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Injection Timing Effect on Emisson Characteristic of a Dual-Fuel Diesel Engine

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Abstract

The maritime industry is facing increasingly stringent emission regulations, driving the development of cleaner combustion technologies such as dual-fuel diesel engines fueled by natural gas. Among various operational parameters, pilot diesel injection timing plays a crucial role in determining combustion characteristics and exhaust emissions. This study numerically investigates the effect of Start of Injection (SOI) on the emission characteristics of a methane dual-fuel diesel engine using three-dimensional computational fluid dynamics (CFD) simulations in ANSYS Forte. A 45° sector model with a re-entrant piston bowl geometry was employed to represent the combustion chamber, and the model was validated against published experimental data for the same engine. The simulations were conducted at an engine speed of 1335 rpm by varying the pilot diesel SOI from −37.5° to −27.5° CA bTDC. The results indicate that retarding the injection timing significantly increases incomplete combustion products, with CO emissions rising from 3314.75 ppm to 11989.00 ppm and UHC emissions increasing from 490.87 ppm to 2557.44 ppm. Conversely, NOx emissions decrease from 938.59 ppm to 479.03 ppm because delayed combustion reduces the peak in-cylinder temperature and suppresses thermal NOx formation. These findings demonstrate a clear emission trade-off associated with injection timing, where reducing NOx is accompanied by increases in CO and UHC emissions. A marginal trade-off analysis further identifies −35° to −32.5° CA bTDC as the optimum injection window, beyond which the CO and UHC penalty paid per unit of NOx removed increases fivefold.

Keywords: Dual-fuel diesel engine; methane; start of injection; exhaust emissions

1. Introduction

The stringent enforcement of international regulations, particularly MARPOL Annex VI, currently serves as a primary driver for the global maritime sector to pursue comprehensive decarbonization and air pollution mitigation (Vakili et al., 2025). This ecological urgency stems from the fact that the maritime transport sector, which underpins nearly 90% of global commodity trade, accounts for approximately 3% of total global emissions, with carbon dioxide (CO2) volumes exhibiting a continous upward trajectory from 2012 to 2023 (Xu et al., 2025). The industry's chronic reliance on conventional fossil-fueled diesel engines continuously release a highly complex spectrum of hazardous pollutants (Saxena et al., 2021). Among these compounds, nitrogen oxide (NOx) emissions act as one of the most critical pollutants, serving as a primary precursor to acid rain and ocean acidification that severely damages marine ecosystems (Esmaelnajad and Farrokhi, 2024). Concurrently, incomplete hydrocarbon combustion within the engine cylinders triggers the significant release of carbon monoxide (CO) and unburned hydrocarbon (UHC) emissions. The accumulation of these NOx, CO, and UHC emissions from shipping activities not only accelerates atmospheric degradation but also poses toxic health risks, leading to acute cardiorespiratory diseases in human populations (Yu et al., 2025)

In response to these regulatory pressures and environmental impacts, the integration of dual-fuel engine technology has emerged as a highly potential propulsion alternative to fundamentally reduce the carbon footprint (Karim, 2015). The operational strategy of this system relies on utilizing natural gas as the primary fuel source, combined with the injection of a small amount of diesel acting as a pilot fuel to trigger ignition. The exceptional capability of natural gas to form a homogeneous mixture with air is a key advantage, as it promotes high combustion efficiency while suppressing the formation of toxic exhaust gases right from the initial combustion phase (Lounici et al., 2014).

