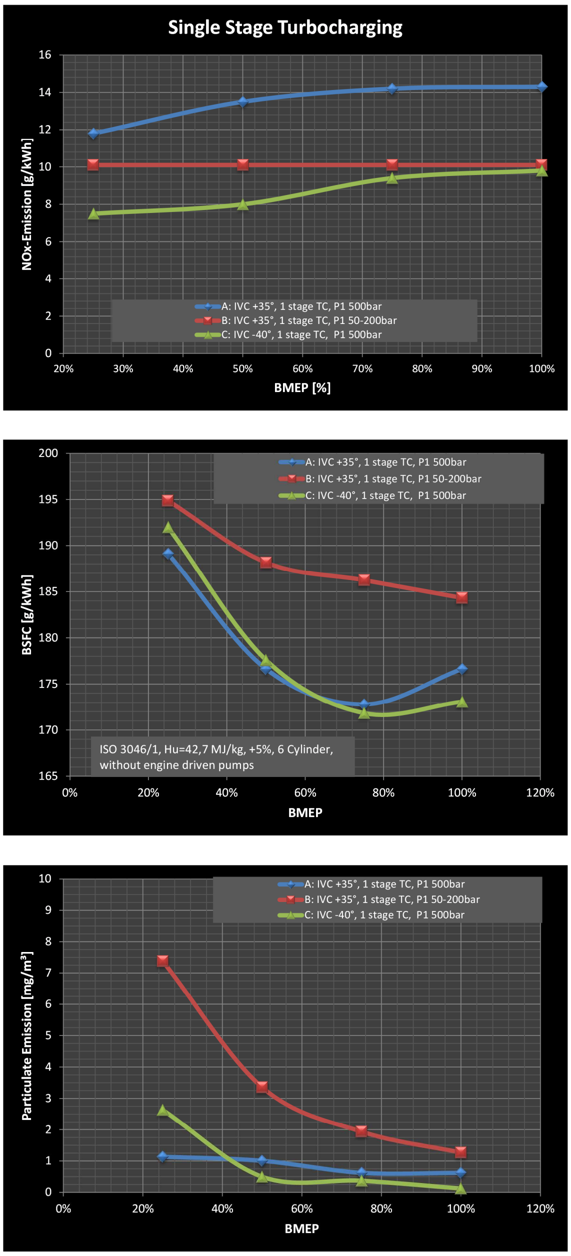

Figure 4: CLEAN I test results

Two Stage Turbocharging and Miller 40

As a result of limited pressure ratio and efficiency of single stage turbocharging the application of more extreme Miller-Cycle Timing was not possible. Consequently, the engine was converted to two stage turbocharging with inter stage charge air cooling in our current joint research program.

Additional modifications to exhaust gas system and valve overlap were applied, aimed at optimization of air throughput and turbocharger response especially at engine startup and acceleration, but also under part load conditions.

Engine Configuration	Inlet Valve Closing	Turbocharger Configuration	First stage Injection pressure
A	+35°	1-stage	500 bar
C	-40°	1-stage mod.	500 bar
D	-42°	2-stage	500 bar
E	-55°	2-stage	500 bar
F	-63°	2-stage	300 bar

Table 4: Extreme Miller engine configurations

As a result of these changes engine operation was possible under all conditions mentioned above. No additional measures like flexible Inlet Valve Timing or external air supply, even under extreme miller conditions, are necessary. Save temperature limits for exhaust gas system and turbochargers could be maintained in all operation modes.

A comparison of test results of engine configurations at IVC around 40°CA BDC (C,D) shows a small increase in NO_x due to a higher value at 50% load, but well below the IMO Tier II level (see Table 4).

While BSFC is unchanged at full load conditions a significant increase was found taking the whole ISO E2-cycle into account, as a result of higher part load consumption. PM-emissions are nearly unchanged (Table 5).

Engine Configuration	E2-Cycle						BSFC min	
	NOx		BSFC		PM			
	g/kWh	Δ%	g/kWh	Δ%	mg/m³	Δ%	g/kWh	Δ%
A	14,0	-	175	-	0,69	-	173	-
C	9,3	-34	174	-1	0,43	-38	172	-1
D	9,6	-32	177	1	0,43	-38	173	0
E	8,0	-43	172	-2	0,67	-3	168	-3
F	5,6	-60	175	0	1,07	55	171	-1

Table 5: Extreme Miller test results

Overall 2-stage turbocharging offers no significant advantage at Miller 40 inlet valve timing compared to the single-stage system under current conditions. This might change taking future charging system optimizations, especially for part load operation, into account.

