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Development of China First Ammonia Dual-fuel large engine for marine applications

New Engine Concepts & Systems

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ABSTRACT

A concerted efforts have been devoted by the “Marine Clean Fuel Joint-Study Union” led by COSCO SHIPPING Heavy Industry Co Ltd in China to accomplish the emission reduction target toward IMO zero- or carbon neutral efficacy. The major issues of using the current marine fossil fuels are the exhaust emission of GHG, NOx, SOx and PM, which will certainly be eliminated by switching to alternative fuel such as Ammonia. CRRC Dalian joined this consortium to supply the Ammonia fueled-engines in collaboration with COSCO to produce the first tugboat in China with Ammonia fuel for the maritime industry sustainability.

CRRC Dalian will supply two of the newly developed ammonia dual-fuel engines “12V240H-DFA” to be installed into a newly built ammonia tugboat, which is required to reach a certain target for diesel fuel substitution. The new engine will be able to switch between Ammonia and Diesel for its duty operations, giving a great flexibility advantage in the transition time towards the journey of decarburization of the industry. This type of engine is expected to be widely used as Ammonia is well placed to be taken up as a future marine fuel. However, it faces some serious challenges associated with the handling, storage, bunkering infrastructure and health & safety. These issues require effective process, specialised equipment and facilities, which have developed, verified and fully approved by the Chinese Classification Society (CCS).

This work reports the finding of the newly developed engine based on the proven CRRC dual fuel 12V240H-DFA, which has undergone a series of design changes and new addition of multi-point injection system, VG turbocharger, control system and EFI pilot diesel system. The engine design has been certified to IGF compliance by CCS’s relevant ammonia standards such as Double Wall & Ventilation, Ammonia Supply Interlock, Ammonia Automatic Vent, Nitrogen Purge, Independent Security System, Knock/Misfire Monitor, Explosion Relief Valve, Crankcase Inert and Leakage Detector.

CRRC Dalian has completed all the design and analysis to optimise the new Ammonia DF engine and verified by R&D testing to the target specified by the boat owner. The engine has reached the required service power output, the fuel substitution targets and the thermal efficiency with stable and safe combustion. The engine has been validated to all performance intent and undergoing fine tuning calibration for optimum configuration. The engine has also achieved the target emission compliance with the Chinese standard for marine engines “GB15097-2016 stage 2” with the aid of fitting aftertreatment system of both SCR and ASC to deal with NOx and Ammonia slip respectively. The design, simulations, prototype test results and installation on the boat will be presented in details.

1 INTRODUCTION

Ammonia has been considered as a viable alternative fuel to the current fossil fuel to get rid of the carbon. The commercial availability and existing logistic of Ammonia distribution in bulk at many ports worldwide [1], gives it an advantage over other carbon-free fuels to be used in internal combustion engines.

Major shipyards in China have been active to provide carbon-free retrofit application and COSCO shipyard is one of the leading maritime institutions to introduce a carbon-free operation. A new tugboat has been developed to run on Ammonia with initial introduction target to reach 80% substitution of diesel fuel.

Ammonia is a promising hydrogen carrier [2] owing to its high hydrogen content (17.65 wt.%), established handling and distribution of the fuel ability to be stored in liquefied phase at 10 bar or -33°C, compared with Hydrogen fuel storage requires high pressure vessels of up to 70 MPa while liquid storage needs cryogenic tanks maintained at -253°C. It is therefore the fuel ammonia has a clear advantage in the handling of the fuel at room temperature. It has been reported that liquid hydrogen is estimated to be at least ten times more expensive to produce and store than liquid ammonia due to the requirement to reach very low temperatures [3].

However, Ammonia is toxic a chemical substance and great care needs to be exercised in supplying, storing and admission to engine. Also, Ammonia has high ignition energy and slow flame speed characteristics, which makes the combustion incomplete with unburned fuel reduces the thermal efficiency compared with Diesel combustion. The exhaust emission of the burned fuel Ammonia must be controlled to eliminate the Oxide of Nitrogen and Ammonia slip.

Since ammonia is toxic substance, the safety aspects need to be carefully considered to ensure a good level of health and safety protocol to be implemented. While ammonia has a toxicity concern, the limited available industry standard (not regulated yet) to use special piping system, incorporate gas detectors in test-cell and the use of personal protective equipment (PPE). A complete system of sensors, measurement and control devices have been added to the engine to deal with potential risk of ammonia leakage, as a prevention method to start with. The system was also considered in detail to deal with the likely event of ammonia leakage. It is of paramount action to ensure the leakage of ammonia would pose no danger exposed to human or the environment. Hazard and operability (HAZOP) study was completed to ensure health and safety will be fully maintained in case of a failure, which has been built in the design and validation process such as FMEA (failure mode effect analysis) and DVPSOR (design validation plan sign off report) prior to sign off the engine to service release.

In contrast to other forms of e-fuels, ammonia is the only carbon-free hydrogen carrier that can be synthesised from renewable sources. This was reported [4] by Siemens in the UK Nel Hydrogen, where ammonia was produced by combining hydrogen from water splitting with nitrogen from the air. The abundance of nitrogen in the air supports the use of a carbon-free ammonia as hydrogen carrier fuel for a future, large-scale and sustainable energy storage cycle.

2 AMMONIA IN DUAL-FUEL (DF) ENGINE

The conventional DF engine uses the diesel fuel as a pilot igniter to the main fuel of natural gas or CH4. The main advantage of replacing CH4 fuel with Ammonia is due to carbon free and thus no CO2-emissions will be set free by the combustion of NH3. However, the combustion properties of Ammonia as shown in table 1, to be poorer than CH4, due to the significantly lower heat value (LHV), lower max burning speed, and the lower air-fuel ratio (AFR) range. Furthermore, the toxicity of Ammonia is one of the main challenges.

The traditional Methane slip associated with conventional DF and Gas engines are also a concern to address the NH3-slip from the new Ammonia DF engine. This issue will be dealt with by aftertreatment system, which is above the odour threshold of 5-25ppm. It is therefore important to start the engine with diesel only to pre-heat the exhaust system as a pre-request for the aftertreatment to work properly.