Despite offering substantial potential for emission reduction, the practical implementation of dual-fuel diesel engines is confronted with intensely intricate internal combustion mechanism, necessitating rigid numerical evaluation to unravel the underlying chemical and physical dynamics. In this combustion environment, adjusting the pilot injection timing exerts a profound control over the local equivalence ratio and in-cylinder temperature history, which are fundamental governing factors for pollutant formation (Wang et al., 2016). This operational adjustment inherently triggers a critical and complex emission trade-off dilemma, in which manipulating the injection timing to suppress thermal nitrogen oxide (NOx) formation through temperature control often leads to a localized quenching effect or lower bulk temperatures, which conversely accelerates the incomplete oxidation of carbonaceous species, resulting in higher carbon monoxide (CO) and unburned hydrocarbon (UHC) concentrations. To critically analyze this fundamental emission behavior and establish an optimized boundary between chemical pathways, the current study conducts a targeted simulation-based investigation to systematically map the specific ramifications of varying the Start of Injection (SOI) timings, specifically at angle of -37,5, -35, -32,5, -30, and -27,5 CAo bTDC on the emission formation mechanism of dual-fuel compression-ignition engine.

2. Fundamental Theory

2.1. Dual-Fuel Diesel Engine

A dual-fuel diesel engine operates on a hybrid combustion mechanism that systematically integrates the principles of both spark-ignition (SI) and compression-ignition (CI) engines. In this configuration, a low-reactivity primary fuel is introduced into the intake manifold or port to form a homogeneous air-fuel mixture during the intake stroke. Subsequently, a high-reactivity pilot fuel, typically diesel, is directly injected into the combustion chamber near the end of the compression stroke to undergo auto-ignition (Karim, 2015). The auto-ignition of the pilot diesel creates multiple distributed ignition kernels that serve as high-energy ignition sources, which then propagate flames throughout the surrounding premixed charge (Lounici et al., 2014). This advanced multiphase combustion strategy allows the engine to maintain the high thermal efficiency inherent to diesel engines while significantly reducing dependency on conventional liquid fossil fuels.

2.2. Natural Gas

Natural gas is widely regarded as one of the most promising alternative primary fuels for dual-fuel applications due to its high hydrogen-to-carbon ratio and excellent air-mixing capability. Because natural gas is predominantly methane, its fundamental combustion behavior and chemical kinetics are primarily governed by methane's properties (Wei & Geng, 2016). Therefore, to provide a clear and controlled thermodynamic evaluation, this study specifically utilizes pure methane (CH_4) as the representative main fuel. Using methane simplifies the complex chemical kinetic mechanisms during the simulation, allowing for a highly accurate prediction of the natural gas combustion pathways without the unpredictable interference of higher-order hydrocarbon fractions.

2.3 Pilot Injection Timing

The operational performance and combustion stability of a dual-fuel engine are profoundly sensitive to the pilot fuel injection timing, commonly referred to as the Start of Injection (SOI). The SOI directly governs the ignition delay period, the spatial distribution of the pilot fuel, and the overall combustion phasing within the cylinder. As demonstrated by Wang et al., (2016), controlling the diesel injection timing over a wide range significantly impacts the pilot diesel ignition mode; specifically, advancing the injection timing can induce a two-stage autoignition mode that heavily dictates the subsequent combustion quality and thermal efficiency. Furthermore, altering the SOI is a primary strategy to manage in-cylinder oxidation rates and emission formations. A numerical investigation by Pranta & Cho, (2025) highlighted that advancing the SOI enhances the oxidation process, which can effectively reduce NOx and CO emissions. However, this adjustment simultaneously triggers an increase in UHC emissions due to delayed fuel-air mixing characteristics. It should be noted, however, that this UHC trend was obtained for a single-fuel diesel engine; as discussed in Section 4.2, the opposite sign is expected in a fully premixed dual-fuel charge. Therefore, systematically evaluating and determining the optimal SOI is a critical aspect of balancing combustion performance with the inherent emission trade-offs in dual-fuel operations.

2.4 Exhaust Emission Characteristic

The intricate combustion dynamics in dual-fuel engines inevitably result in a characteristic trade-off among critical exhaust emissions, specifically Nitrogen Oxides (NOx), Carbon Monoxide (CO), and Unburned Hydrocarbons (UHC) (Heywood, 2018). The formation of thermal NOx is predominantly dictated by the extended Zeldovich mechanism, which is exponentially dependent on the peak in-cylinder temperature and local oxygen concentration. While adjusting the pilot injection can mitigate these extreme peak temperatures to successfully suppress NOx, this thermal reduction frequently induces a negative side effect. Lower bulk temperatures and localized flame quenching near the cylinder walls hinder the complete oxidation of carbonaceous species. This quenching effect, combined with the entrapment of the unburned methane-air mixture within the cylinder crevices, directly elevates the emissions of CO and UHC (Kakaee et al., 2014).

