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A clean, efficient solution for IMO Tier 3: Gas and Dual-Fuel Engines

INTRODUCTION

Pure gas and dual fuel (DF) engines are widely discussed alternatives for marine propulsion, because they are able to comply with the NOx emission limits set forth by IMO Tier III. However, the performance of today's established marine engine designs is limited mainly by the phenomenon of knocking combustion. In the case of pure gas engines, this limitation sets the achievable efficiency and power density. Additionally, in the case of DF engines, operation in diesel mode also suffers from lower efficiency.

Based on a cycle simulation study, this article introduces a concept for DF engines, which allows for increasing the power density while reducing the fuel consumption in both the diesel and the gas operation mode. Moreover, it will be shown that applying variable valve train technique, for instance the ABB solution VCM® [10], has the potential to resolve the design compromises of DF engines.

The proposed concept for the gas mode will also be applicable to pure gas engines since VCM enables the individual optimization of the gas and diesel mode operation.

AVAILABLE TECHNOLOGY AND CURRENT DEVELOPMENT PATHS

Established DF Engines

Today's commercially available marine DF engines have a bmep in the range of 20 to 22 bar. They feature a single stage turbocharging system combined with moderate Miller cycle and fixed valve timing. The compression ratio □ is rather low in order to prevent engine knock in the gas mode. Often the bore size is somewhat enlarged to match the output of their diesel counterparts. Commonly, DF engines are operated at constant engine speed. However, engines for FPP operation have also been announced lately, [2], [3].

Gas Engine Control Strategies

The power of port injected gas engines is controlled by the gas admission valve in the inlet ports, while the air excess ratio □V is adjusted by
established DF engines, an Exhaust Waste Gate (EWG) is used for the above purpose.

Key Points of Future Engine Development

For the future development of DF engines the following four points are expected to be of major importance:

1. Improvement of efficiency in both gas and diesel mode
2. Extended power density
3. Improvement of load step response or engine acceleration without decrease of steady state engine efficiency
4. Enabling direct drive propulsion by mitigating the tendency to knocking combustion.

OPPORTUNITIES FOR DF AND PURE GAS ENGINES

Improving Efficiency

Nowadays, it is a well-known fact that introducing strong Miller cycle and two-stage turbocharging contributes to improving engine efficiency and allows for a higher power density, see e.g. [1]. With Power2®, ABB provides a two-stage turbocharging solution in place that supports OEMs in implementing such concepts.

Control of unwanted knocking combustion is a key factor to increase power density and efficiency of engines operating according to the Otto cycle. It leads to limited design values of compression ratio and bmep. The higher the required design power density, the lower the allowable maximum compression ratio e will be, [5]. Present engines use the moderate charge pressure of single-stage turbochargers to achieve power densities of roughly bmep = 20 bar at a compression ratio of about e = 11 to 13. Because of the constraints imposed by the gas mode operation, engine efficiency suffers especially in diesel mode, for which a compression ratio around e = 16 would be favorable.

By increasing the Miller effect with a corresponding early intake valve closure in-cylinder cycle temperatures can be lowered allowing for increasing of compression ratio or/and power density. This again requires higher charge air pressure which can be provided by two-stage turbocharging. The very high two-stage turbocharging efficiency strongly improves the gas exchange work.

Improving Load Response without Deterioration of Engine Efficiency

Air excess ratio control based on variable valve control allows for highly improved load response even at an increased level of engine efficiency. The gas exchange losses are substantially reduced and the lowered process temperature due to the increased Miller effect substantially increases the closed cycle efficiency.

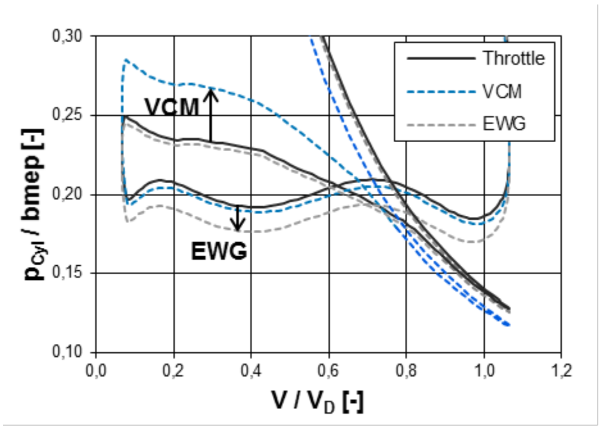

Figure 1 –Gas exchange with VCM, EWG and throttle valve

Improving Power Density and Enabling FPP Engine Operation

Engine operation at reduced engine speed and increased torque, e.g. FPP operation, is a demanding task due to knock and control margin issues. Again, this challenge can be met by applying strong Miller timing and variable valve timing.