The aftertreatment system is combined Selective Catalyst Reduction plus Ammonia Slip Catalyst (SCR+ASC) as SCR tackles NOx and ASC tackles NH3-slip. This newly developed aftertreatment system is a first-article production supplied by a local Chinese manufacturer to be approved after 6 months of service and de-meriting then sign-off for full production.

Table 1. Comparison of CH4 and NH3 as main fuel in Dual-Fuel Engines

Main DF Fuel Properties	NH3	CH4
LHV (MJ/Kg)	18.6	50
Laminar burning speed	0.07	0.37
Min auto ignition temp, C	650	630
Flammability AFR	0.63-1.5	0.5-1.7
Adiabatic flame temp, C	1800	1950

3 AMMONIA COMPARISON TO DIESEL

Table 2 shows a comparison of the main properties between the current conventional marine diesel oil fuel and the new alternative carbon free Ammonia fuel.

Table 2. Comparison of Diesel and NH3 fuels [5]

Fuel Properties	Diesel	Ammonia
Laminar flame speed [cm/s]	40	7
LHV MJ/kg	42.7	18.6
LHV MJ/lt	35.7	12.7(-33C) 10.6(45C)
Storage state at 1.013bar	Liquid	Liquid -33C
Fuel tank size relative to MGO	1	2.8 (-33C)
Min Ignition energy MJ	0.24	14
Explosives mixture by vol%	3.4	20
Explosion Limit by vol% (lo-hi)	0.6-12.6	15.4-33.6
Excess Air/Fuel ratio, Lambda	1.5-2	0.5-1.6
Autoignition Temperature	>225	650
Stoichiometric Air/Fuel Kg/Kg	14.5	6.1
Air Specific ratio Kg Air/MJ	0.34	0.33
Flashpoint in deg. C	52-80	132
Kinematic viscosity at 20°C in cSt	2.5	14.73 (gas)
Vapor pressure at 20 C in bar	0.5E-3	2.2 – 8.5

The main differences between Ammonia and Diesel are much lower values than diesel for the laminar flame speed, low heat value (LHV), and the stoichiometric air fuel ratio, whereas the air specific energy ratio which is the amount of air required to release energy by Diesel and Ammonia heat release shows to be of similar parish.

Ammonia has relatively narrow flammability range in air by volume at 15 – 28 %, compared to other future fuels like hydrogen that has a wide flammability range at 4 – 75 %. Unlike with hydrogen, explosion risk is not a major concern with ammonia. However, the toxic properties of ammonia will require special attention when designing the ammonia engine and the surrounding systems in order that ammonia can be used safely as fuel in Internal Combustion Engines (ICE's).

According to the laminar flame speeds shown in Table 2, Ammonia burns much slower than the diesel fuels. This has a direct implication on the rate of combustion speed and the heat release. Ammonia combustion with different pilot diesel concentration quantities is used to accelerate the burning rate and adjust the heat release.

The minimum ignition energy for ammonia is more than 50 times higher than for the diesel fuel. Ammonia burns much easier at higher volumetric ratios than diesel. It is still more reasonable than Hydrogen with its very fast burn rate compared with Ammonia. The autoignition temperature is relatively low for diesel fuel, which makes it more compatible with diffusion combustion. The other considered fuels are all on a higher level, ideally suited to an Otto cycle; compression ignition of Ammonia in the Diesel cycle is on the other hand much more challenging than for diesel fuel.

The table shows the difference in viscosity and vapor pressure, which will impact on the lubrication performance and in particular on the oil cavitation formation behaviour. The new fuel properties will also impact on the fuel injection system and the material used, as such the flow characteristics and anti-wear coatings to ensure optimum performance and maintain the established life cost cycle of the directly affected parts with the new replaced fuel.

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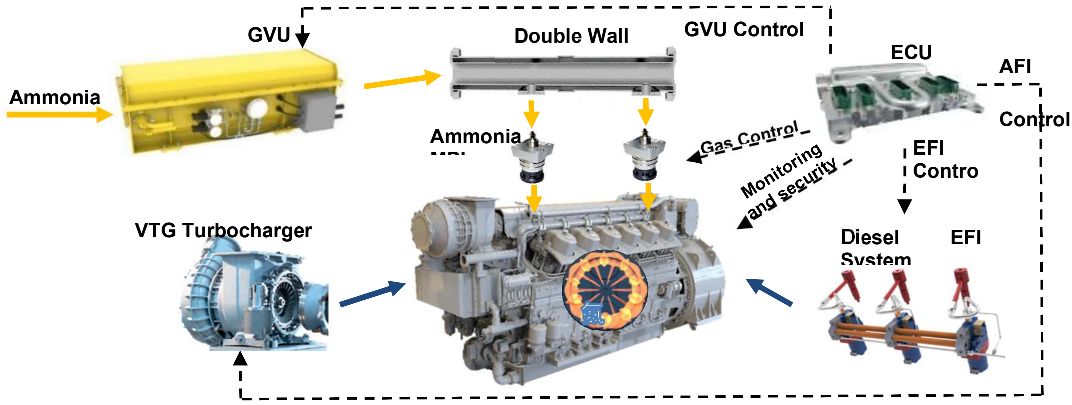

Figure 1. Overview schematic of NH3-DF engine

The significant difference between the conventional diesel and the new Ammonia fuel gives doubt for concern and therefore it needs to be prudent to assess the engine systems such as the fuel injection equipment due the fundamental changes in fuel properties. The combustion of Ammonia is another fundamental new change and will need to be thoroughly considered, which will be discussed in detail in this paper

The turbine inlet temperature mainly depends on the excess air ratio and the specific heat capacity of the involved chemical species (the application of scavenging as for medium-speed engines dilutes the combustion gas with fresh air and has therefore an additional effect on the turbine inlet temperature).