3. Methodology

The diesel engine used as the simulation object in this study is a FAW CA6DL2-35 engine (Wang et al., 2016), developed by the China FAW Group Cooperation R&D Center. The main engine specifications are summarized in Table 1.

Table 1. Engine Specification

Parameter	**Specification**
Bore	112 mm
Stroke	145 mm
Displacement	8.6 L
Compression ratio	17,2:1
Number of injector holes	8

The combustion chamber geometry was using a 45° sector to reduce computational cost while maintaining combustion characteristics. The piston was modeled with a re-entrant piston bowl geometry, which is characterized by a narrowed bowl lip that enhances squish flow and promotes higher turbulence intensity during the compression process as shown in Figure 1.

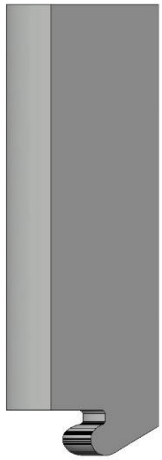

Figure 1. Engine Model

A structured 45° sector mesh was generated in ANSYS Forte, and its configuration is summarized in Table 2. The computational domain consists of a total of 6,222 cells, providing sufficient spatial resolution to capture the in-cylinder combustion and emission formation processes while maintaining computational efficiency.

Table 2. Mesh Configuration

Orientation	**Zone**	**Cell**
Circumferential	-	26
Radial	I1	5
	I2	5
	I3	10
	I4	3
Axial	K1	3
	K2	3
	K3	3
	K4	20
	K5	4
Smoothing passes	-	20

Table 3 outlines the detailed fuel specifications, encompassing the primary thermodynamic and auto-ignition properties of both diesel and methane.

Table 3. Fuel Properties

Fuel Property	**Diesel**	**Methane**
Auto-ignition temperature (^oC)	210	580
Lower heating value (MJ/kg)	43.5	50
Stoichiometric air-fuel	14.3	16.4

ratio (mass)

The pilot fuel injection parameters are detailed in Table 4 to govern the liquid fuel delivery process. The setup employs a single-hole, solid-cone pulsed injector regulated by the KH-RT breakup model to dictate droplet atomization and spray evaporation. The simulation configuration defines the injection timing and duration to control the ignition delay and spatial distribution of the fuel, while a fixed pilot fuel mass is introduced to act as the primary thermal ignition source.

Table 4. Injector and Nozzle Setup

Setup parameter	Value	Unit
Inflow droplet temperature	322	K
Injected parcel count	3,000	-
Discharge coefficient	0.7	-
Cone angle	10	degree
Nozzle diameter	0.25	mm
Injection Duration	12.5	CA
Total injected (pilot) mass	0.042992	g

The boundary conditions for the cylinder domain are outlined in Table 5 to accurately model the engine's physical and thermal environment. Specific thermal boundaries are applied to the piston, cylinder head, and cylinder wall to computationally simulate localized heat transfer and thermal losses. Furthermore, geometric constraints are defined to govern the engine kinematics and precisely regulate the piston motion throughout the cycle.

Table 5. Boundary Condition

Boundary condition	Value	Unit
Piston surface temperature	500	K
Cylinder head temperature	500	K
Cylinder wall temperature	430	K
Connecting rod length	29	cm

The closed-cycle simulation is configured to capture the in-cylinder thermodynamic phenomena spanning from the intake valve closing to the exhaust valve opening. As outlined in Table 6, the initial conditions are defined to establish the baseline thermodynamic state of the mixture prior to compression. Furthermore, simulation controls including the operational crank angle window and engine speed, are set to govern the computational duration, while specific time-step restrictions are implemented to ensure the temporal resolution maintains numerical stability and accuracy throughout the transient calculation.

