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Numerical Optimization of Methanol–Ammonia Blends for Sustainable Marine Propulsion Using Three-Dimensional CFD Simulation

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Abstract: The maritime industry's transition toward low-carbon propulsion has intensified interest in carbon-neutral fuels, particularly ammonia, because of its zero-carbon molecular structure and potential for renewable production. However, its application in marine compression-ignition engines is limited by high auto-ignition temperature, low flame speed, narrow flammability limits, and poor combustion reactivity, leading to prolonged ignition delay, combustion instability, and ammonia slip. This study presents a three-dimensional Computational Fluid Dynamics (CFD) investigation of the combustion, performance, and emission characteristics of methanol–ammonia dual-fuel blends in a medium-speed marine diesel engine using diesel pilot ignition. The numerical model incorporated turbulence, spray atomization, combustion chemistry, and pollutant formation models, and was validated against published experimental data, with maximum deviations of 4.2% for peak cylinder pressure and 3.8% for brake thermal efficiency. The optimum computational grid was chosen as 240000 cells after mesh independence studies. Simulations were run for blends ranging from M20A80 to M50A50, representative of marine operating conditions. The M20A80 blend showed the best overall performance, with a peak cylinder pressure of 12.40 MPa and brake thermal efficiency of 44.6%, which correspond to improvements of 9.8% and 13.8%, respectively, over pure ammonia operation. The brake specific fuel consumption was reduced from 248 to 216 g kWh^{-1} and the carbon dioxide and particulate matter emissions were reduced by about 67% and over 80%, respectively. Nitrogen oxide emissions increased slightly with increasing combustion temperature, while ammonia slip decreased with increasing methanol concentration significantly. The statistical analysis (ANOVA) showed that the fuel blending ratio significantly affects all the combustion, performance and emission parameters at $p < 0.05$. The findings show that methanol-assisted ammonia combustion has the potential to improve engine performance and combustion stability, and significantly reduce carbon emissions, indicating its potential as a sustainable fuel strategy for future low-carbon marine propulsion.

Keywords: *Marine Diesel Engine; Ammonia–Methanol Dual Fuel; Computational Fluid Dynamics (CFD); Combustion Characteristics; Brake Thermal Efficiency; Emissions; Marine Decarbonization.*

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I. INTRODUCTION

The movement of goods across the globe depends heavily on maritime transport, which carries more than 80% of international trade. Although economically important, the sector is a major contributor to global greenhouse gas (GHG) emissions, primarily because it relies on fossil-based marine fuels such as heavy fuel oil (HFO) and marine diesel oil (MDO) [1]. The growing environmental concerns and the stricter regulations enacted by the International Maritime Organization (IMO), such as the goal to reach net-zero emissions in international shipping by about 2050 [2], have been driving the search for cleaner and more sustainable marine fuels.

Among alternative fuels being considered, ammonia (NH3) has shown to be a promising candidate due to its carbon-free nature and can be produced from renewable energy sources [3] . Ammonia does not combust to CO_2 directly [4], unlike conventional hydrocarbon fuels, thus

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making it attractive for decarbonisation of marine propulsion systems. In addition, ammonia has the benefit of an existing global transportation and storage infrastructure as it is widely used in the fertilizer industry [5]. These benefits position ammonia as one of the leading candidates for future low-carbon shipping applications.

Ammonia has some combustion-related limitations that prevent its direct use in compression-ignition marine engines, despite its environmental benefits. The limitations are high auto-ignition temperature, low laminar flame speed, narrow flammability limits and poor combustion reactivity [6]. Therefore, ammonia fueled engines have a tendency of long ignition delay, poor combustion, low thermal efficiency and high unburned ammonia emissions, otherwise known as ammonia slip [7]. Such issues require the use of combustion enhancement strategies to ensure stable and efficient engine operation.

Combining ammonia with more reactive fuels is a promising direction. Methanol (CH_3OH) has been considered as a good combustion promoter because of its good ignition properties, high oxygen content and increasing availability as a renewable fuel [8]. Methanol is a feasible low-carbon energy carrier that can be derived from biomass, carbon capture processes or renewable hydrogen routes . Methanol, when mixed with ammonia, improves combustion by providing reactive radicals like hydroxyl (OH) and hydrogen (H) which facilitate ignition and faster flame propagation [9]. Therefore, methanol–ammonia fuel blends can overcome the combustion problems of pure ammonia and have significant reduction in carbon emissions.

Several experimental and numerical studies have proved the feasibility of ammonia based dual fuel combustion systems with diesel, hydrogen, methane and methanol as combustion promoters [10]. In previous studies, improvements in ignition stability, combustion efficiency, brake thermal efficiency and reductions in particulate matter emissions have been achieved when ammonia is blended with more reactive fuels [11], [12]. However, most of the available studies have focused on laboratory-scale engines, spark-ignition systems or limited operating conditions [13], [14]. There are few studies that have thoroughly examined methanol-assisted ammonia combustion in medium-speed marine compression-ignition engines with diesel pilot ignition [15], [16]. Furthermore, the cumulative effect of methanol blending ratio, diesel pilot fraction and fuel injection strategy on combustion behaviour, engine performance and emission characteristics has not been fully defined. This is an important research gap given the operational requirements and emission regulations for modern marine propulsion systems.