4 12V240H-DFA ENGINE DEVLOPMENT

The new Ammonia dual fuel engine “12V240H-DFA” has emerged from the original DF baseline engine and the following modification were found necessary to be introduced for the development of the new engine. The parent engine was originally developed as diesel engine and served reliably within the railway, power generation and marine application for 3 decades. The first dual-fuel version was emerged from this original engine for using natural gas ignited by diesel pilot fuel. The design brief was to convert this latest DF engine from burning natural gas to Ammonia by the same principle of ignition i.e. pilot diesel fuel. The intention is to make minor changes to the engine to lower the development time and introduce the engine to service in a record short time. The Ammonia dual-fuel engine has the following systems added specifically to operate and control the new engine in safe and optimum efficiency manners, as shown in the schematic overview shown in Figure 1. The main added systems for the build of the new Ammonia dual fuel engine are as follows

- Based on 12V240H diesel engine to develop.
- Ammonia multi points injection,
- VTG Turbocharger,
- diesel EFI.
- Double wall system,
- Ammonia supply interlock,
- Leakage monitor,
- Automatic shut-off and vent,
- Nitrogen purge,
- Explosion relief valves

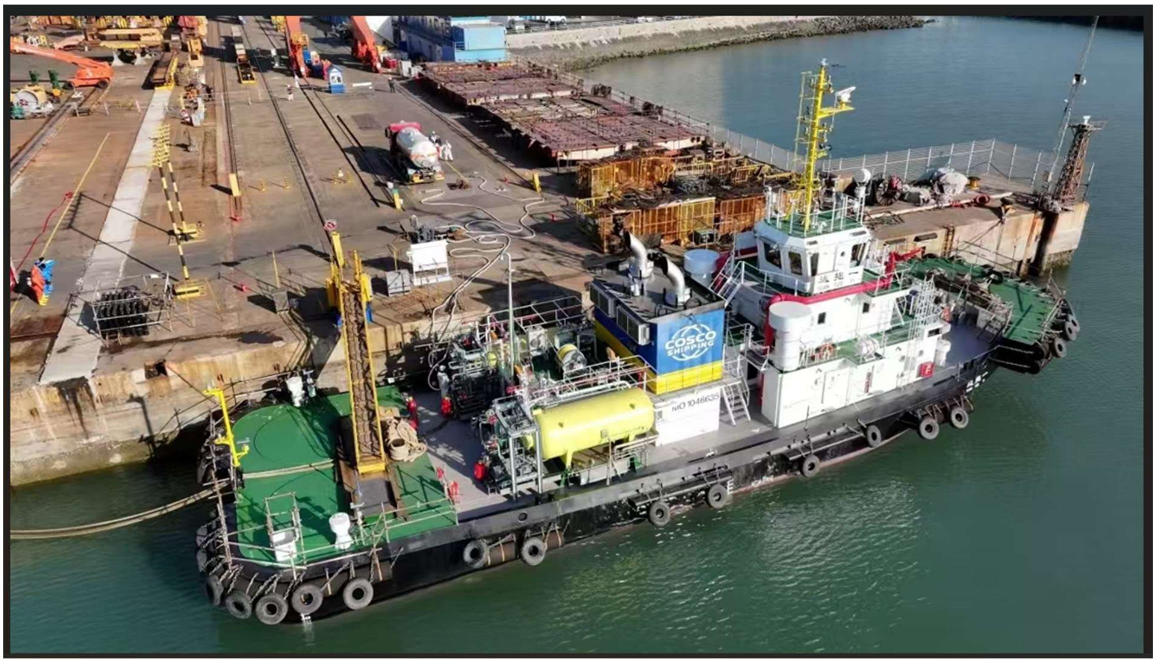

Figure 2. Ammonia DF COSCO Tugboat with two 12V240H-DFA Engines

The engine main design briefs are to develop a new dual-fuel ammonia engine based on the followings:

a. Use as much of parts from the baseline gas dual-fuel engine.

b. Not exceeding the cylinder peak firing pressure to that of the baseline engine

c. Not exceeding the combustion and exhaust temperatures to that of the baseline engine

Two engines are contracted to be installed on first vessel in China developed by Dalian Cosco Shipping Heavy Industries CO., LTD., as shown Figure 2, where Ammonia fuel tugboat to entre service in the first quarter of 2025.

The baseline engine running of diesel fuel configuration are kept the same. The rated power in the diesel mode and DF mode was developed to output yield of 2500 KW at 1000 RPM, which has been derated due to customer's demand for the tugboat as shown in the table 3 below.

Table 3. 12V240H-DFA Main Engine Parameters

Parameters	Units	Value
Cylinder configuration	------	V12
Bore/Stroke	mm	240/275
Rated Power	KW	2022
Rated Speed	RPM	1000
Idle Speed	RPM	400
BSFC (Diesel ISO3046)	g/kWh	199
Diesel Substation DF NH3	------	80%
Lube Oil Consumption	g/kWh	<0.6
Start Method	-------	Motor
Dry Weight	Kg	19,780
Dimensions	M	5x1.8x2.7

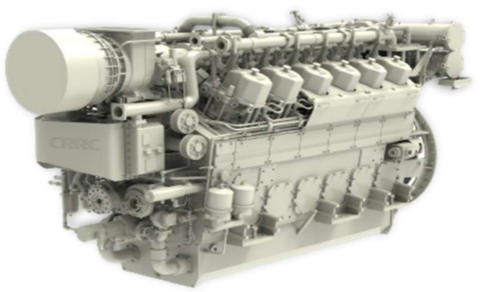

Figure 3. 12V240H-DFA Engine Overview

5 THE FUEL INJECTION SYSTEM

Ammonia fuel are admitted using air port injection system using Sogav65 (Figure 4) fuel Injection valves which have been tuned carefully during the detailed calibration and development of the engine to achieve optimum performance for the aimed diesel substitution.

Figure 4. Woodward Sogav65 Ammonia Valve

The characteristic and control of metering the Ammonia fuel has been achieved with the capacity of the fuel valve and the duration of the opening and closing of the flow characteristics curve.

The assumptions of the current waveform rise times, fall times, and other waveform parameters are obtained from the calculation recommended formula given by the manufacturer for the Equivalent Average Direct Current (EADC). This will overestimate the current waveform at or slightly over the solenoid's rated EADC value.

6 ENGINE DEVELOPMENT TESTING

6.1 Engine Test Cell

Engine development and calibration of the new Ammonia dual-fuel engine has been carried out on the dedicated R&D test cell at the CRRC factory in Lvshun. The test cell has been re-equipped with the new fuel Ammonia and whatever required to ensure all health and safety aspects have been carefully assessed and applied to prevent any risk to the working personal to run engine testing. Figure 5 shows the test cell used to carry out the development testing of the new Ammonia DF engine.