Table 6. Simulation Control

Simulation Control	Value	Unit
Initial Pressure	0.15	MPa
Initial Temperature	360	K
Turbulence	Constant	-
Velocity	Constant	-
Initial Crank Angle	-147	Degree

Final Crank Angle	135	Degree
RPM	1.335	Rpm
Cycle Type	4 Stroke	-
Initial Time Step	0,0000006	Second
Maximum Time Step	0,000001	Second

Prior to the parametric study, a mesh convergence check was carried out to ensure that the results are not governed by the spatial discretisation. Three sector meshes of 2,352, 6,222 and 10,585 cells were run at three injection timings, and the peak in-cylinder pressure was compared with the experimental value reported by Wang et al. (2016). As summarised in Table X, all cases deviate by less than 7 %, confirming that the solution is only weakly sensitive to cell count. The 6,222-cell mesh gives the smallest mean absolute deviation, 1.23 % against 3.01 % for the coarse mesh and 3.08 % for the fine mesh, and was therefore adopted for the whole simulation series.

Table 7. Mesh Convergence

SOI	*Mesh Size*	Max Pressure (MPa)	Deviation
-32,5	2.352	13,08	2,63%
-32,5	6.222	12,76	0,09%
-32,5	10.585	13,01	2,04%

With the mesh fixed, the model was validated against the same experimental data. The comparison uses the peak in-cylinder pressure, since it reflects the combined accuracy of the compression process, the ignition delay and the overall combustion phasing. The simulation gives a peak pressure of 12.84 MPa against a measured 12.75 MPa, a relative error of 0.71 %, and the computed pressure trace follows the measured curve closely throughout the closed part of the cycle, as shown in Figure X. This level of agreement indicates that the model reproduces the in-cylinder process with sufficient accuracy for the comparative injection-timing study that follows.

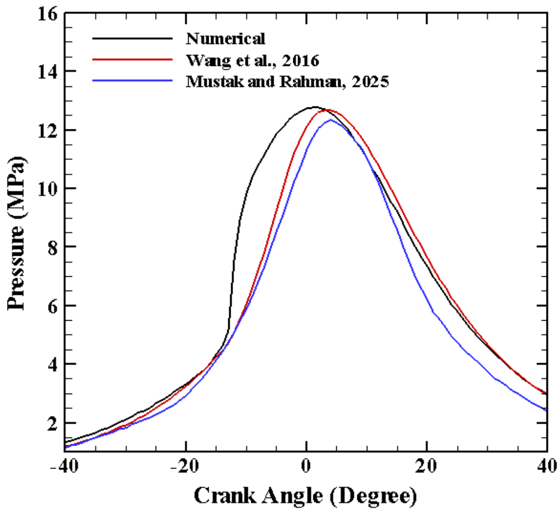

Figure 2. Model Validation

3. Results and Discussion

3.1 Carbon Monoxide (CO)

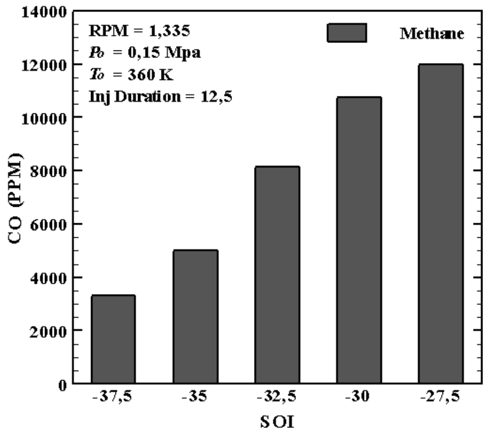

Figure 3. Effect of SOI on Carbon Monoxide (CO) Emissions

Figure 2 shows that CO emissions increased consistently as the start of injection (SOI) was retarded. The CO concentration increased from 3314.75 ppm at an SOI of −37.5° CA to 5010.88 ppm (−35° CA), 8140.67 ppm (−32.5° CA), 10766.60 ppm (−30° CA), and reached 11989.00 ppm at −27.5° CA, representing an increase of approximately 262% compared to the earliest injection timing. This trend is attributed to the shorter time available for fuel atomization, air–fuel mixing, and oxidation before the expansion stroke begins. Consequently, the combustion temperature decreases, limiting the oxidation of carbon monoxide into carbon dioxide (CO_2). In addition, methane possesses a relatively high autoignition temperature and a slower flame propagation rate than conventional diesel fuel, which further reduces combustion completeness and promotes CO formation under retarded injection conditions.