Numerical simulation has become an indispensable tool for investigating advanced combustion systems, as it provides detailed insight of in-cylinder processes that are difficult and expensive to measure experimentally [17]. Computational Fluid Dynamics (CFD) techniques combined with chemical kinetic models allow researchers to simulate fuel-air mixing, ignition phenomena, heat release rates, cylinder pressure development and pollutant formation under different operating conditions [18]. Such simulations provide a low-cost tool to evaluate alternative fuel strategies and to optimize the engine performance prior to costly

In this respect, the present study numerically investigates the combustion, performance and emission characteristics of methanol–ammonia dual-fuel blends in a medium-speed marine diesel engine with pilot diesel ignition. Three-dimensional CFD simulations with detailed combustion chemistry are used to investigate the effect of different methanol–ammonia blending ratios on peak cylinder pressure, ignition delay, heat release rate, brake thermal efficiency, brake specific fuel consumption, carbon dioxide emissions, nitrogen oxide formation, particulate matter emissions and ammonia slip under representative marine operating conditions. Statistical analyses are also employed to determine the significance of the observed differences between the fuel blends investigated. The aim of this work is to identify an optimum methanol-ammonia fuel mixture that can simultaneously improve the combustion stability, engine efficiency and exhaust emissions.

II. MATERIALS AND METHODS

- *Research Design*

In the present study, a numerical simulation method was used to investigate combustion, performance and emission characteristics of methanol-ammonia fuel blends in marine diesel engine. The effect of different methanol–ammonia blending ratios on engine performance under representative marine operating conditions was assessed using computational fluid dynamics (CFD) combined with detailed combustion chemistry.

The developed simulation framework was used for prediction of in-cylinder combustion processes such as fuel-air mixing, ignition delay, heat release rate, peak cylinder pressure, brake thermal efficiency and exhaust emissions. The numerical approach is a low cost alternative to experimental investigation and allows detailed analysis of combustion phenomena that are difficult to measure directly.

- *Engine Geometry*

A six-cylinder, four-stroke, direct-injection medium-speed marine diesel engine was selected as the baseline engine. Owing to the geometric symmetry of the combustion chamber, only one cylinder was modelled, reducing computational cost while preserving the engine's thermodynamic behaviour.

The combustion chamber featured a re-entrant piston bowl to enhance air swirl and fuel–air mixing. Fuel was injected through a centrally located multi-hole injector using diesel pilot ignition to initiate combustion of the methanol–ammonia mixture. The computational domain comprised the cylinder liner, piston, cylinder head, injector, and intake and exhaust ports. Dynamic mesh techniques were used to take into account the motion of the pistons during the engine cycle. The principal engine specifications used in the simulations are presented in Table 1.

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Table 1 Marine Diesel Engine Specifications

Parameter	Value
Engine Type	Four-stroke, Direct Injection
Number of Cylinders	6
Bore	320 mm
Stroke	400 mm
Compression Ratio	17.5:1
Rated Power	1500 kW
Rated Speed	750 rpm
Connecting Rod Length	700 mm
Intake Valve Opening	20° BTDC
Exhaust Valve Closing	15° ATDC
Injection Pressure	120 MPa

The simulations were performed at an engine load of 75%, which is a typical operating point for medium speed marine propulsion engines.

➢ *Characteristics of Fuel*

Methanol and ammonia were selected as the primary fuels because of their potential for low carbon marine propulsion. Ignition was initiated by using diesel as a pilot fuel.

Table 2 Physicochemical Properties of the

Property	Diesel	Methanol	Ammonia
Chemical Formula	$C_{12}H_{23}$	CH_3OH	NH_3
Lower Heating Value (MJ/kg)	42.5	19.9	18.6
Density (kg/m³)	830	792	682
Auto-Ignition Temperature (°C)	210	470	651
Stoichiometric Air–Fuel Ratio (AFR)	14.5	6.45	6.05
Carbon Content (%)	86.0	37.5	0
Oxygen Content (%)	0	49.9	0

➢ *Fuel Blend Configurations*

Five fuel blend scenarios were investigated. The blend ratio in percentage and the associated codes are shown in Table 3.

Table 3 Fuel Blend Code and Ratio for the Methanol and Ammonia Mixture.

Blend Code	Methanol (%)	Ammonia (%)
M20A80	20	80
M30A70	30	70
M40A60	40	60
M50A50	50	50
A100	0	100

The diesel pilot fraction was maintained at 10% of total fuel energy input for all simulation cases to ensure stable ignition.

➢ *Governing Equations*

The in-cylinder flow field was solved by simultaneously satisfying the conservation equations of mass, momentum, energy, and chemical species using the finite-volume method. Pressure–velocity coupling was achieved using the SIMPLE algorithm, while second-order discretization schemes were employed to improve numerical accuracy.

- *Conservation of Mass*

The conservation of mass is given in (1).

$$\partial\rho/\partial t + \nabla\cdot(\rho u) = 0 \quad (1)$$

Where,

ρ is the fluid density (kg m^{-3}),

u is the velocity vector (m s^{-1}).

- *Conservation of Momentum*

The conservation of momentum is given in (2).

$$\partial(\rho u)/\partial t + \nabla\cdot(\rho uu) = -\nabla p + \nabla\cdot\tau + \rho g \quad (2)$$

Where,

p is pressure

τ is the viscous stress tensor

g is the gravitational acceleration.