Figure 5. R&D test cell for the new ammonia dual-fuel engine 12V240H-DFA

The new equipment incorporated to the engine test cell used for the new development of the Ammonia DF engine have been implemented. The usage of the personal protective equipment (PPE), which has been considered to provide protection against traces of low concentrations of ammonia continuously and at short period protection of relatively higher concentrations of ammonia. The main elements of the PPE adopted are as follows:

1. Concealed gas-tight mask, considered suitable material against exposure to ammonia.
2. Detector device for personal usage when development engineers and testers need to entre test cell.

CCTV cameras have been installed in few zones on the test cell to expose all dead zones to be noticed and visualised by the development engineers in the test cell control room. More surveying cameras have also been added on top of the roof of the laboratory to monitor the flare continuously and alarm the system in case of fire propagating.

The rest of the sensors and switches are as per CRRC standard instrumentation package of the R&D and prototype engine, which includes the following:

- ✓ The temperatures of the inlet air,
- ✓ the exhaust & turbine inlet gas,
- ✓ diesel fuel,
- ✓ ammonia before injection, and
- ✓ the intake ports.

Cylinder pressure traces have been measured using a piezoelectric pressure transducer with a resolution of 1024 measuring points per shaft rotation and for 100 consecutive cycles.

An electric motor dynamometer was coupled to the engine to control the engine load and rotational speed. All measured parameters have been monitored with test cell software and hardware.

Introducing more ammonia into the intake manifold to obtain a higher substitution and lower the air fuel ratio for optimum combustion efficiency by reducing the air mass flow rate. As shown above in Table 2, the lower heat value of the ammonia compared with the conventional fuel of diesel, would require much higher mass flow rate to achieve the same power as obtained by the baseline diesel engine. Also as shown in the same table that the stoichiometric air fuel ratio of the mixture decreases while ammonia ratio increasing ammonia ratio, as they vary from 14.5 to 6.1 for diesel and ammonia respectively. Therefore, the excess air fuel ratio, λ varies between 0.5 and 1.6 for all operating points, as reported in the same table.

6.2 Ammonia Station

As part of the due diligence consideration to take a good care for the health and safety aspects, a new ammonia station has been installed outside the R&D test cell buildings. Figure 6 shows an overview of the ammonia station built specifically to provide safe ammonia delivery to the test cell and engine inside the building. The supply of ammonia allows for receiving six tanks with capacity to carry a total of 3 tons and they are linked together to keep continuous supply. The ammonia station controls the ammonia supply with all sensors and instrumentation are fed from the gas cylinder and the over piping plumbing to ensure the station runs efficiently but more importantly safe for engineers operagoing nearby and the environment. With the precaution to preventing backflow in the system and minimize the pressure oscillations in the system, a surge tank was installed in the Ammonia station.

Figure 6. Ammonia Station for supply to test-cell

6.3 Ammonia Injection system

A Coriolis flow meter has been fitted to measure the ammonia mass flow rate in the test cell. To provide more accurate measurement system and engine performance parameters, an air mass by using water differential level to measure air mass flow.

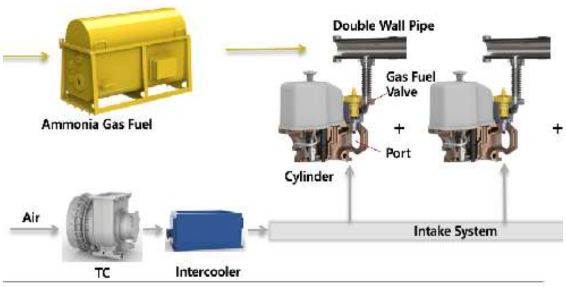

Figure 7. Induction and mixing system of the ammonia dual-fuel engine

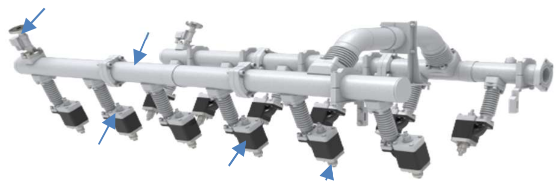

Figure 8. Multi point port system of ammonia injection

6.4 Ammonia Calibration testing

Although the engine simulation was carried out in details to assess and find the engine optimum performance by analysis, the engine was put to test to validate the predictive work and further fine tuning of the combustion and the output main parameters. The engine has been fully instrumented with the R&D specific sensors and instrumentation to monitor the engine fluid flow, pressure, and temperature of fluids and metal at all areas of interest. Figure 5 shows the engine test cell with the development of the new ammonia dual fuel engine "12V240H-DFA".

6.5 Ammonia Substitution testing

The main advantage of Diesel substitution with ammonia was merely for the removing of the carbon or significantly reducing the level of CO_2 from the exhaust system compared to diesel or gas dual-fuel combustion. The major issue with ammonia dual fuel engine performance and efficiency is the identified decreased combustion stability (correlated by the measured indicated mean pressure, IMEP), which results in significant loss of combustion efficiency due to increased unburned fuel in the exhaust gas.

The testing programme has been devised to test all percentage of diesel substitution with ammonia at different boundary conditions and varying load and speed to create a map of performance with all eventuality to obtain the optimum operating points.

Diesel substitution rate parametric study to achieve the target specified, which is defined as follows;

$$DSR\ \% = \frac{\emptyset - \partial}{\emptyset}\ x\ 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (1)$$

Where,

DSR = Diesel substitution rate

$\emptyset$ = Pure diesel fuel consumption

∂ = Diesel fuel consumption in dual fuel mode

The other parameter was created for the test results and assessment was the Ammonia weight consumption expressed as the ammonia energy substitution and defines as follows:

$$AES\% = LHV_{NH3} * \frac{\Omega}{\Sigma} \ldots\ldots\ldots\ldots\ldots\ldots\ (2)$$

where,

AES = Ammonia Energy Substitution

LHV_{NH3} = Low heat value of ammonia

Ω = Ammonia flow rate

∑ = total fuel energy

6.6 Performance optimisation testing

Engine performance has been extensively tested for the optimisation of the engine performance parameters such as the power output, thermal efficiency expressed as fuel ammonia consumption, mean effective pressure, cylinder pressure and exhaust temperatures. The physical and chemical properties of the new fuel ammonia with its significant difference from the currently applied marine diesel oil (MDO) would inevitably impact on the engine combustion and in turn would require changes to the fuel injection and air boosting systems. The infer flammability and combustion of ammonia properties in comparison with diesel oil and natural gas combustion and their tendency towards a reduction in the excess air ratio requirement for Otto cycle combustion, as diesel pilot ignitor used for the dual-fuel ammonia.