The direction and the order of magnitude of this trend are consistent with previously published dual-fuel data. Working experimentally on the same FAW CA6DL2-35 engine, Wang et al., (2016) reported a monotonic rise in CO as the pilot diesel injection was retarded within the single-stage ignition regime, and attributed it to the contraction of the interval between the end of injection and the onset of expansion. Yousefi et al., (2019) likewise observed CO to increase as the diesel injection was retarded across a comparable timing range. The 262 % increase obtained here over a 10° CA retard is of the same order as the two- to three-fold increases reported in those studies, which supports the physical consistency of the present model. Where the present result adds to the literature is in the shape of the response: the CO curve is markedly non-linear, the steepest gradient occurring between −35° and −32.5° CA bTDC at 1,251.9

ppm per degree CA, whereas the experimental studies cited above, which sampled the timing range more coarsely, describe the trend as approximately linear.

3.2 Unburned Hydrocarbon (UHC)

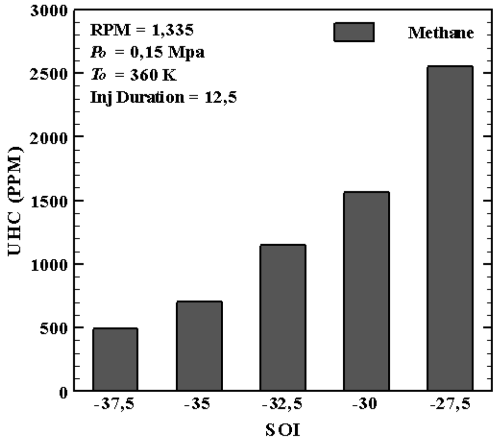

Figure 4. Effect of SOI on Unburned Hydrocarbon (UHC) Emissions

A similar trend was observed for UHC emissions, which increased significantly with retarded SOI. The UHC concentration rose from 490.87 ppm at −37.5° CA to 703.51 ppm, 1146.77 ppm, 1566.57 ppm, and finally 2557.44 ppm at −27.5° CA, corresponding to an increase of more than five times relative to the earliest injection timing. The increase in UHC indicates a larger fraction of unburned fuel escaping the combustion process. Retarding the injection timing shortens the premixing period, resulting in locally rich and lean mixtures that are difficult to burn completely. Furthermore, portions of the methane–air mixture may become trapped within the piston crevice volume or experience flame quenching near the combustion chamber walls, preventing complete flame propagation. As a result, a considerable amount of unburned hydrocarbons is discharged with the exhaust gases.

This behaviour is in agreement with the experimental evidence on premixed-charge dual-fuel operation. Wei & Geng, (2016), in their review of natural-gas / diesel dual-fuel engines, identified crevice trapping and wall quenching of the premixed methane as the two dominant UHC sources, and noted that both are aggravated whenever combustion phasing is displaced further into the expansion stroke, (Saxena et al., 2021) reached the same conclusion for methanol / diesel dual-fuel operation, reporting UHC to be the species most sensitive to a loss of bulk temperature. Pranta & Cho, (2025), cited in Section 2.3, reported UHC to increase when the SOI was advanced, which is the opposite sign to the present result. The difference is attributable to the combustion mode rather than to a numerical inconsistency. Their study concerned a single-fuel diesel engine, in which excessive advance creates over-lean and over-mixed pockets ahead of the flame that fail to ignite; in the present dual-fuel configuration the methane charge is already fully premixed before the pilot ignites, so advancing the pilot injection simply grants the methane flame more time and a higher temperature in which to consume it. This reconciliation is one of the specific contributions of the present work, and indicates that UHC-versus-SOI correlations established for conventional diesel operation cannot be transferred directly to methane dual-fuel engines.