SIMULATION-BASED APPROACH TO NEW DF AND GAS ENGINE CONCEPTS

Starting point of the simulation-based study is an engine model calibrated with measured data obtained from a single stage turbocharged DF engine with moderate Miller cycle and fixed camshaft featuring a standard main diesel injection system, a CR system for pilot fuel injection and a port injection system for gas admission. This simulation model has been extended and modified with the following features:

- two-stage turbocharging system
- increased compression ratio e
- strong Miller effect
- variable inlet valve train

The increase of the cylinder compression ratio ☐ will c
efficiency. In order to prevent knocking combustion in the gas mode, the Miller effect has to be increased and/or the combustion phasing needs to be retarded. Moreover, the right choice of the parameters such as compression ratio, Miller effect, and combustion phasing is not only restricted by the combustion knock limit, but also by safeguarding conditions for safe ignition of the pilot diesel spray. In addition, other design limits such as the maximum allowable cylinder pressure and turbine inlet temperature have to be considered as well.

Key Model Assumptions

a) Combustion: Wiebe model
Gas mode: constant model parameters (for constant speed)
Diesel mode: recalculated parameters for each operating point according to Woschni and Anisits, including modification from ABB’s experience

b) Pilot Spray Ignition Delay □ID
Ignition delay according to calibrated model based on [6]

c) Knocking
Engine knock has been estimated based on a widely used phenomenological knock model, [7].

d) UHC emission
Constant percentage of unburned fuel was assumed due to a missing modeling approach.

e) VCM power demand
No power demand arising from the VCM system has been considered. Measurements and simulations show very low losses. Furthermore, it is proven that VCM allows for much faster closing of the valves than conventional valve train systems. It is expected that the improvement of the gas exchange process will help to cancel out the rather small additional power demand.

f) Gas Supply System
No additional power consumption assumed.

Simulation of Engine and Turbocharging System

Engine cycle simulations have been carried out using the ABB in-house simulation software SISY and.

Design Parameter Optimization

Increased compression ratio e and Miller effect are expected to increase engine efficiency, whereas the increase of the compression ratio is expected to be especially beneficial for the diesel cycle. However, the compression ratio e is limited by geometrical constraints. Furthermore, the efficiency benefits at high values of compression ratio will be restrained by increasing friction and heat losses.

Optimization calculations have been carried out at full engine load for several values of bmep considering both gas and diesel mode engine operation in order to arrive at optimum engine design parameters. For the full load optimization a two-stage turbocharging system with constant turbocharger component efficiencies has been assumed.

The compression ratio, the IVC timing and combustion phasing of diesel and gas modes have been adjusted to achieve maximum engine efficiency. However, the feasible range of design parameters is restricted according to:

Gas Mode Limits	Diesel Mode Limits
Max. knocking integral value	Max. turbine inlet temperature
Max. pilot spray ignition delay	Max. ignition delay
Air excess ratio constant	Min. air excess ratio
Max. cylinder pressure	Max. cylinder pressure

Table 1 – Limiting conditions

The results in Figure 2 show that the engine performance benefits considerably from an increase in the compression ratio. The plot shows the increase of thermal engine efficiency for several values of bmep as a function of the compression ratio. The increase refers to the efficiency achieved at the lowest compression ratio and power density. According to the plot an efficiency increase of more than +2% points is still possible compared with today's established engine technology.