The wide window of air fuel ratio for stable combustion properties and the related engine parameter settings, however, have a large influence on the operating conditions of the air boosting system [7,8]. This has been demonstrated for the requirement of different turbocharger pressure ratio or different turbine area against the air density at turbine inlet. The impact of such measures on the boosting system was considered in details by the simulation study for the engine and reported below. The variation of excess air ratio and combustion duration resulted in a large impact on the turbocharging requirements. The effect of the geometric compression ratio has been considered by analytical prediction and found to be of less significant and therefore variable compression ratio was not taken further. The optimum performance has been achieved with the help of the variable geometry turbocharger selected after several iteration by simulation and verified by development testing and calibration.

6.7 Emission compliance testing

One of the serious challenges experienced by the development testing is completion of the dual fuel combustion of ammonia gas with diesel ignition. The excess air ratio (lambda) has been investigated as the impact on combustion completion and the resulted unburned ammonia, or the ammonia-slip emissions. A significant fraction of unburned ammonia has been detected in the exhaust gas flow due to combustion instability. However, lowering the excess air ratio would improves the emission of unburned ammonia. An extensive study was performed to obtain optimum running cases for both performance and emission sides.

Also, a reduction of N_2O emission has been considered as another priority during the engine development and calibration as it has been assigned by one of the main aims for the new development of the ammonia dual-fuel engine. This has been recognised as a significant achievement for the global warming potential (GWP) of nitrous oxide (N_2O), which is about 265 times that of carbon dioxide (CO_2) over a 100-year time horizon [6]. A minimization of N2O emissions have been achieved with engine calibration and addition of exhaust aftertreatment system.

7 PREDICTIVE WORK & SIMULATION

7.1 One-Dimensional Analysis

Shanghai Jiao Tong University has carried out 1D thermodynamic simulation for the analysis and optimisation of the new Ammonia dual-fuel engine performance, combustion and emission. The design parameters such as the compression ratio of the original machine was not changed to keep the engine components change to a minimum for the benefit of maintaining the high reliability of the original engine. The objective and achievement of the assessment have focused on the followings:

- Performance of turbocharger at the target power output
- Optimisation and matching the adjustment position of the VGT turbine
- Maintain the maximum firing pressure (as a measure of the engine mechanical load design limit of the original engine
- Maintain the thermal load limit (presented as heat flux, gas and metal temperatures) design limit of the original engine
- Map out the performance for the calibration of the prototype ammonia-diesel dual-fuel engine and issue validation request.
- In all-diesel modes, the thermal efficiency and emission level are not lower than those of the prototype diesel engine.
- In dual-fuel mode, the booster matching, diesel substitution rate, ammonia injection pressure and pulse width, thermal efficiency, thermal balance, exhaust gas composition, and other key parameters are calculated and simulated.
- In diesel mode, no exhaust gas post-treatment device is installed, and the emission meets the requirements of the phase II of GB15097-2016

- In dual-fuel mode, aftertreatment system was simulated to lower NOx and Ammonia slip to the required limit specified by authority.
- A commercial 1D simulation software used for the calibration of 95DF ammonia-diesel dual-fuel combustion model.

Modeling of 12V240DF one-dimensional engine working process has been carried out to include the followings:

- Discretization of the engine system
- Establish full system from intake to exhaust
- Exhaust system with VGT turbine module
- Air intake manifold module
- Diesel high-pressure common rail module
- Ammonia fuel intake tract Jet mold

Based on the laws of conservation of mass, momentum and energy, the 1D simulation was fully completed to yield the verified prediction of the followings:

- intake and exhaust flow
- in-cylinder combustion global parameters
- firing pressure and heat transfer
- peripheral auxiliary mechanisms
- input parametric data versus desired comparative results
- find the best balance between heterogeneity and accuracy.

The results as shown below focused on the prediction of the maximum firing pressure, thermal efficiency acceptance criterion, achieved the target for diesel substitution rate as the main success criterion.

The predictive test matrix of the main points for the rated power output and the prob law partial load-speed has been shown in Table 5. The 3D matrix has included the optimisation of the diesel injection in terms of injection timing sweep, injection pressure/rate, and the start of injection.

The parametric predictive work was carried out on the two important aspects of the Ammonia mass ratio and the Ammonia substitution rate to identify both optimum cases and the low issues and their effect on the new engine performance and efficiency. Figures 11 shows the prediction resulted from the 1D simulation software GT Power.

Figure 12 shows the compressor map with the cases considered by the 1D simulation. The parametric assessment to achieve an optimum performance with high turbocharger efficiency zone. The operation point on the compressor map has also shown a healthy margin to surge for good safety running of the engine.

Table 4. Predictive test matrix

RPM	KW	NH3 Mass Rate%	NH3 Substitution Ratio%
1000	2500	0,30,50,70,78	0,15,29,47,53
1000	2200	0,30,50,70,79,84,94	0,15,28,45,53,60,80
1000	1719		
1000	1616		
1000	1011	Maximum Possible	Maximum possible
947	1719		
909	1616		
794	1011		
630	505		

The cylinder pressure profile with crank angle for different rate of Ammonia substitution are shown in figure 9. The limiting max firing pressure of 160 bar has been kept at the mechanical load of the engine same as the baseline engine as the main and critical engine components have not been changed with this new Ammonia version of the dual fuel engine. The figures also show the heat release profile at these different rates of Ammonia concentration, which have shown quite differences in terms of the rate slopes of the rise, fall and the duration. The higher concentration of Ammonia of 80% has shown Pmax is well within the limit and in acceptable heat release efficiency.

Figure 10 also shows the operating condition on the variable geometry compressor map with healthy surge margin and acceptable boost pressure i.e. on optimum performance for the rated power output and safe running the engine continuously.