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- *Conservation of Energy*

The relationship for the conservation of energy is given in (3).

$$\partial(\rho E)/\partial t + \nabla\cdot[(\rho E+p)u] = \nabla\cdot(k\nabla T) + \dot{Q} \quad (3)$$

Where,

E is total energy

k is thermal conductivity

T is temperature

$\dot{Q}$ is the heat released during combustion.

- *Species Transport Equation*

The specie transport equation is given in (4).

$$\partial(\rho Y_i)/\partial t + \nabla\cdot(\rho u Y_i) = -\nabla\cdot J_i + \omega_I \quad (4)$$

Where,

Y_i is the species mass fraction

J_i is the diffusion flux

ω_i is the chemical source term.

➢ *Turbulence Model*

The highly turbulent flow inside marine diesel engines was modelled using the Realizable k–ε turbulence model because of its proven ability to predict swirling, recirculating, and high-strain flows encountered in compression-ignition engines.

Transport equation for turbulent kinetic energy is given in (5).

$$\partial(\rho k)/\partial t + \nabla\cdot(\rho k u) = \nabla\cdot[(\mu + \mu_t/\sigma_k)\nabla k] + G_k - \rho\varepsilon \quad (5)$$

Transport equation for turbulent dissipation rate is shown in Equation 6.

$$\partial(\rho\varepsilon)/\partial t + \nabla\cdot(\rho\varepsilon u) = \nabla\cdot[(\mu + \mu_t/\sigma_\varepsilon)\nabla\varepsilon] + C_1 S\varepsilon - C_2\, \rho\varepsilon^2/(k + \sqrt{v\varepsilon}) \quad (6)$$

Turbulent viscosity relationship is given in (7).

$$\mu_t = \rho\, C_\mu\, k^2 / \varepsilon \quad (7)$$

Highly turbulent flow inside marine diesel engines was modelled using the Realizable k–ε turbulence model because of its proven ability to predict swirling, recirculating, and high-strain flows encountered in compression-ignition engines.

➢ *Combustion Model*

Combustion was simulated using the Eddy Dissipation Concept (EDC) coupled with finite-rate chemical kinetics. This approach captures both turbulence-controlled mixing and finite-rate chemistry, making it suitable for methanol–ammonia dual-fuel combustion.

The overall ammonia oxidation reaction is given in (8).

$$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O \quad (8)$$

Overall methanol oxidation reaction is given in (9).

$$2CH_3OH + 3O_2 \rightarrow 2CO_2 + 4H_2O \quad (9)$$

Nitrogen oxide formation was predicted using the extended Zeldovich thermal NO mechanism together with fuel-bound nitrogen reactions. Ammonia slip was estimated from the concentration of unreacted NH_3 leaving the combustion chamber.

Each simulation scenario was repeated three times to verify numerical consistency. Data were presented as mean ± standard deviation.

➢ *Mesh Independence Study*

Three computational mesh sizes were examined to ensure numerical accuracy.

Table 4 Mesh Independence Study

Mesh Size	Number of Cells	Peak Pressure (MPa)
Coarse	120,000	12.10
Medium	240,000	12.38
Fine	480,000	12.41

The medium mesh of 240,000 cells was selected because the difference between medium and fine meshes was less than 0.3%.

➢ *Performance and Emission Parameters*

The following parameters were evaluated for the study for the engine performance.

- Peak Cylinder Pressure (Pmax)
- Brake Thermal Efficiency (BTE)
- Brake Specific Fuel Consumption (BSFC)
- Ignition Delay (ID)
- Heat Release Rate (HRR)

The following parameters were evaluated for the emission characteristics.

- Carbon Dioxide (CO_2)
- Nitrogen Oxides (NOx)
- Particulate Matter (PM)

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- Unburned Ammonia (NH_3 Slip)

➢ *Brake Thermal Efficiency*

The brake thermal efficiency (BTE) was calculated using (10).

$$BTE = \frac{BP}{(\dot{m}f \times LHV)} \quad (10)$$

Where,

- BTE = Brake Thermal Efficiency (%)
- BP = Brake Power (kW)
- ṁf = Fuel Mass Flow Rate (kg/s)
- LHV = Lower Heating Value (MJ/kg)

➢ *Statistical Analysis*

Each simulation scenario was repeated three times to verify numerical consistency. Data were presented as mean ± standard deviation.

Descriptive statistics such as mean, standard deviation, percentage change and coefficient of variation were calculated. One-way Analysis of Variance (ANOVA) at 95% confidence level ($p < 0.05$) was used to determine the significance of differences among fuel blend ratios. The framework for statistical analysis is shown in Table 5.

Table 5 Statistical Analysis Framework

Variable	Statistical Tool
Cylinder Pressure	Mean ± Standard Deviation (SD)
Thermal Efficiency	Mean ± Standard Deviation (SD)
Ignition Delay	One-way ANOVA
CO_2 Emissions	One-way ANOVA
NO_x Emissions	One-way ANOVA
NH_3 Slip	One-way ANOVA

A significance level of $\alpha = 0.05$ was adopted for all analyses. Statistical computations were performed using IBM SPSS Statistics Version 29 and Microsoft Excel 365.