3.3 Nitrogen Oxides (NOx)

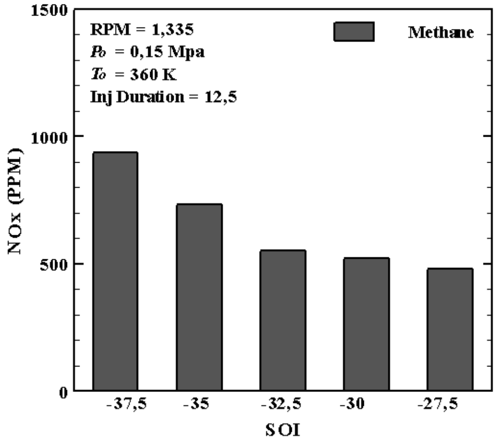

Figure 5. Effect of SOI on Nitrogen Oxides (NOx) Emissions

Unlike CO and UHC, NOx emissions decreased as the injection timing was retarded. The NOx concentration declined from 938.59 ppm at −37.5° CA to 732.47 ppm, 550.59 ppm, 520.52 ppm, and 479.03 ppm at −27.5° CA, representing an overall reduction of approximately 49%. This decrease is primarily associated with the delayed combustion phasing, which lowers both the peak in-cylinder pressure and combustion temperature. Since thermal NOx formation through the extended Zeldovich mechanism is highly dependent on high-temperature conditions, particularly above approximately 2000 K, the reduction in peak combustion temperature significantly suppresses NOx formation. Therefore, retarding the SOI effectively mitigates NOx emissions but simultaneously deteriorates combustion efficiency.

The 49% reduction in NOx observed in this study falls within the range reported in the literature for retard-based NOx control strategies in dual-fuel engines. For instance, Liu et al., (2013) documented reductions of 30–50% for a CNG/diesel engine over a comparable injection timing window. Similarly, (Wang et al., 2016) identified the same inverse relationship between NOx and incomplete-combustion products on the same engine platform used in this study, while Kakaee et al., (2014) explained this behavior through the exponential temperature sensitivity of the extended Zeldovich mechanism. The consistency in both the direction and magnitude of this trend across four independent studies suggests that the NOx sub-model employed here is performing reliably.

4. Conclusion

This study numerically investigated the effect of pilot diesel Start of Injection (SOI) on the exhaust emission characteristics of a methane dual-fuel diesel engine using three-dimensional CFD simulations in ANSYS Forte, employing a 45° sector model with a re-entrant piston bowl geometry validated against published experimental data for the same engine. The simulation results demonstrated that retarding the SOI from −37.5° CA to −27.5° CA significantly affected the emission formation process. CO emissions increased from 3314.75 ppm to 11989.00 ppm, while UHC emissions increased from 490.87 ppm to 2557.44 ppm, indicating that delayed injection reduced combustion completeness due to shorter premixing time and lower oxidation rates. In contrast, NOx emissions decreased from 938.59 ppm to 479.03 ppm because retarded combustion lowered the peak in-cylinder temperature, thereby suppressing thermal NOx formation through the extended Zeldovich mechanism. These findings confirm the inherent emission trade-off associated with injection timing in methane dual-fuel diesel engines, where reducing NOx is accompanied by increased CO and UHC emissions.

Beyond confirming this trade-off, a marginal analysis of the emission response identified −35° to −32.5° CA bTDC as the optimum injection window, beyond which the CO and UHC penalty incurred per unit of NOx removed increases roughly fivefold. This result directly addresses the study's objective of characterizing the emission trade-off across the tested SOI range, and indicates that injection timing should not be retarded indiscriminately to suppress NOx, since the incomplete-combustion penalty grows disproportionately past this window. Selecting an injection timing within this identified range is therefore essential to achieve an optimal balance between combustion efficiency and emission performance. Future studies should investigate the combined effects of SOI with pilot fuel quantity, injection pressure, and hydrogen substitution ratio to further improve combustion and minimize exhaust emissions.