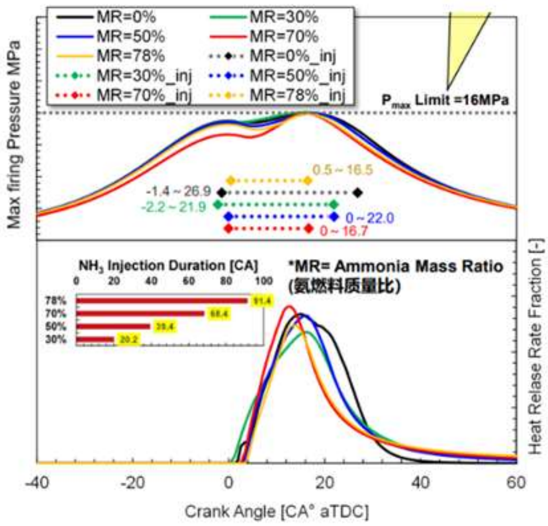

Figure 9. 1D simulation prediction of cylinder pressure and heat release at different NH3 rates.

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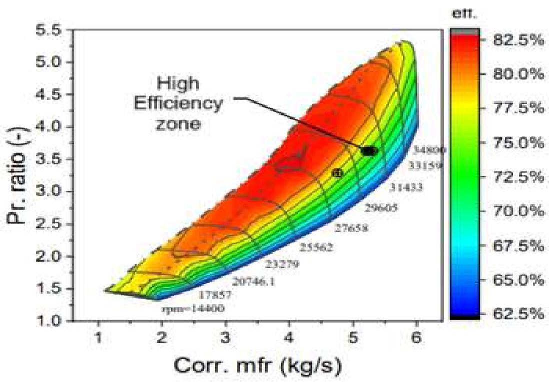

Figure 10. VGT optimised matched compressor map by 1D simulation analysis

7.2 3D CFD Simulations

7.2.1 CFD Combustion Modelling

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Table 5. CFD Simulation data

CFD Model Phenomenon	Simulation Model
Turbulence	Rans
Evaporation	Forsling
Turbulent Dispersion	TKE preserving model
Collision	NTC Collision
Drop drag	Dynamic drop drags
Break up	KH-RT
Spray-wall interaction	Wall film
Splash	O'Rourke
Wall heat flux	O'Rourke & Amsden
Combustion	SAGE
Reaction Mechanism	Song+C7

The CFD mesh as shown in Figure 11, which shows the detailed geometric of the combustion chambers to include the cylinder liver, cylinder head flame face, piston and valves. The number of meshes formed by the computer simulation package “inverse” has reached 140706 meshed cells.

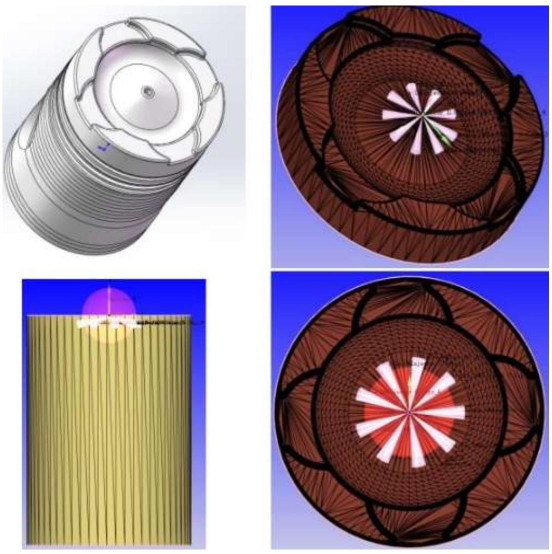

Figure 11. 3D CFD combustion simulation model

Table 6 shows an example of the parametric predictive cases carried out to optimise the rated power output of 2200 KW and 1000 RPM. Similarly, the cases for all power stated in Table 4 for constant and variable prop law cases.

Table 6. CFD Simulation cases considered

Ammonia Mass Ratio%	Diesel Substitution Rate %	Diesel Start of Injection	Diesel Injection Duration
30	15	-6.5	19.0
50	28	-6.5	16.5
70	45	-4.0	12.5
87	60	-2.5	9.5
94	80	-1.0	4.7

7.2.2 CFD Detailed Results

Figure 12 shows the cylinder pressure and the heat release rates for different Ammonia substitution rates, which have been achieved with different air fuel ratios for the rated power required contractually. The predicted firing pressure and heat release are in full agreement between the 1-D simulation and the 3D CFD calculation, which gives high confidence for the predictive work to be believable before the engine put to the verification testing.

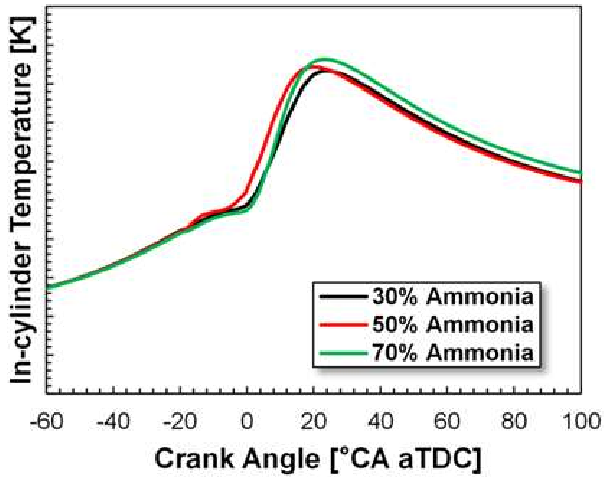

Figure 13. CFD Predicted in-cylinder temperatures at the rated power with varying Ammonia rate

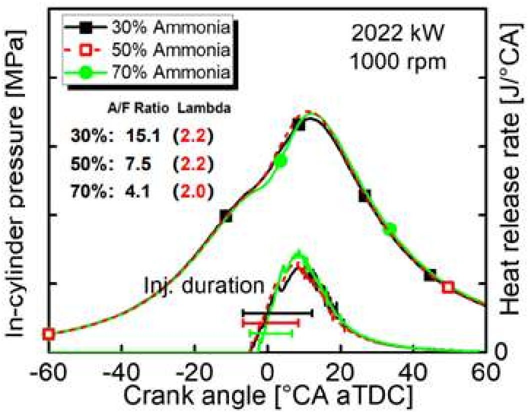

Figure 12. CFD Prediction of Pmax & HR at the rated power for different Ammonia rate.