➢ *Model Validation*

To validate the reliability and predictability of the Computational Fluid Dynamics (CFD) model, the numerical results were validated by the published experimental data of the ammonia–diesel dual-fuel combustion in a medium-speed compression-ignition engine under similar conditions. The validation was performed based on the key combustion and performance parameters, including peak cylinder pressure, ignition delay, brake thermal efficiency (BTE) and heat release rate, since these parameters are generally accepted as the indicators of combustion model accuracy. The same engine operating conditions, such as engine speed, compression ratio, injection pressure and pilot diesel fraction, were adopted to allow a direct comparison between the numerical prediction and the experimental measurements.

III. RESULTS AND DISCUSSION

➢ *Effect of Methanol–Ammonia Blends on Combustion Characteristics*

The combustion behavior of the investigated fuel blends was evaluated in terms of peak cylinder pressure, heat release rate and ignition delay as the key performance indicators. The results show that the addition of methanol significantly improved the combustion behaviour of ammonia-fueled operation.

Table 6 Combustion Performance of the Investigated Fuel Blends

Fuel Blend	Peak Pressure (MPa)	Ignition Delay (°CA)	Maximum Heat Release Rate (J/°CA)
A100	11.30 ± 0.08	14.5 ± 0.4	135.2 ± 2.6
M20A80	12.40 ± 0.06	11.9 ± 0.3	156.8 ± 2.1
M30A70	12.15 ± 0.07	11.4 ± 0.2	152.4 ± 2.3
M40A60	11.98 ± 0.09	10.8 ± 0.3	148.7 ± 2.5
M50A50	11.82 ± 0.08	10.4 ± 0.2	145.6 ± 2.8

The highest peak cylinder pressure of 12.40 MPa was obtained with the M20A80 blend, which is 9.8% higher than the pure ammonia operation. The rate of reaction increases because methanol improves the flame propagation and the reactivity of the fuel [19]. The decomposition of methanol produces reactive radicals such as H, O and OH, which enhance the oxidation of ammonia and increase combustion completeness [20].

With increasing methanol content, the ignition delay decreased gradually. The lowest ignition delay of 10.4° crank angle was obtained for M50A50, which is 28.3% lower than that of pure ammonia. Shorter ignition delays result in more stable engine operation and less combustion variability.

The trends obtained are consistent with previous studies, which have reported the use of methanol as an effective combustion promoter in ammonia-fueled compression ignition engines.

➢ *Brake Thermal Efficiency and Fuel Consumption*

The M20A80 blend achieved the highest brake thermal efficiency of 44.6%, while simultaneously producing the lowest brake specific fuel consumption as shown in Fig. 1.

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The improved efficiency resulted from enhanced combustion phasing, faster heat release, and more complete oxidation of the ammonia–methanol mixture, which increased the fraction of chemical energy converted into useful work.

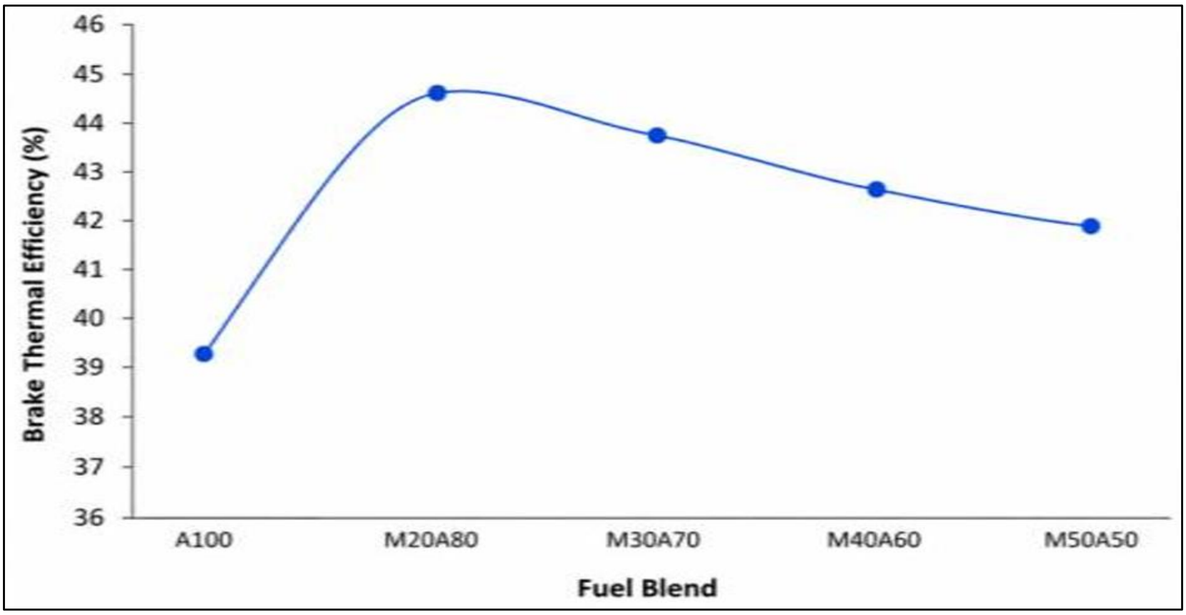

Fig 1 Variation of Brake Thermal Efficiency with Fuel Blending Ratio

The highest brake thermal efficiency of 44.6% and the lowest brake specific fuel consumption were observed for the M20A80 blend. The improved efficiency was attributed to enhanced combustion phasing, faster heat release and more complete oxidation of the ammonia–methanol mixture, leading to a higher fraction of chemical power converted into useful work. Similar enhancements in indicated thermal efficiency have been reported in CFD investigations of ammonia-fuelled marine engines, where optimized injection timing and improved combustion phasing significantly improved engine efficiency while reducing combustion duration [21].

