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Retrofitting Marine Internal Combustion (IC) Engines for Methanol Fuel Integration

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Abstract: The maritime sector is undergoing a significant transformation as it seeks to meet increasingly stringent environmental regulations imposed by international bodies such as the International Maritime Organization (IMO). Among the various alternative fuels being explored, methanol has emerged as a strong candidate due to its low emissions, ease of storage, and potential for carbon neutrality when produced from renewable sources. This paper investigates the feasibility and methodology of retrofitting conventional marine internal combustion (IC) engines for methanol usage, providing a comprehensive analysis of both low-pressure and high-pressure methanol fuel supply systems. The study delves into the working principles, components, advantages, and disadvantages of these systems, focusing on performance, safety, cost, and environmental impact. Furthermore, it examines dual-fuel strategies involving methanol and pilot diesel, particularly in the context of single-point injection (SPI) and multi-point injection (MPI) systems. The retrofitting process is explored in detail, including engine design modifications, injector configurations, and combustion behaviour with methanol's distinct physical and chemical properties. Comparative evaluations are provided to highlight the trade-offs between simpler low-pressure systems and more efficient but complex high-pressure configurations. Emphasis is placed on emissions reduction, engine efficiency, and the practicality of implementation in existing vessels. The paper concludes that while technical challenges remain—such as methanol's lower energy density and corrosiveness—appropriate retrofitting solutions can effectively bridge the transition toward cleaner and more sustainable marine propulsion systems.
Keywords: Low-Pressure Methanol Supply, High-Pressure Methanol Injection, Single-Point Injection (SPI), Multi-Point Injection (MPI), Methanol Combustion Characteristics, Methanol Injector Hub, Engine Design Modifications, Marine Engine Retrofitting, Internal Combustion Engines, Dual-Fuel Systems, Sustainable Shipping

Objective

To investigate and evaluate the retrofitting approaches of conventional marine diesel engines for methanol use, analyzing the design modifications, injection systems, and fuel handling requirements, while assessing the technical, economic, and environmental implications of low- and high-pressure methanol fuel supply systems in the context of sustainable marine propulsion.

I. INTRODUCTION

The global maritime industry is undergoing a transformative shift in response to increasing environmental regulations and the urgent need to reduce greenhouse gas emissions. Traditionally dependent on heavy fuel oil and marine diesel, shipping has long been identified as a significant contributor to air pollution and carbon emissions. In light of the International Maritime Organization's (IMO) decarbonization targets and stricter environmental compliance norms, the sector is now exploring alternative fuels that are cleaner, safer, and more sustainable. Among these, methanol has emerged as a promising candidate due to its favorable combustion properties, potential for renewable production, and comparatively lower emissions profile.

Methanol, a simple alcohol, offers a compelling blend of practical advantages—it is liquid at ambient conditions, making it compatible with existing fuel handling infrastructure, and it burns cleaner Compared to fossil fuels, it releases much lower amounts of sulfur oxides (SO_x), nitrogen oxides (NO_x), and airborne particles. Furthermore, methanol can be synthesized from a variety of feedstocks, including biomass and captured carbon dioxide, positioning it as a viable pathway toward carbon-neutral maritime operations. Retrofitting existing marine internal combustion (IC) engines to operate on methanol provides an immediate and economically feasible solution for shipowners seeking to transition to low-carbon operations without replacing entire engine systems. This approach involves modifications to fuel injection systems, combustion chambers, and engine control units, tailored to accommodate the distinct physical and chemical properties of methanol. Retrofitting strategies include both single-point and multi-point injection methods, each with unique implications for engine performance, emissions, and overall efficiency.

This paper presents an in-depth analysis of the technological readiness of methanol-fueled engines, the comparative performance of low-pressure versus high-pressure injection systems, and the practical considerations of retrofitting marine diesel engines. It also explores the operational trade-offs, safety challenges, and infrastructure limitations associated with methanol adoption, while highlighting the long-term benefits of aligning marine propulsion systems with emerging green energy paradigms. As the maritime sector moves toward cleaner propulsion technologies, understanding the retrofitting process for methanol use becomes crucial in shaping a sustainable future for marine transport.

II. RETROFIT OF MARINE DIESEL ENGINE FOR USE OF METHANOL

A. Engines and Fuel Systems

Multiple companies have established ready-to-use shipping engines along with supply systems for methanol. The commercial market already presents fully operational Methanol internal combustion engines (ICE) which demonstrate high technological sophistication. Numerous trials with operating fuel cells powered by methanol exist in marine conditions worldwide while development continues.