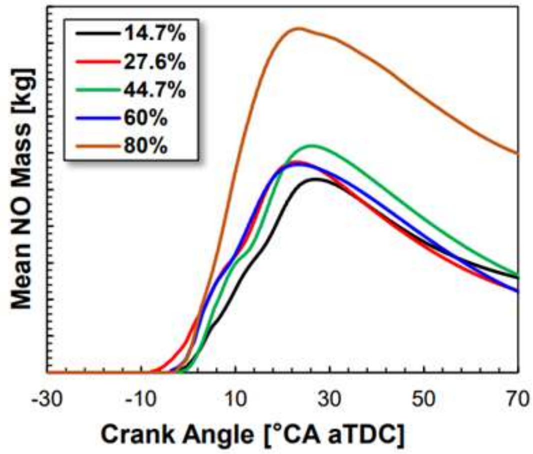

Figure 14. CFD Prediction of Nitrogen Oxide formation at rated power for different NH_3 rate

The detailed results of the cylinder temperature variation with time (crank angle) are shown in Figure 13, which has given the highest temperature resulted, as expected, to coincide with the highest rate of Ammonia substitution rate. This has also reflected with the NOx emission formation at source in-cylinder to be highest with the same trend with the combustion temperature at 80% ammonia, as the concentration variation also shown in Figure 14 predicting the fuel mass concentration as expected.

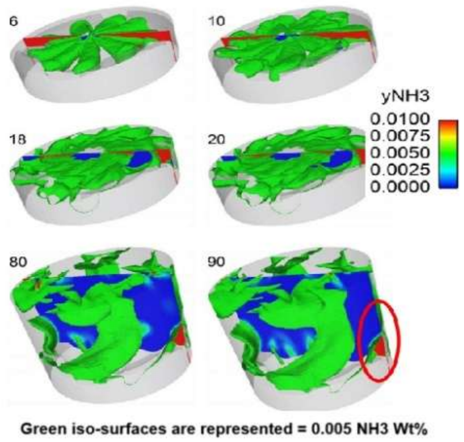

Figure 15. CFD Predicted iso-surface of Unburned Ammonia at the rated power and 70% Ammonia

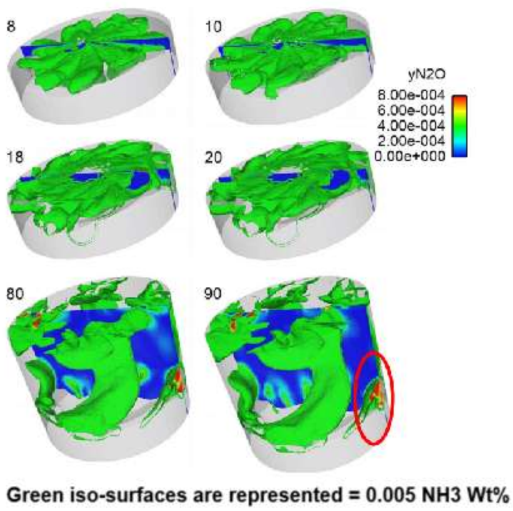

Figure 16. CFD Predicted iso-surface of N2O at the rated power and 70% Ammonia

The 3D results of the NH3 formation are very important to be reliably predicted as it will give a clear idea on the amount of ammonia residual unburnt and this is shown in Figure 15. The resulting N2O emission (Fig.16) are also important to be accurately predicted with 3D details to show both emission of Nitride oxide and the ammonia slip to be formed from this engine combustion products. The significant amount of unburnt ammonia as percentage of fuel unburnt with the cases considered in details for different NH3 concentration and crank angles.

7.2.3 Engine Integrity Assessment

7.2.3.1 Thermal Load

Table 6 shows the predicted CFD Summary of thermal load with diesel only and with Ammonia dual fuel combustion at base rating of 2500 KW & 1000 RPM. The table clearly shows how safe the new ammonia DF engine compared with the baseline gas DF engine. All the parameters are either of similar value or even lower to make the thermal load of the new engine lower and this will improve the low cycle fatigue life of the engine, which are mainly governed by the thermal load exerted on the combustion chamber and exhaust systems of the engine.

Table 6. Thermal load comparison between baseline DF and Ammonia DF engines

CFD Predicted thermal loading	0%NH3	47%NH3
Piston thermal conductivity (W/m-K)	60.5	60.6
Ambient temperature @ contact area with combustion chamber (K)	822	789
Convective heat transfer coefficient @ contact area with combustion chamber (W/m^2-K)	1418	1260
Convective heat transfer coefficient @ other regions (W/m^2-K)	500	500
Near-surface heat flux distribution max (MW)	0.744	0.512
Piston maximum metal temperature (°C)	430	400

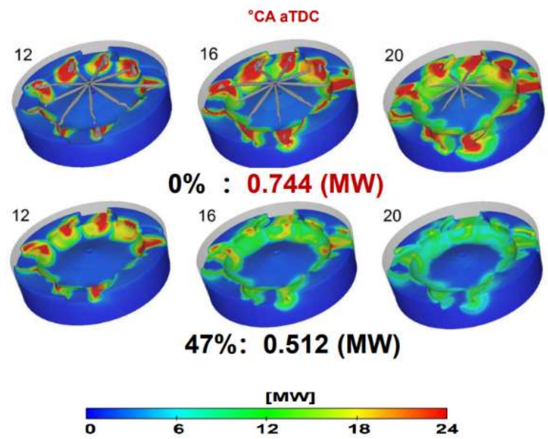

Figure 17. CFD predicted iso-surface of thermal load with diesel and DF 47% Ammonia substitution.

Figures 17 and 18 show the benefit of reducing the metal temperature of the combustion chamber components as the peak temperature of the piston crown reduced from 429 °C with 0% DSR i.e., diesel only to 396 °C with DSR of 47%. The heat flux has also reduced by 42% from diesel only combustion to Ammonia combustion with DSR 47%. This has a great benefit of reducing thermal load when switching from diesel to ammonia dual fuel.