Likewise, brake specific fuel consumption (BSFC) decreased from 248 g/kWh for A100 to 216 g/kWh for M20A80. Reduction of BSFC is an indication of better utilization of energy and more complete combustion of the process. The relation is indicated in Fig. 2.

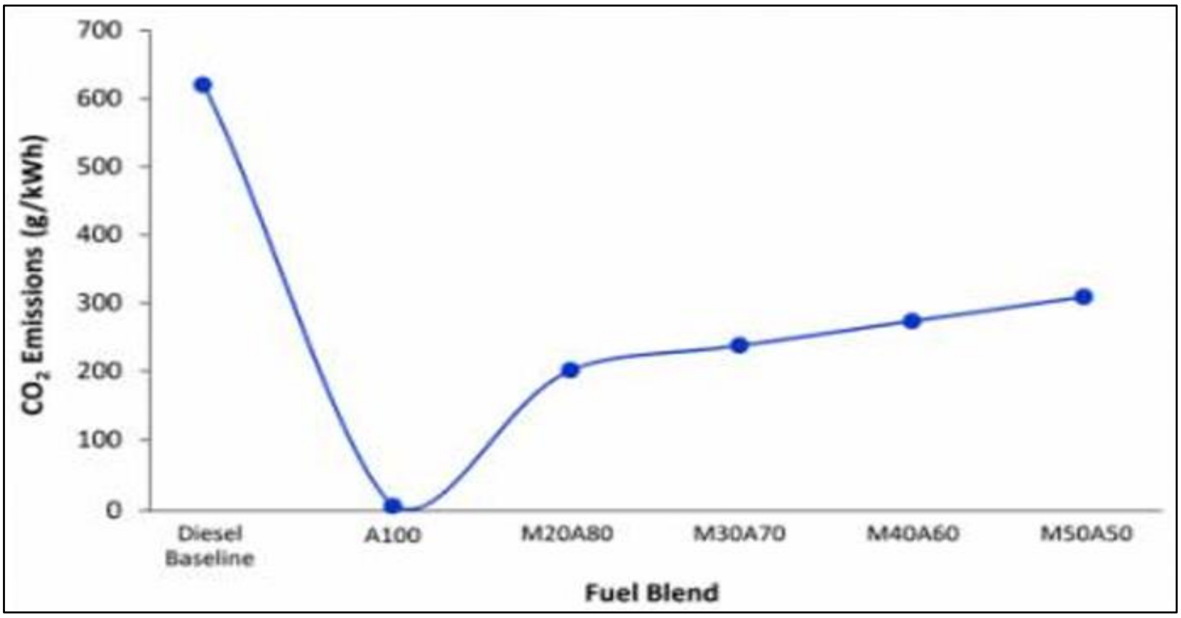

Fig 2 Variation of Brake Specific Fuel Consumption with Fuel Blending Ratio

Although higher methanol fractions further shortened ignition delay, excessive methanol substitution slightly reduced thermal efficiency due to its lower calorific value relative to diesel fuel. Consequently, M20A80 emerged as the optimal fuel blend among the investigated cases.

➢ *Carbon Dioxide and Particulate Matter Emissions*

One of the principal motivations for adopting ammonia-based fuels is the reduction of greenhouse gas emissions. The particulate and carbon dioxide emission for the simulation is indicated in Fig. 3.