Anglo Belgian Corporation NV together with MAN Energy Solutions, Rolls-Royce-owned mtu Solutions, Caterpillar, China State Ship Building, and Hyundai Heavy Industries have built a low-pressure fuel system which Engine crew apply a method of injecting methanol into the system at a pressure of 10 bar and a temperature range of 25 °C to 50 °C. MAN Energy Solutions maintains a fuel distribution system using approximately 10 Bar pressure which transports fuel from storage tanks through engine rooms until the specified preparation process finishes before Fuel Booster Injection Valve (FBIV) receives pressurized fuel at up to 300 Bar.

Wärtsilä together with other companies inject methanol into their engine at 400-bar pressurization. The system enables mixed solutions of water and fuel through the Fuel Booster Injection Valve which helps decrease operational costs and environmental impacts.

The proposed engine configuration will serve as the power source for the MV Eemsborg general cargo vessel through a 4.5 MW Wärtsilä engine system.

1) Low Pressure Methanol Supply System

The image depicts a Low Pressure Methanol Supply System, which is designed to supply methanol as a fuel to an engine:

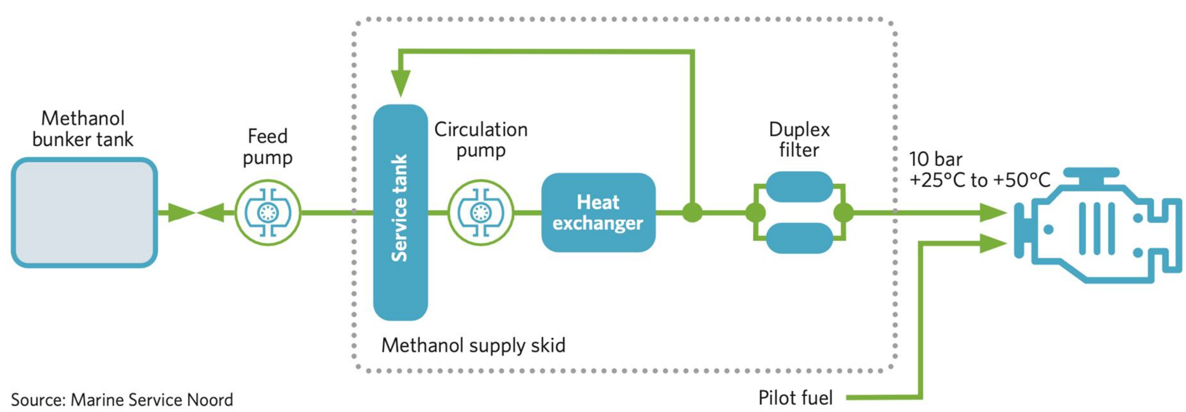

Figure 1 : Low pressure methanol supply system
(Source: www.methanol.org)

1. Methanol Bunker Tank: This tank store methanol, which is used as a fuel. The methanol from this tank is transferred through a series of components to the engine.

2. Feed Pump: The feed pump is responsible for drawing methanol from the bunker tank and delivering it to the service tank. This pump operates at low pressure to maintain a steady flow of methanol through the system.
3. Service Tank: The service tank acts as an intermediary storage tank. It ensures that there is a constant and reliable supply of methanol for the engine.
4. Circulation Pump: The circulation pump continuously circulates methanol within the methanol supply skid to maintain an even temperature and prevent fuel stagnation in the system. This ensures a consistent supply to the engine and regulates fuel flow.
5. Heat Exchanger: The methanol passes through a heat exchanger to ensure it stays within the appropriate temperature range for combustion in the engine. In this system, the temperature is controlled between +25°C and +50°C.
6. Duplex Filter: A duplex filter is in place to remove any impurities or particulates from the methanol before it reaches the engine, ensuring clean fuel delivery and protecting the engine from contaminants.
7. Engine: The methanol is delivered to the engine at a low pressure of 10 bar and within the specified temperature range. Methanol is mixed with a small amount of pilot fuel (likely diesel) to initiate combustion in the engine.
8. Pilot Fuel: In methanol-fueled engines, a small amount of pilot fuel is injected to help ignite the methanol in the combustion chamber due to methanol's higher ignition temperature compared to diesel.