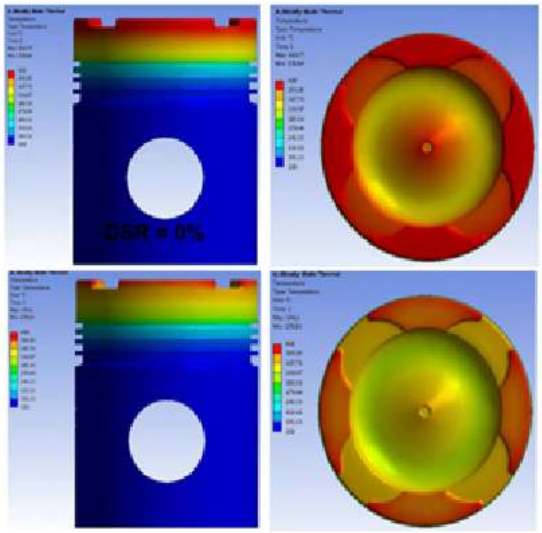

Figure 18. CFD predicted temperature distribution for Ammonia of 0% (top) and 47% (Bottom).

8 EXPERIMENTAL VALIDATIONS

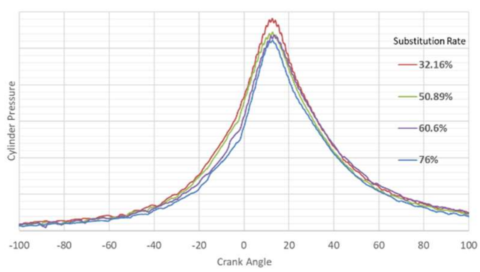

Figure 19. Measured Pmax at the rated power with varying Diesel substitution

The measured in-cylinder pressure shown in Figure 19 agrees fully with the predicted by the 1D and 3D CFD calculation in terms of peak value, rise, fall and the timing with crank-angle, which gives high confidence in the design and analysis carried out.

The high percentage of unburnedammonia as shown earlier has resulted in lowering the thermal efficiency compared with baseline fossil fuel DF engine. The efficiency has shown a declining trend as in Figure 20 and the trend was reduced to go too low when the boost pressure reduces to give richer fuel to air ratio. As shown in Figure 21 that with high level of concentration of diesel substitution with ammonia such as the target (80%), the air/fuel ratio has to be lower down to 1.32 to give optimum performance. This has been traded of between exhaust temperature not to be increased with lower air/fuel ratio above the allowed limit as shown in Figure 22 below.

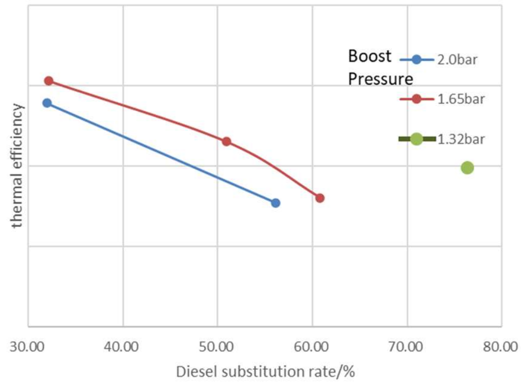

Figure 20. Measured thermal efficiency at the rated power with varying Diesel substitution

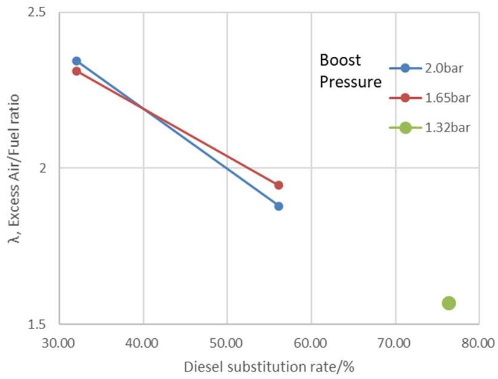

Figure 21. Measured excess air fuel ratio at the rated power with varying Diesel substitution

The trade off in performance and NOx emission are also inevitable as with lower air/fuel ratio to limit the instability of the combustion and reduce the unburnt ammonia, the price of higher NOx has also shown in figure 23, as with 1,32 air/fuel ratio the level are much higher than it is allowed and this would need to be dealt with by aftertreatment to lower both NOx and ammonia slip in the exhaust products of the combustion.

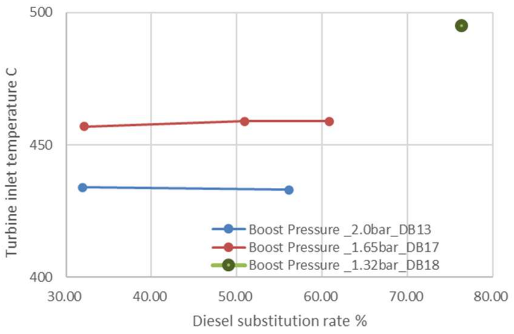

Figure 22. Measured Turbine inlet temperature at the rated power with varying Diesel Substitution

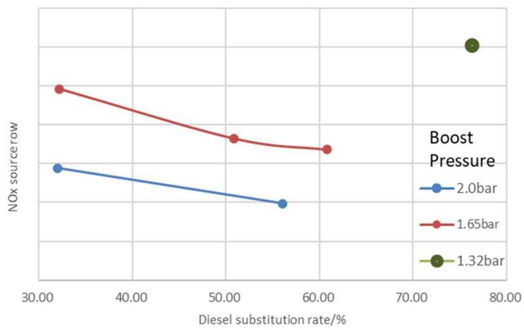

Figure 23. Measured NOx at the rated power with varying Diesel substitution

9. MATERIAL EFFECT BY AMMONIA

Design analysis to investigate the compatibility of engine component materials with Ammonia fuel has been carried out. It is known that Copper and Zink alloys may have detrimental effect by the ammonia and this has been reviewed before engine was tested. For full demeriting the parts, the engine has been dismantled and all components been examined in details and documenting for any potential severe impact. A potential issue might have been due to the contamination of the lubricating oil or sealing air with ammonia, which could attack the Copper alloys of the bearings. A specific care has been taken for the selection of sealing materials and this has been reviewed by the suppliers and approved prior to use them with ammonia.

10 CONCLUSIONS

CRRC R&D team has successfully developed the new ammonia dual-fuel "12V240H-DFA" from the baseline Natural Gas dual-fuel engine. The engine has been optimised by extensive simulation and fully validated by calibration and development testing and then signed off for serial production. The first two engines have been released to service on Tugboat developed by Dalian Cosco Shipping Heavy CO., LTD as a first Ammonia fuel boat serving on Chinese waters.

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