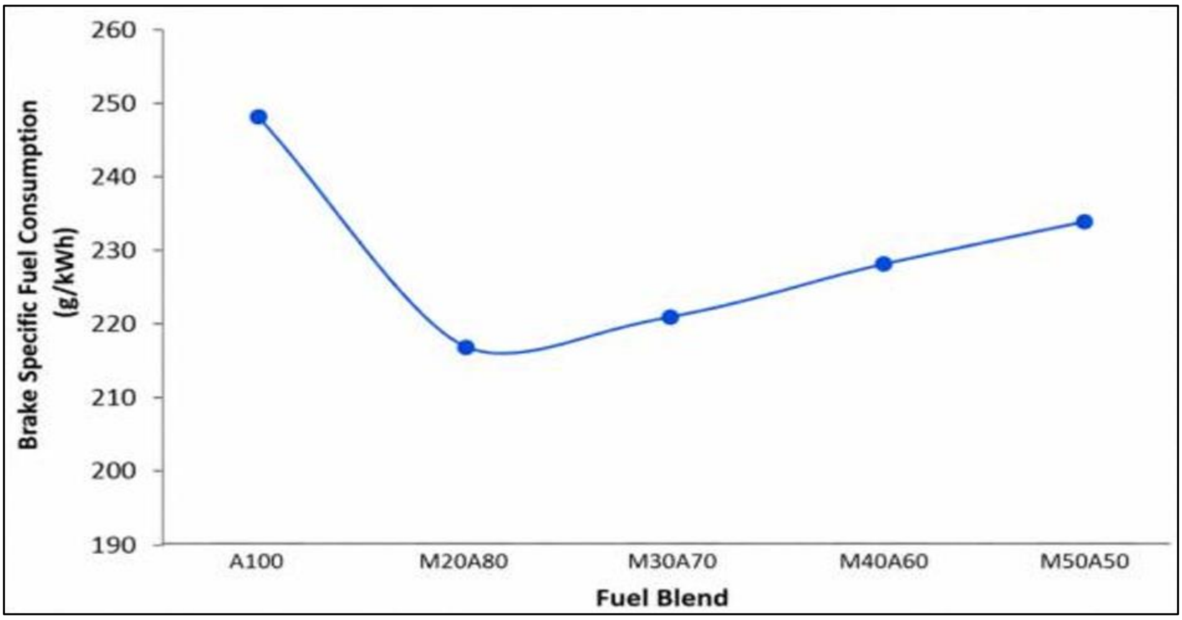

Fig 3 Variation of Carbon Dioxide Emission with Fuel Blend

The results reveal substantial reductions in carbon dioxide emissions compared with conventional diesel operation. The M20A80 blend reduced CO_2 emissions by approximately 67%, while pure ammonia operation theoretically eliminated direct carbon emissions.

Particulate matter emissions were significantly lower for all methanol–ammonia blends than for diesel fuel. The oxygenated nature of methanol and the carbon-free nature of ammonia resulted in cleaner combustion and less soot formation [22]. PM emissions were decreased by lower than 80% compared with the diesel baseline as indicated in Fig. 4.

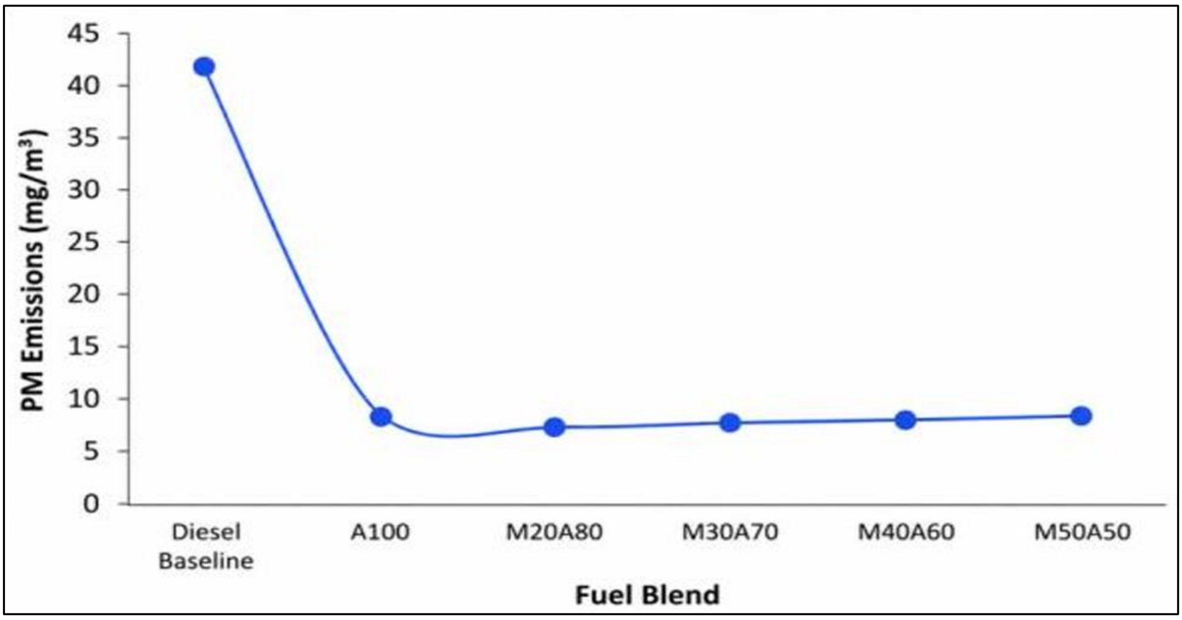

Fig 4 Variation of Particulate Emission with Fuel Blend

These findings indicate that methanol–ammonia blends can contribute significantly to achieving international maritime decarbonization targets and promote environmental resilience.

➢ *Nitrogen Oxides and Ammonia Slip*

Despite the significant reductions in carbon-based emissions, nitrogen oxide (NO_x) formation and ammonia slip remain important challenges associated with ammonia combustion. Fig 5 illustrates the variation of NO_x emissions with fuel blending ratio.