- **Advantages of Low Pressure Methanol Engines:**

1. Cleaner Emissions: Burning methanol yields fewer noxious emissions than the benchmark marine fuels such as heavy fuel oil and diesel. It generates lower emissions of sulfur oxides (SOx), nitrogen oxides (NOx), and particulate matter, complying with both local regulations and international environmental standards set by the IMO.
2. Improved Fuel Safety: It is also safer operating a low pressure system than a high pressure system this is due to the fact that in case of leakage or explosion, the pressure inside does not pose a very high risk of people being blown up. As it has been described methanol is in liquid form at currents temperatures that mean that compared to the gaseous fuels the handling and storage condition requirements are safer and easier.
3. Fuel Availability: Methanol is also used commonly as a fuel because it is used in several industries including chemical industry. Furthermore, it can be synthesised from biomass feedstocks or made from captured CO to make it part carbon-neutral fuel candidate.
4. Simpler Engine Design: As a result, low-pressure engines are less complex, with fewer parts leading to lower costs in maintenance as well as decreased rates of occurrence of critical failures. They do not need high pressure injection systems which may be costly and poses a challenge to operate.
5. Reduced Equipment Wear: Preventing pressurisation of the fuel system decreases the stress specifically on the fuel pumps, filters, and pipes. This leads to less fatigue and whereby the required machinery and tools are utilized for many years considering the time taken to repair them.
6. Lower Operational Costs: Several parts such as high-pressure injection systems are normally absent and due to minimal ways that require frequent service, costs of operations are normally lower than those of high-pressure engines.
7. Renewable Energy Potential: Methanol can be synthesised from green hydrogen, carbon capturing and biomass; and these are renewable energy sources, ending the image of pollution by marine transport in the longer term.

- **Disadvantages of Low Pressure Methanol Engines:**

1. Lower Efficiency: Methanol operated low pressure engines tend to be slightly less thermally efficient than their high pressure counterparts, therefore, they will burn fuel at a higher rate to deliver the same level of power. This results in increased fuel usage, which in turn reduces the engine’s overall efficiency.
2. Pilot Fuel Dependency: These engines use a little pilot fuel normally diesel or any other standard fuel because methanol has a high ignition point. This takes away the essence of it a little because pilot fuel still generates emissions.
3. Energy Density: The energy density of methanol is significantly less than conventional marine fuels (approximately 50% of that of diesel in terms of energy per volume); hence, a greater amount of fuel must be carried on ships to provide the same sailing distance. This can however be a disadvantage especially in bulk shipping where space and weight aspect are of paramount importance.
4. Corrosive Properties: Methanol is generally corrosive to some material especially metals that cause high maintenance in the engine and fuel storage systems and the need to use special materials.

5. Infrastructure Limitations: The current fuel supply infrastructure at ports is still in most cases, optimised for traditional fuels such as diesel and heavy fuel oil. Currently, the infrastructure involving methanol as a refueling method is comparatively not well-developed in many parts of the world, which in turn restraints the methanol available for shipping needs worldwide.
6. Toxicity: Methanol can be fatal if swallowed or inhaled in large volumes and thus has to be handled with care in case of accidents such as spills or leaks affecting the crew or the environment.
7. igher Initial Costs: While low-pressure systems are easier to implement than high-pressure systems, the conversion or construction of new ships to methanol as a fuel will be capital-intensive requiring new designs of engines/boilers, storage among other bi-products and supply line systems that may act as a disincentive to shipowners.

2) High-Pressure Methanol Supply Systems

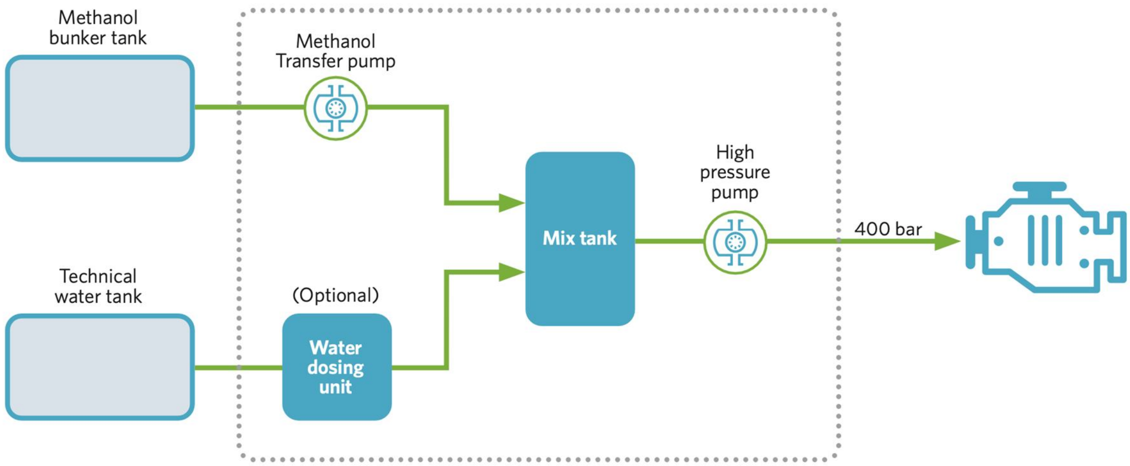

Figure 2: High pressure methanol supply system
(Source: www.methanol.org)