References

Heywood, J. B. (2018). *Internal Combustion Engine Fundamentals (2nd ed.). McGraw-Hill Education.*

Kakaee, A. H., Paykani, A., & Ghajar, M. (2014). The influence of fuel composition on the combustion and emission characteristics of natural gas fueled engines. In *Renewable and Sustainable Energy Reviews* (Vol. 38, pp. 64–78). Elsevier Ltd. https://doi.org/10.1016/j.rser.2014.05.080

Karim, G. A. (2015). *Dual-Fuel Diesel Engines. CRC Press.*

Liu, J., Yang, F., Wang, H., Ouyang, M., & Hao, S. (2013). Effects of pilot fuel quantity on the emissions characteristics of a CNG/diesel dual fuel engine with optimized pilot injection timing. *Applied Energy*, *110*, 201–206. https://doi.org/10.1016/j.apenergy.2013.03.024

Lounici, M. S., Loubar, K., Tarabet, L., Balistrou, M., Niculescu, D. C., & Tazerout, M. (2014). Towards improvement of natural gas-diesel dual fuel mode: An experimental investigation on performance and exhaust emissions. *Energy*, *64*, 200–211. https://doi.org/10.1016/j.energy.2013.10.091

Pranta, M. H., & Cho, H. M. (2025). Numerical Analysis of Diesel Engine Combustion and Performance with Single-Component Surrogate Fuel. *Energies*, *18*(5). https://doi.org/10.3390/en18051082

Saxena, M. R., Maurya, R. K., & Mishra, P. (2021). Assessment of performance, combustion and emissions characteristics of methanol-diesel dual-fuel compression ignition engine: A review. In *Journal of Traffic and Transportation Engineering (English Edition)* (Vol. 8, Number 5, pp. 638–680). Chang'an University. https://doi.org/10.1016/j.jtte.2021.02.003

Vakili, S., White, P., & Turnock, S. (2025). Advancing a sustainable maritime future: Integrating energy efficiency and underwater radiated noise reduction strategies in commercial shipping. *Marine Pollution Bulletin*, *215*. https://doi.org/10.1016/j.marpolbul.2025.117835

Wang, Z., Zhao, Z., Wang, D., Tan, M., Han, Y., Liu, Z., & Dou, H. (2016). Impact of pilot diesel ignition mode on combustion and emissions characteristics of a diesel/natural gas dual fuel heavy-duty engine. *Fuel*, *167*, 248–256. https://doi.org/10.1016/j.fuel.2015.11.077

Wei, L., & Geng, P. (2016). A review on natural gas/diesel dual fuel combustion, emissions and performance. In *Fuel Processing Technology* (Vol. 142, pp. 264–278). Elsevier. https://doi.org/10.1016/j.fuproc.2015.09.018

Xu, H., Kwon, S. K., Go, M. S., & Li, J. Q. (2025). Symmetry-Oriented Design Optimization for Enhancing Fatigue Life of Marine Liquid Hydrogen Storage Tanks Under Asymmetric Sloshing Loads. *Symmetry*, *17*(9). https://doi.org/10.3390/sym17091497

Yousefi, A., Guo, H., & Birouk, M. (2019). Effect of diesel injection timing on the combustion of natural gas/diesel dual-fuel engine at low-high load and low-high speed conditions. *Fuel*, *235*, 838–846. https://doi.org/10.1016/j.fuel.2018.08.064

Yu, G., Zhang, Y., Wang, Q., Han, Z., Jiang, S., Yang, F., Yang, X., & Huang, C. (2025). Changes in the impacts of ship emissions on PM2.5 and its components in China under the staged fuel oil policies. *Atmospheric Chemistry and Physics*, *25*(16), 9497–9518. https://doi.org/10.5194/acp-25-9497-2025