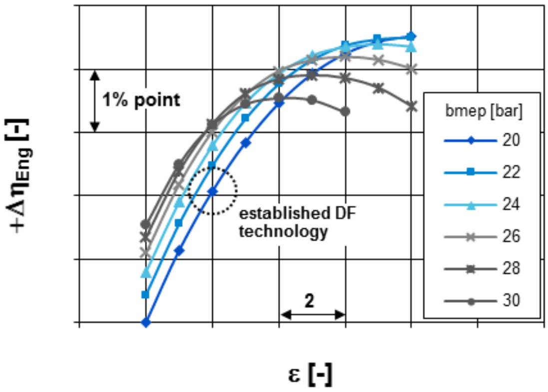

Figure 2 – Average of diesel and gas mode engine efficiency gains

Since both the Diesel and the Otto process are limited by the maximum cylinder pressure and knocking combustion respectively, an increase in compression ratio needs to go hand in hand with an increase in Miller effect, thus increased charge air pressure.

Case Studies

Based on the optimization results shown, the engine parameters for a more detailed case study have been chosen:

Simulation Case:	TC system	bmep	bore	ε	λ_v control
EWG	single stage	Ref	Ref	Ref	EWG
EWG-2s	two-stage	+30%	-6%	+4	EWG HP+LP
VCM	two-stage	+30%	-6%	+4	VCM

The investigation compares an engine setup with single stage turbocharging and EWG control (reference case EWG) to a future engine setup with two-stage turbocharging. The latter case allows for increased power density enabled by a strong Miller effect. The increased bmep allows for a reduction in cylinder bore diameter. Since a reduction of the bore leads to a reduced bearing force, the maximum cylinder pressure limit can be increased in the latter case (for the cases of future engine design a further increase of the firing pressure is considered beyond the scaling due to the bore size reduction). Due to the strong Miller timing, a large step in compression ratio can be afforded. Two different control systems have been compared for the cases with two-stage turbocharging. In the case EWG-2s, the air excess ratio is controlled by an EWG bypassing both turbine stages. In the VCM case, the intake charge mixture is controlled just by a variable inlet valve closure timing (IVC).

a) DEP Engine Operation

Figure 3 shows the reduction of fuel consumption as function of engine load achieved in the cases EWG-2s and VCM compared to the reference case EWG in gas mode. In the case of diesel mode refer to Figure 4.

As expected from the optimization results, the potential gain of engine efficiency is very high. In both operating modes a reduction of fuel consumption in the range of 10 to 15 g/kWh is predicted by simulation at full engine load. While in diesel mode the VCM case shows better performance towards full load, in gas mode the EWG-2s displays a more pronounced potential at engine part load.

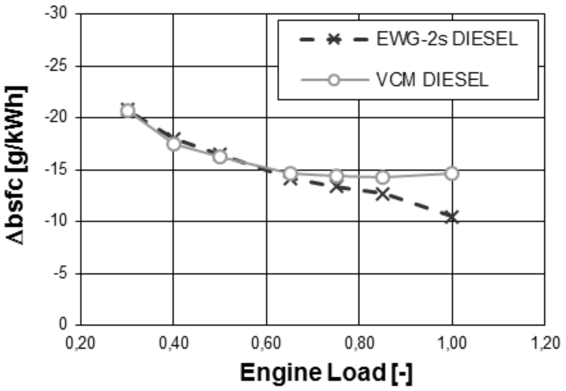

Figure 3 – DEP diesel mode fuel saving

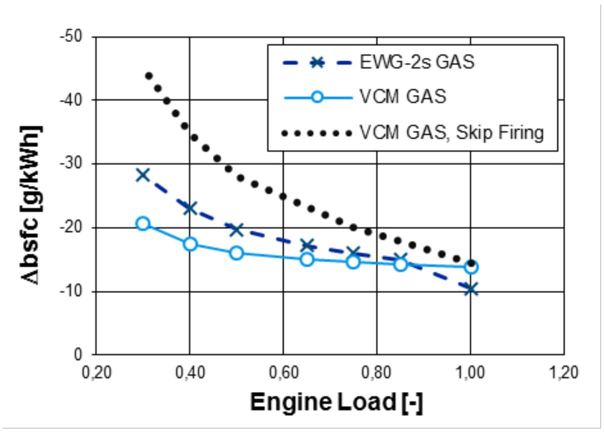

Figure 4 – DEP gas mode fuel saving

The required cylinder throttling towards part load by further advancing of the IVC event (VCM case) leads to a very high reduction of the in-cylinder temperature level. As a result, the ignition of the pilot diesel spray is impeded. The retarded combustion thus produced leads to the depicted difference in fuel consumptions. Among other valve control strategies, the issue of excessive Miller timing for DEP part load operation could be mitigated by the application of skip firing.

b) FPP Engine Operation

For FPP engine operation, the cases EWG and VCM have been simulated with the same design parameters as in the DEP section shown above and consequently exhibit the same performance parameters at nominal load. However, the reference case performance is different because for an applicable low load engine behavior, a part load optimized turbine specification and an inlet valve closure timing shift below the 50% load point is applied because the control margin at part load becomes too small.