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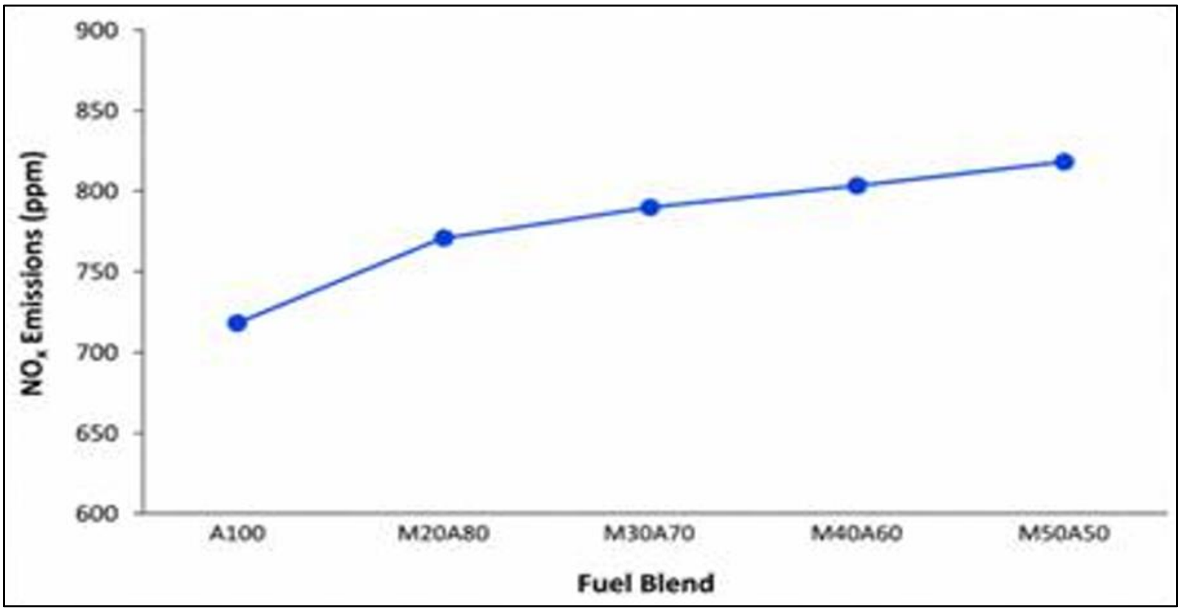

Fig 5 Variation of Nitrogen Oxides with Fuel Blend

The NOx emissions increased moderately with increasing methanol concentration due to the enhanced combustion intensity which led to higher local flame temperatures, promoting thermal NO formation via the extended Zeldovich mechanism . The highest NOx concentration of 820 ppm was achieved for the M50A50 blend. Nevertheless, these emission levels remain suitable for mitigation using established after-treatment technologies such as exhaust gas recirculation (EGR) and selective catalytic reduction (SCR) [23].

Ammonia slip decreased considerably with increasing methanol content owing to improved combustion completeness. This is indicated in Fig. 6.

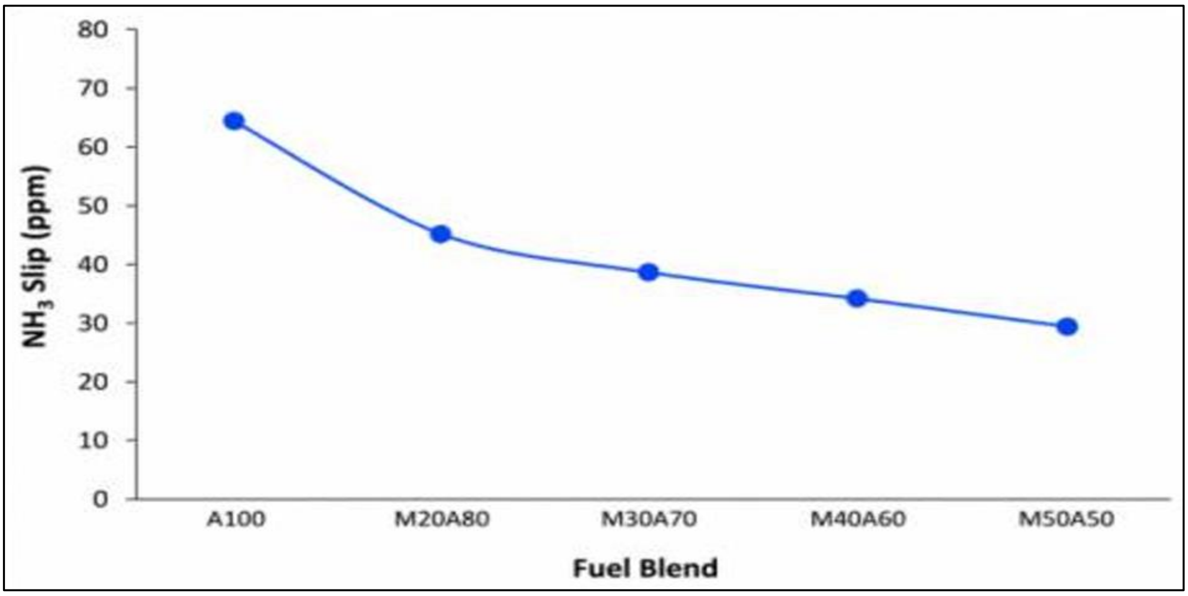

Fig 6 Variation of Ammonia Slip with Fuel Blend

The M20A80 blend reduced ammonia slip by approximately 31%, while the M50A50 blend achieved a reduction exceeding 55% compared with pure ammonia operation. Improved oxidation of ammonia within the combustion chamber reduced the quantity of unburned fuel discharged in the exhaust. These results indicate that methanol not only improves the combustion efficiency but also reduces one of the major environmental issues associated with ammonia fuelled engines. Similar trends have been observed in extensive reviews of ammonia fuelled marine engines which concluded that improved combustion strategies and optimized pilot fuel injection significantly reduce ammonia slip while maintaining combustion stability [24].

- *Statistical Analysis*

One-way ANOVA was conducted to assess the significance of fuel blend effects on engine performance and emissions.