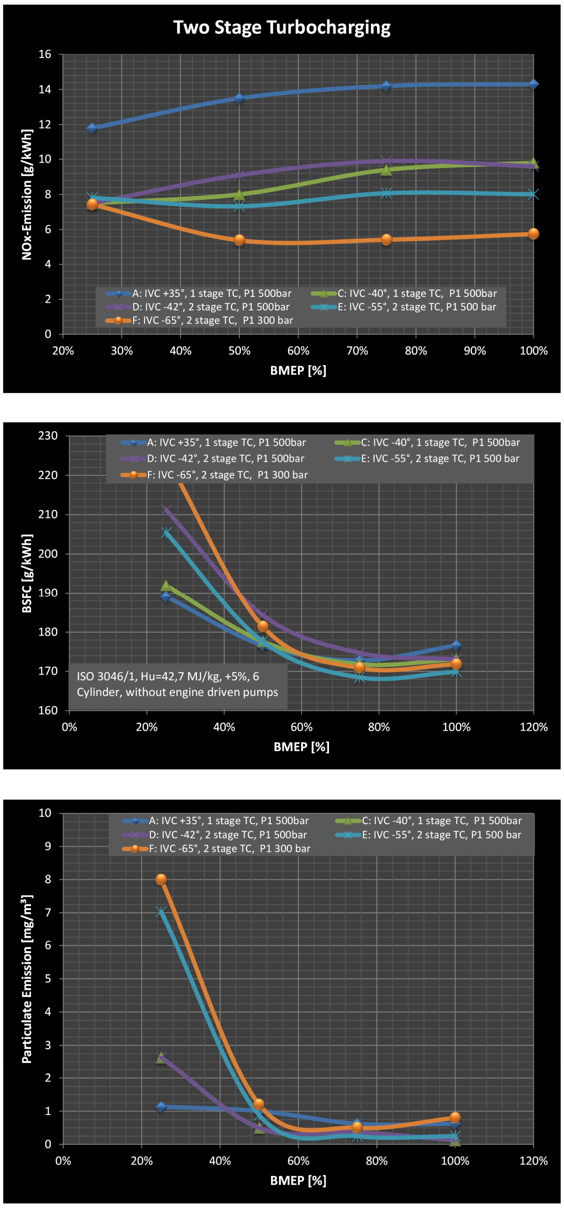

Figure 5: Comparison of extreme Miller test results

Extreme Miller

At extreme Miller configurations 2-stage Turbocharging is the only possibility to achieve the necessary high charge air pressures of up to 6.2bar.

With more extreme Miller Timing NO_x-emissions can be further reduced down to 5.6 g/kWh at IVC 63°CA b. BDC.

Apparently, a BSFC optimum is located at IVC 55°CA b. BDC with NO_x-emissions 20% below IMO Tier II limit.

Minimum BSFC is found 168 g/kWh at 75% load, but part load BSFC is significantly increasing above the level of the reference configuration A.

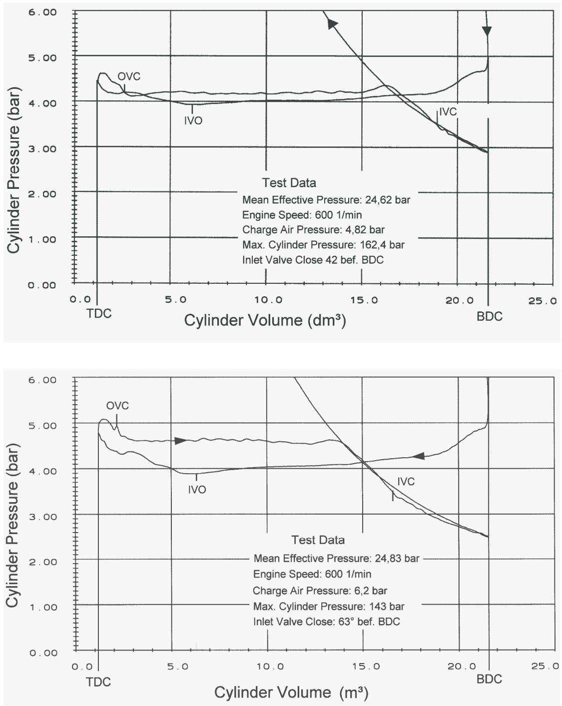

Figure 6: Low pressure p-V-Diagram Miller 42 and 63

Theoretically, the low NO_x-emission level provides a possibility for further BSFC optimization (e.g. using advanced injection timing), but this needs to be examined. Possible gains are certainly small, as the NO_x/SOI gradient is relatively steep.