The schematic diagram illustrates the working process of a low-pressure methanol fuel supply system used to power an engine, typically in a marine environment. Here's the step-by-step process:
1. Methanol Bunker Tank: This tank contains the methanol fuel used for absorption and atomization of the fuel. Basically it stores methanol in its internal from which methanol is dispensed to the engine in case of fuel requirement. From the bunker tank, methanol flows through the feed line via the feed pump to bring it through more conditioning to before reaching the engine.
2. Feed Pump: This is a centrifugal type feed pump whose tasks involve pumping methanol from the bunker tank to the service tank. Methanol is taken at low pressure and then transferred to the next step of the process that is conditioning.
3. Service Tank: The service tank stores methanol only for a while and provides the methanol supply skid. Methanol from the service tank goes to methanol supply, circulate and condition methanol supply skid as well as deliver methanol to the engine.
4. Circulation Pump: This pump maintains steady, methanol flow in the methanol supply skid to avoid stagnation of fuel that may degrade the methanol supply. Methanol is used to flow along the skid to ensure the proper temperature and flow is achieves before it proceeds towards the engine section. This circulation aids in creation of a balanced circulation.
5. Heat Exchanger: The heat exchanger makes corrections on the totality of methanol so that it falls to within the most appropriate temperature range for combustion within the engine which majors on +25°C to +50°C. Methanol goes through the heat exchanger where it is either warmed or cooled depending on the prevailing climate to any desired temperature of between two hundred and four hundred degrees Fahrenheit for proper combustion in the engine.
6. Duplex Filter: Indeed, the duplex filter eliminating contaminants and particles from the methanol before delivery to the engine is extremely significant. Methanol enters the engine through a duplex filter since most of the engines in the market have a lubrication system to remove any contaminants that may cause damage to the engine through debris or particulate matter.
7. Engine Supply: Methanol which has been filtered and then conditioned is injected into engines for combustion.

Currently at a relatively low 10 bar pressure and temperature ranged between +25 C and +50 C, the methanol is then Metered into the engine where it is sprayed together with a small quantity of pilot fuel; which may be diesel or any other fuel with relatively low ignition temperature. This pilot fuel aids in the ignition of methanol because methanol has a relatively higher ignition temperature.

8. Pilot Fuel: Some pilot fuel, like diesel, is added simultaneously with methanol into combustion chamber of the engine.

The pilot fuel triggers the burning process and enables the ideal burning of Methanol. This is important as methanol has got higher flash point than the normal fuels that are used in vehicles.

Working Process: The methanol starts in the bunker tank, is pumped through the feed pump into the service tank, and then circulated by the circulation pump. The methanol passes through a heat exchanger to reach the correct temperature, is filtered by the duplex filter, and finally injected into the engine. A small amount of pilot fuel helps initiate combustion, making the engine run on methanol at a controlled low pressure of 10 bar and a temperature range of +25°C to +50°C.

This process ensures that methanol is safely and effectively used as a low-pressure fuel, with appropriate filtering, temperature regulation, and a steady fuel supply for efficient engine operation.

- **Advantages of High-Pressure Methanol Engines:**

1. Higher Efficiency: Improved combustion: According to high pressure systems, methanol gets a better atomization in combustion chamber which leads to complete combustion. This enhances fuel efficiency compared with low pressure integral Spritor system hence compliance with desire fuel efficiency.
2. Lower Pilot Fuel Requirement: High pressure methanol engine require little if any pilot fuel such as, diesel at times they do not use any at all. This enables the engine to incorporate the methanol more efficiently without dilution by fossil fuels hence enhancing general environmental performance.
3. Lower Fuel Consumption: Owing to its performance, high pressure systems use less methanol per kW of power produced. This tends to help in cutting down the operating expenses hence the fuel costs and assist in enhancing the feasibility of using methanol as a Marine Fuel.
4. Lower Emissions: Like any low pressure systems, high pressure methanol engines reduce SOx, NOx and particulate matter emissions to the environment. Nevertheless, because of additional complete combustion is achieved, the concentrations of CO2 and unburned HC emissions may be lower than for the ship.
5. Enhanced Power Output: Thus, the task of high-pressure methanol engine is high for these kinds of engine because of their high combustion control and efficiency, and has possibility for larger vessels or more energy demand application.
6. Better Cold Start Performance: Methanol blended fuels can be propelled by high-pressure systems to deliver improved cold start since the fuel can be injected with the force required to overcome the ignition problems of methanol in cold temperatures.