Figure 5 and Figure 6 show the specific fuel saving relative to the reference. It is evident that the simulations predict a substantial reduction of fuel consumption in the whole engine load range; in gas mode with a special asset with VCM.

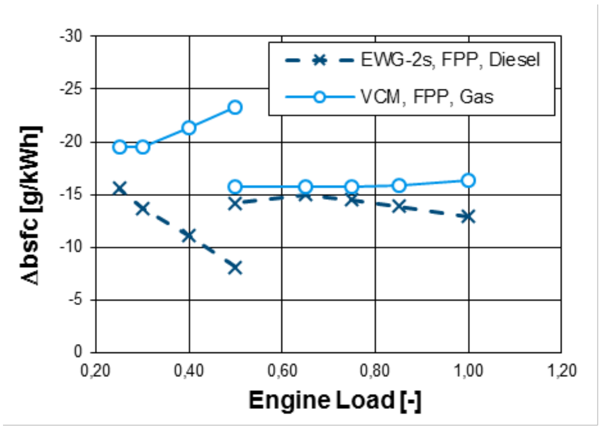

Figure 5 – FPP gas mode fuel saving

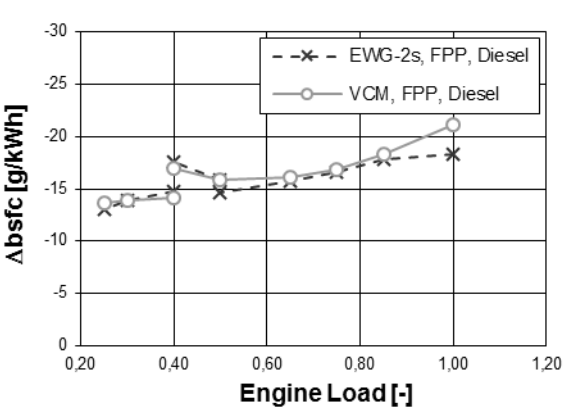

Figure 6 – FPP diesel mode fuel saving

CHALLENGES

The above proposed concept for DF engines discloses new potential for efficiency and power density improvement of gas and DF engines. However, engine operation parameter values are outside of known ranges. It lies in the nature of such extrapolations that certain challenges might arise. At least the following topics have to be addressed properly:

- Homogeneous mixture cylinder charging
- UHC Emission
- Diesel Pilot Spray Ignition
- Lubrication Oil Ignition
- Combustion Chamber Design

CONCLUSIONS

Based on an extensive simulation study, efficiency and power density of pure gas and DF engines can be substantially improved, closing the gap towards today's diesel engines. Increased power density would provide for reducing the enlarged bore diameter of today's gas and DF engines to the level of diesel engines of the same frame size.

Required technology building blocks:

- Highly efficient two-stage turbocharging in order to provide a suitable boost pressure
- Variable IVC timing for air/fuel ratio control and switching between fuels optimized diesel and gas operation mode
- Pilot fuel injection system capable of flexible SOI setting
- Optimized but fixed compression ratio e
- Mechanical structure for a gas engine with bmep = 26 bar and cylinder firing pressure up to 220 bar

Engine control with an exhaust waste gate solution could be shown with improvements comparable to those achieved with VCM. However, solutions with VCM show several advantages:

- Increased transient response
- Higher margin with regard to knock limit
- Facilitated engine start
- Fuel efficient control of air excess ratio without control device being exposed to hot exhaust gases (HFO operation)

Today, pure gas and DF engines already operate under the NOx and SOx limits in ECAs. Therefore, they represent an interesting alternative to diesel engines equipped with EGR or exhaust gas after-treatment as IMO Tier 3 abatement technologies.

With Power2 and VCM, ABB offers the key technology for the implementation of the concept outlined in this article. Power2 has been successfully introduced in the market, a second generation is under development in order to meet the future needs of ABB customers, [8].

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