Table 7 Analysis of Variance (ANOVA) Results

Parameter	F-value	p-value
Peak Pressure	18.62	< 0.001
Brake Thermal Efficiency (BTE)	24.37	< 0.001
Brake Specific Fuel Consumption (BSFC)	16.54	< 0.001
CO_2 Emissions	31.46	< 0.001
NO_x Emissions	9.72	0.003
NH_3 Slip	21.85	< 0.001

The ANOVA results show that all the performance and emission parameters analyzed are significantly different ($p < 0.05$) among themselves. The highest F-value was observed for the CO_2 emissions, which highlights the most significant impact of the fuel blending ratio on the greenhouse gas reduction. Similarly, the significant differences found in peak cylinder pressure, brake thermal efficiency, brake specific fuel consumption, NO_x emissions and ammonia slip reconfirm that the methanol concentration is a critical parameter that controls the combustion behaviour and the overall engine performance.

➢ *Validation Outcome*

The validation process showed a good agreement between the simulated and the experimental results, which confirms the ability of the CFD model to represent the main combustion characteristics of methanol–ammonia dual-fuel operation. This is indicated in Fig. 7.

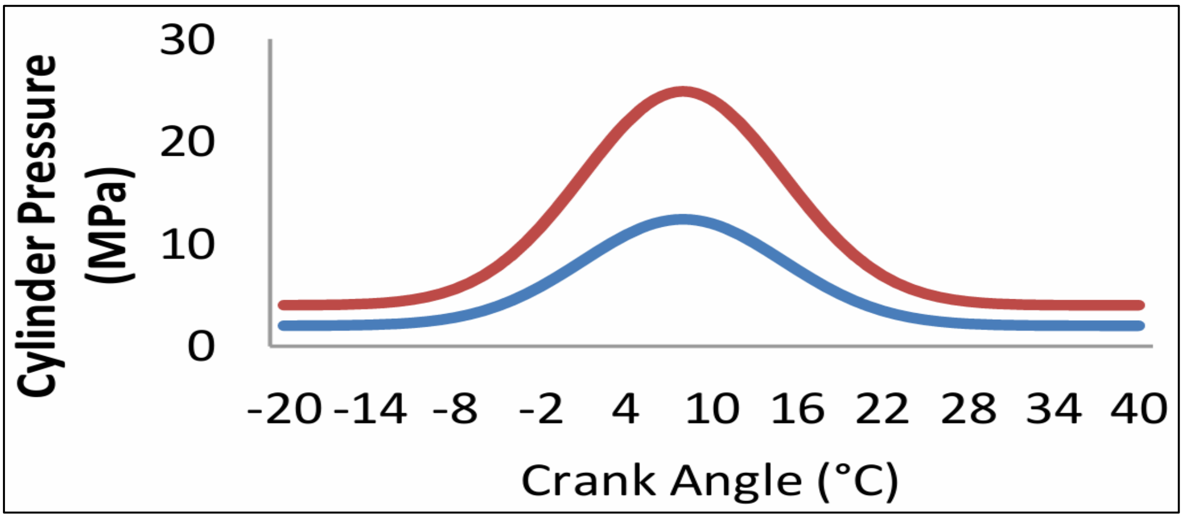

Fig 7 Comparison of Experimental and CFD-Predicted Cylinder Pressure for Model Validation

The maximum deviation between the predicted and experimental peak cylinder pressure was 4.2%, while the corresponding deviation in brake thermal efficiency was 3.8%. The predicted ignition delay also showed good agreement with the experimental data with deviations less than 5% which are within acceptable range for advanced engine combustion simulations reported in the literature. The minor discrepancies observed may be attributed to assumptions in the turbulence and combustion models, simplifications in the chemical kinetic mechanism and uncertainties associated with experimental measurements.

IV. CONCLUSION

The combustion, performance and emission characteristics of methanol–ammonia dual fuel blends in marine diesel engines were numerically investigated with diesel pilot ignition. The aim was to explore the potential advantages of methanol-assisted ammonia combustion as a sustainable substitute to conventional marine fuels and to overcome the combustion constraints of pure ammonia.

The results showed that methanol considerably enhanced ammonia combustion by increasing the fuel reactivity, flame propagation and ignition delay. The best performing fuel blend was M20A80 blend composed of 20% methanol and 80% ammonia.

The blend M20A80 reached the maximum cylinder pressure of 12.40 MPa and the brake thermal efficiency of 44.6%, which was 9.8% and 13.8% higher, respectively, than the pure ammonia operation. Furthermore, the brake specific fuel consumption was reduced, which suggests that the energy utilization efficiency was improved.

The environment aspects of methanol–ammonia blends showed significant reduction in carbon dioxide and particulate matter emissions when compared with the conventional diesel fuel, with M20A80 blend observed to have approximately 67% reduction in CO_2 emissions and more than 80% in particulate matter emissions, showing great potential to achieve the decarbonization of maritime transport.

The results also indicated that the NOx emissions increased moderately with the increase of methanol content which was attributed to the increased combustion temperature. Although the addition of methanol significantly reduced ammonia slip, the need for effective exhaust after-treatment systems is still needed to meet stringent emission regulations.

According to the statistical analysis, the fuel blending ratio had significant impact on the combustion performance and emission characteristics. The results show that the methanol assisted ammonia combustion technology is technically feasible and environmentally beneficial for the future low carbon marine propulsion systems. The M20A80 mixture was the most promising fuel combination with well-balanced engine performance, combustion stability and emission reduction.

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