Engine configuration F (IVC 63°CA b BDC) shows slightly increased BSFC at high loads, but part load fuel consumption increases even more.

Particulate emissions are showing a similar behavior: While full load emissions at high loads are lower or similar to base configuration (A) emissions, part load emissions are increasing drastically.

This is likely a consequence of insufficient charge air supply at part and low load. Injection needle opening pressure stays high at 1200 bar due to the high first stage injection pressure. Spray formation is optimized even at low load conditions.

Increase of part load BSFC and PM-emissions, paired with increasing exhaust gas temperatures and decreasing combustion air ratio, are obviously indicating a border regarding more extreme miller timing, at least under the given conditions.

With advancing miller valve timing charge air pressure is rising. On the other hand peak cylinder pressure is decreasing, offering possibilities for further optimizations like advanced turbo charging or increased compression ratio (figure 6).

<u>IMO Tier III ECA emission concept</u>

Targeting IMO Tier III ECA emission limits for Nitrogen Oxide the influence of fuel injection intensity under extreme miller conditions were examined, decreasing the first stage injection pressure to 100bar.

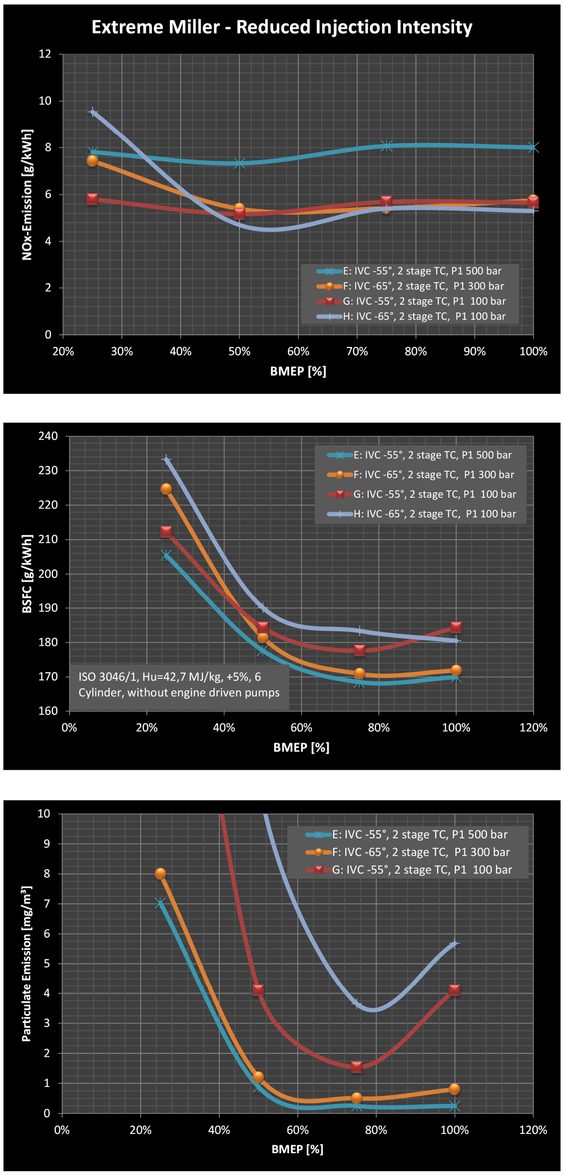

Figure 7: Influence of injection intensity at extreme miller configurations

Engine Configuration	Inlet Valve Closing	Turbocharger FWE Configuration	First stage Injection pressure
A	+35°	1-stage	500 bar
E	-55°	2-stage	500 bar
F	-63°	2-stage	300 bar
G	-55°	2-stage	100 bar
H	-63°	2-stage	100 bar
I	-55°	2-st., FWE 25%	100 bar
K	-55°	2-st., FWE 40%	100 bar

Table 7: Extreme Miller Configurations: Reduced injection Intensity and FWE

Under Miller 55 conditions the influence of injection intensity on NO_x-emission and BSFC is similar to the effects observed at standard timing, but PM-emissions at low- and full load are increasing beyond acceptable levels. NO_x-emissions are reduced to 5,6 g/kWh, similar values as before under Miler 63 conditions with high injection intensity, but BSFC is increased to values known from engine configuration B (Standard Timing + reduced Injection intensity). PM-emissions are increasing beyond the level of configuration B.