- **Disadvantages of High-Pressure Methanol Engines:**

1. Complex and Expensive Equipment: High pressure methanol systems demand sophisticated injection systems that are not only able, but also willing and capable of injecting fuel at high pressures (approximately up to 300 bar or more). These structures are far more complex and expensive to produce, deploy and service than their generic counterparts.
2. Higher Maintenance Requirements: High pressure fuel systems make these components more sensitive to wear and tear, and hence more often require servicing. The increased stress on high-pressure pumps, injectors and seals can lead to more frequent downtime and a higher general unit cost.
3. Safety Concerns: Such factors as fuel leakage, high pressure fuel spray dangers and fire hazards are established to be more amplified under high pressure working pressures. Methanol is explosive, and high-pressure systems require much higher safety designs to prevent system failure or accidents.
4. Energy-Intensive Fuel Delivery: Higher pressure systems with high pressure difference take lots of energy to compress and distribute methanol into the combustion chamber. This can to some extent reduce the improvements that have been achieved in fuel efficiency since the pumping and pressurization equipments augments the energy demands of the engine.
5. Corrosive Nature of Methanol: However, methanol has high corrosion effect at high pressures and therefore, the materials used in the engine and fuel delivery systems must be carefully chosen so as to prevent early deformation or failure. This can add the total cost of the system as very specific components will have to be procured.

6. Higher Capital Investment: This is strongly reflected by the fact that there are high initial costs invested in high-pressure methanol engines compared to equipments using low pressure. High quality steel for building specialized vessels, pump and injector assemblies, high pressure fuel pumps and other sophisticate necessities can prove to be expensive generating initial costs that may be unheard of for small shipping companies.
7. Limited Infrastructure: While methanol refueling infrastructure is slowly growing, the requirements for handling high-pressure methanol fuel add another layer of complexity. Special fuel handling, storage, and bunkering systems may need to be adapted or installed to support high-pressure methanol fuel systems, limiting their feasibility in certain regions.

3) Comparison between Low Pressure Methanol Engine & High Pressure Methanol Engine:

	Low Pressure Methanol Engine	High Pressure Methanol Engine
Fuel Injection Pressure	Operates at 10 bar.	Operates at upto 300 bar or more.
Equipments & Complexity	Simple design & Cheap components.	Complex design & expensive equipments.
Maintenance	Easier maintenance & Low maintenance cost.	Higher Maintenance & More Maintenance cost.
Cost	Lower Initial cost.	Higher initial cost.
Fuel Consumption	Higher fuel consumption.	Lower fuel consumption.
Fuel Efficiency	Low Efficiency.	Higher Efficiency.
Emissions	Higher emission due to incomplete combustion.	Lower emission due to complete combustion.
Safety	Lower pressure , lower risk of leaks, safer operation.	Higher risk due to high pressure.
Pilot Fuel Usage	Require significant pilot fuel for ignition.	Lower requirement for pilot fuel & also can run without pilot fuel.

III. RETROFIT CONCEPT AND PROCEDURE

Another promising route in dual fuel combustion in engines is the utilization of oxygen containing fuels in combination with regular diesel. Out of all types of gases, methanol has received considerable interest because of its relatively low price, well-developed logistics, and uncomplicated storage demands. Nevertheless, due to its lower CN, potentials of implementing the DMDF engine have been discussed through the following methods in the literature. Converting compression ignition engines to diesel methanol dual fuel system yields lower NOx and soot but comparable performance with that under diesel fuel operation.
The retrofit approaches can be categorized into two main types: methanol injection directly into the combustion chamber, and methanol injection into the intake air before it reaches the cylinder, commonly referred to as port injection. The research on direct methanol injection have indicated that because of the shortcomings faced in mixture solubility and lower heating values of fuel, the percentage of the mixture should not exceed 20%. Direct methanol injection, however, can put into practice higher methanol substitution ratios, and titrating the process of combustion depending on the injection timing.This method is typically implemented as a retrofit and requires either modifications to the cylinder head to accommodate new injectors or the replacement of existing injectors with dual-fuel injectors.On the other hand, methanol port injection provides a simple and affordable option for retrofitting. Injectors can be installed either at a specific location for single-point injection (SPI) or at multiple points for multi-point injection (MPI). In MPI, injectors are positioned close to the engine’s intake valves, necessitating that these areas be physically accessible. It has been observed that engines with crossflow cylinder heads, where the intake is on one side and the exhaust on the opposite side, are generally easier to convert than engines with reverse-flow cylinder heads, which have both intake and exhaust on the same side. This is because crossflow cylinder heads typically offer better access to the intake area.