Under Miller 63 conditions the influence of injection intensity on NO_x-formation is negligible, but BSFC and especially PM-Emission are increasing drastically. Together with general engine data like exhaust gas temperature and combustion air ratio this behavior confirms the border for miller timing under given conditions.

Engine Configuration	E2-Cycle						BSFC min	
	NOx		BSFC		PM			
	g/kWh	Δ%	g/kWh	Δ%	mg/m³	Δ%	g/kWh	Δ%
A	14,0	-	175	-	0,69	-	173	-
E	8,0	-43	172	-2	0,67	-3	168	-3
F	5,6	-60	175	0	1,07	55	171	-1
G	5,6	-60	182	4	3,76	446	178	3
H	5,5	-61	186	6	7,22	948	180	4
I	3,5	-75	176	0	0,26	-62	171	-1
K	2,3	-84						

Table 8: Extreme Miller Results: Reduced injection Intensity and FWE

Based on engine configuration G (Miller 55 + first stage pressure 100bar) a pilot test with Fuel-Water-Emulsion (FWE) was carried out.

Emulsion was produced directly in front of the engine, using an Aqua Fuel emulsion system (formerly known as HDC-System), developed by FMC.

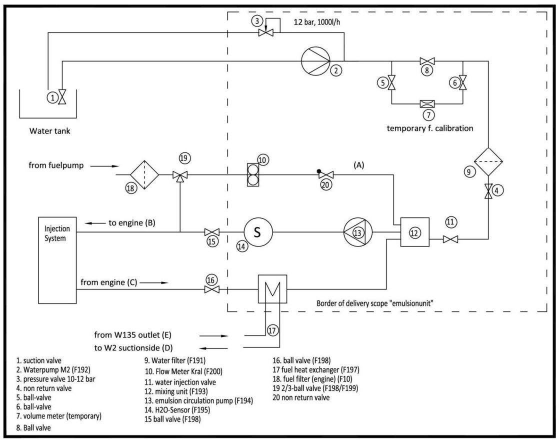

Figure 8: Aqua Fuel Emulsion System

Fuel is circulated continuously between mixing chamber and injection system. Water is injected into the mixing chamber, controlled by a microprocessor system using a Fuel-in-Water Sensor to provide a closed loop water control.

Water content is freely adjusted between 0% and 50%. Due to restrictions of the injection system at low first stage pressures the pilot test was performed at 75% engine load. Water content of the emulsion was adjusted to 25%

NO_x-emissions are decreasing 38% relative to engine condition G to 3,6g/kWh. PM-emissions are reduced by 90%, BSFC by 3%.

Overall this test confirms the efficiency of Fuel-Water-Emulsion known from other applications under extreme miller configurations and allows extrapolation of the result to other loads and water contents.

Starting from engine configuration G (Miller 55 + first stage pressure 100bar) an overall NO_x-emission reduction of 60% is necessary to fulfill IMO Tier III ECA emission regulations at 2.5 g/kWh. Extrapolating from the pilot test this reduction can be achieved with 40% Fuel-Water-Emulsion. This is a common value known from other applications.

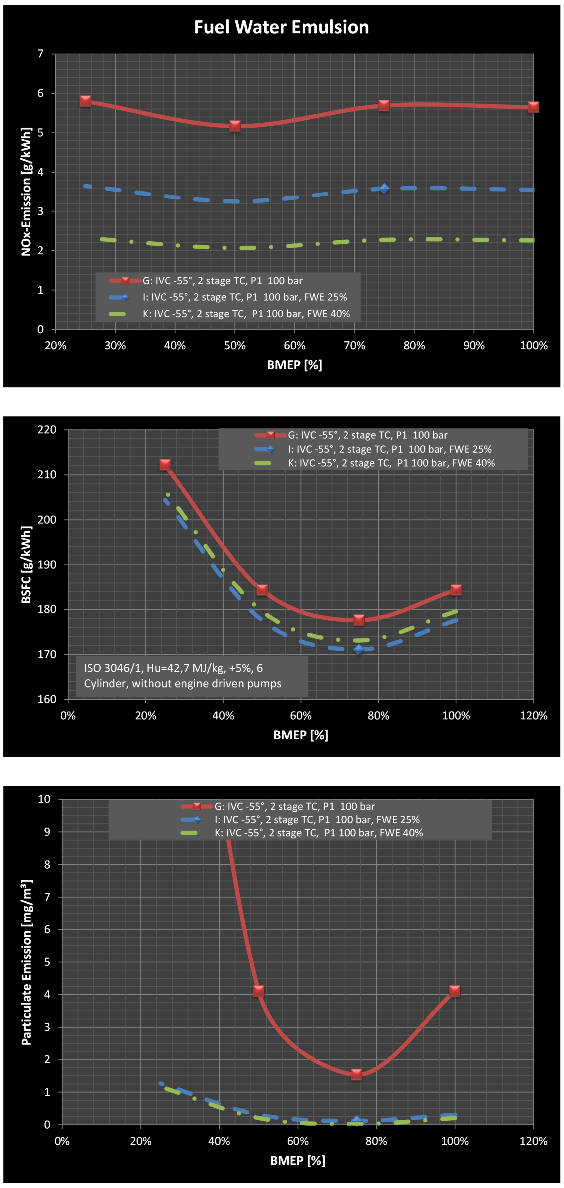

Figure 9: Influence of Fuel-Water-Emulsion under extreme Miller Conditions.

CONCLUSIONS

The combination of

- Extreme Miller Inlet Valve Timing,
- Two Stage Turbocharging,
- Two Stage high pressure injection system and
- Fuel-Water-Emulsion

in combination with optimized engine design provides new possibilities to meet IMO Tier III exhaust emission limits for environmental controlled areas.

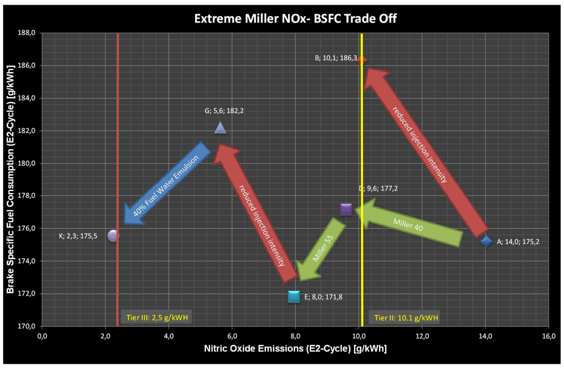

Figure 10: Concept for optimized IMO Tier II and Tier III engine layout

Two stage turbocharging in combination with inlet valve closing at 55°CA b. BDC and optimized high pressure injection provides an easy way to meet IMO Tier II emission limits combined with optimized BSFC, CO_2- and reduced PM-emissions (invisible smoke) without extensive modifications to the engine or exhaust gas after treatment. HFO-operation is unrestricted (figure 10).

For operation inside ECAs the injection intensity is reduced and Fuel-Water-Emulsion added, providing easy means to fulfill IMO Tier III emission rules with only minor BSFC and CO_2-emission penalties. PM-Emissions stay on a very low level due to the high positive impact of Fuel-Water-Emulsion. HFO-operation is unrestricted as long as low sulfur fuel is available or SO_2-scrubbers are operational. Additional measures like EGR or SCR-Catalyst limiting HFO-operation and complicating engine operation and maintenance are not necessary.

For full verification of concept the injection system needs to be upgraded to deal with the higher injected fuel volume during FWE-operation.

Additionally, the charging system needs to be redesigned, particularly with regard to low load operation and utilization of optimization potential given by low cylinder peak pressure.

NOMENCLATURE

BDC	Bottom dead centre	[-]
BSFC	brake specific fuel consumption	[g/kWh]
CA	Crank Angle	[°]
CO2	Carbon Dioxide	[%]
ECA	Emission Controled Ares	[-]
FWE	Fuel-Water-Emulsion	[-]
IVC	geometric Inlet Valve closing point	[°CA]
IVO	geometric Inlet Valve opening point	[°CA]
OVC	geometric Outlet Valve closing point	[°CA]
p1	Injection System first stage pressure	[bar]
PM	Particulate Matter	[mg/m³]
NOx	Nitrogen Oxide	[g/kWh]
SOI	Start of Injection	[°CA]
SO2	Sulfurdioxide	[g/kWh]

ACKNOWLEDGEMENTS

The project was funded by the Federal Ministry of Economics and Technology within the Central Innovation Program for SMEs (ZIM).

The authors like to thank Mr. E. Codan, ABB Turbo Systems Ltd and all partners involved in the project for their support and comments.