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In the SPI approach only injectors are fixed at one particular part of intake manifold where the fuel is injected at standard rate. The methanol is then mixed with air and a close proportioned homogeneous mixture is sprayed into the cylinder. The MPI or Multiple Ports Injection, however, requires the injectors to be installed close to the intake port of each cylinder. In this configuration, fuel is injected during the intake stroke, with the injectors opening and closing once per cycle.

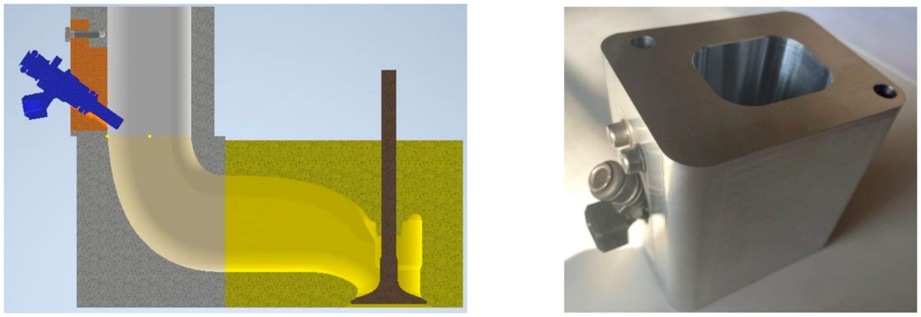

Figure 3: Methanol Injector Hub (Source: avestia.com)

Figure 4: Methanol injector hub and common rail system as installed at the engine
(Source: avestia.com)

A. Working Process of a Single-Point Injector in a Retrofitted Marine Diesel Engine Using Methanol

In a retrofitted marine diesel engine running on methanol, the single-point injection system is a key component. This injector is responsible for delivering methanol into the combustion chamber, where it mixes with air and is ignited, either through compression or with a pilot fuel (such as diesel). Retrofitting to methanol requires specific adaptations to ensure effective injection and combustion, as methanol has different chemical properties compared to diesel.

In a marine diesel engine retrofitted to use methanol, the single-point injector plays a crucial role in delivering and atomizing methanol for efficient combustion. The system must account for methanol's unique properties, such as its lower energy density, higher auto-ignition temperature, and corrosiveness. By carefully controlling the injection timing, pressure, and air-fuel mixing, the retrofitted engine can operate efficiently while reducing emissions and potentially benefiting from the use of renewable methanol sources.

Single-Point Injector:

A single-point injector, also known as a throttle-body injector (TBI), injects fuel at a single point, typically at the throttle body or just upstream of the intake manifold. This contrasts with multi-point injection systems, where fuel is delivered directly to each cylinder's intake port.

In the context of a marine diesel engine retrofitted for methanol use, a single-point injector would inject methanol into the intake air before it enters the combustion chamber. The injected methanol then mixes with the intake air, and the air-fuel mixture is compressed in the cylinder, where ignition occurs.

Working Process:

1. Fuel Supply and Pressurization:

- Methanol is pumped from the fuel tank to the injector at a controlled pressure. Since methanol is less viscous than diesel, the fuel supply system is designed to handle its properties, ensuring a consistent and reliable flow to the injector.
- The fuel pump and pressure regulators ensure that the methanol is delivered to the injector at the correct pressure for atomization and combustion.

2. Injection Timing and Control:

- The engine control unit (ECU) controls the timing and duration of the methanol injection. The timing is crucial because methanol has a lower cetane number and higher auto-ignition temperature compared to diesel. The ECU must adjust the injection parameters to optimize combustion, ensuring efficient power generation and minimizing harmful emissions.
- The injection is timed to coincide with the intake stroke of the engine cycle, where the intake valve is open, allowing the methanol to mix with the incoming air.

3. Fuel Injection:

- The single-point injector atomizes the methanol into a fine spray and injects it into the intake manifold or throttle body. The atomization process is critical because methanol needs to be thoroughly mixed with air to ensure proper combustion.
- The design of the injector is modified to accommodate methanol's properties, ensuring that the spray pattern and droplet size are optimized for methanol’s lower energy content and different combustion characteristics.

4. Air-Fuel Mixing:

- After injection, the methanol mixes with the intake air in the manifold. Methanol’s hygroscopic nature and lower viscosity mean that the mixture process is slightly different from diesel, requiring proper design of the intake system to ensure a homogeneous mixture.
- Effective mixing is crucial to avoid issues such as uneven combustion, knocking, or misfiring, which can be more pronounced with methanol if the air-fuel ratio is not properly controlled.

5. Compression and Ignition:

- During the compression stroke, the air and methanol mixture is compressed within the cylinder. Methanol's higher auto-ignition temperature means that in a conventional diesel engine, spontaneous ignition may not occur as easily as it does with diesel.
- To address this, pilot ignition may be used, where a small amount of diesel is injected before the methanol to initiate combustion. Alternatively, some systems rely on glow plugs or other ignition-assist technologies to ensure reliable ignition.

6. Combustion and Power Generation:

- Once ignited, the methanol-air mixture combusts, generating the necessary pressure to push the piston and produce power.Methanol combusts more cleanly than diesel, resulting in reduced emissions of nitrogen oxides (NOx), sulfur oxides (SOx), and particulate matter.
- The combustion characteristics of methanol differ from diesel, often resulting in lower combustion temperatures, which can reduce thermal stress on the engine components.

7. Exhaust and Emission Control:

- After combustion, the exhaust gases are expelled through the exhaust system. The emissions from methanol combustion include lower levels of nitrogen oxides (NOx) and sulfur oxides (SOx) compared to diesel, but the system may need to handle specific emissions like formaldehyde, which is a byproduct of methanol combustion.
- Appropriate after-treatment systems may be required to manage these emissions and ensure compliance with environmental regulations.

SPI (Single-Point Injection) in dual-fuel systems has several advantages and disadvantages based on its effects on engine performance, emissions, and fuel efficiency.

- **Advantages of SPI Dual-Fuel:**

1. Increased Homogeneity of Mixture:
 - Better Air-Fuel Mixing: SPI systems offer a more homogeneous air-fuel mixture, which can improve combustion consistency across all cylinders.
 - Improved Combustion Efficiency: The more uniform mixture can lead to a more complete combustion process, improving the overall engine efficiency (η ↑ in the chart).

2. Lower Particulate Matter (PM):
 - Cleaner Emissions: The particulate matter (PM) decreases, which is a significant advantage in terms of reducing soot and other harmful emissions.

3. Potential for Higher Engine Efficiency (η ↑):
 - Improved Efficiency: SPI can lead to an increase in thermal efficiency, meaning more of the energy from the fuel is used effectively for power, rather than being wasted.

4. Simplified Fuel System:
 - Cost-Effectiveness: SPI systems, compared to multi-point injection (MPI), often require fewer components, which can reduce the complexity and cost of the fuel system.

- **Disadvantages of SPI Dual-Fuel:**

1. Increased Risk of Knock:
 - Simultaneous Knock in Multiple Cylinders: The homogeneous mixture can lead to knock occurring in several cylinders at once, which can damage the engine and reduce its reliability over time.

2. Removal of Intercooler → Higher Combustion Temperatures:
 - Less Cooling: The removal of the intercooler in some SPI setups leads to less total cooling, which results in higher combustion temperatures (T_comb ↑). This can contribute to increased engine stress and reduce component lifespan.

3. Higher NOx Emissions:
 - Environmental Impact: The higher combustion temperatures lead to an increase in Nitrogen Oxides (NOx), which are harmful pollutants and a key contributor to smog and acid rain.

4. Increase in CO (Carbon Monoxide) and CO_2 (Carbon Dioxide):
 - Worse for Emissions Standards: The chart indicates that CO and CO_2 emissions rise, particularly CO, which is a toxic pollutant. This could make SPI engines less favorable in areas with strict emissions regulations.

5. Less Flexibility in Engine Speed (RPM) Control:
 - RPM Sensitivity: SPI systems show varying effects based on RPM. At lower RPMs (1000-1500), the maximum expansion factor (MEF) is smaller, while at higher RPMs (2000+), it's larger. This indicates a potential issue with consistent performance across different engine speeds.

SPI dual-fuel systems offer efficiency and simplicity benefits, but the drawbacks in terms of emissions, engine knock, and higher combustion temperatures make them less ideal for environments with strict emissions standards or performance consistency across varying conditions.

- **Comparison of SPI and MPI :**

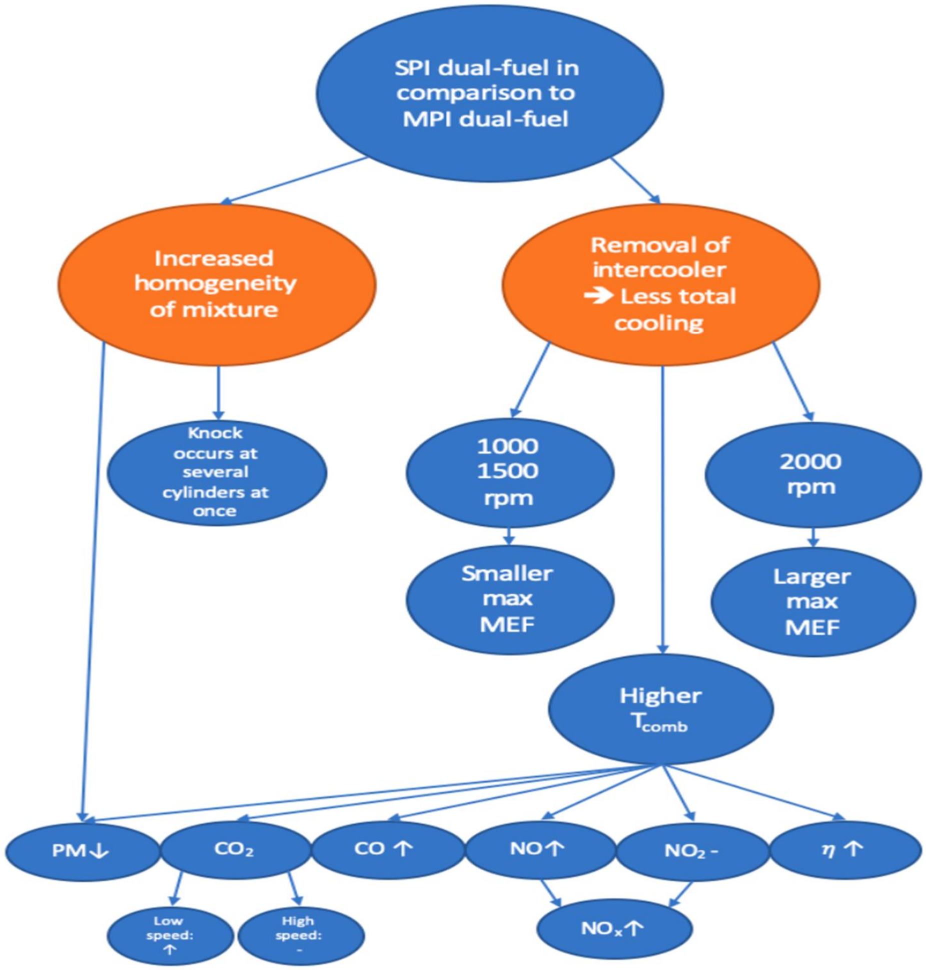

Figure 5: SPI conclusive schematic diagram

B. Working Process of a Multi-Point Injector in a Retrofitted Marine Diesel Engine Using Methanol:

When retrofitting a marine diesel engine to run on methanol, using a multi-point injection system can provide more precise fuel delivery and better combustion efficiency compared to a single-point injector. In a multi-point fuel injection (MPFI) system, each cylinder has its own injector that directly injects methanol into the intake port or cylinder, optimizing the air-fuel mixture for combustion.

The multi-point injection system is particularly beneficial for engines running on methanol, which requires careful control due to its distinct physical and chemical properties compared to diesel.

Multi-Point Injection System:

In a multi-point injection system, methanol is injected separately into each cylinder, typically into the intake port just before the intake valve (port injection) or directly into the cylinder (direct injection). This method ensures that each cylinder receives an optimal amount of methanol, improving the uniformity of the air-fuel mixture and leading to more efficient and cleaner combustion.

Working Process:

1. Fuel Supply and Pressurization:
   - Methanol is stored in a dedicated fuel tank and delivered to the injectors via fuel pumps at a regulated pressure. The fuel system is modified to accommodate methanol's corrosive nature, using materials such as stainless steel and specialized gaskets to prevent degradation.
   - The fuel is pressurized to ensure that each injector can deliver the correct amount of methanol at the required spray pattern and atomization level.

2. Individual Cylinder Injection Control:
   - The engine control unit (ECU) accurately manages the timing and duration of fuel injection for each injector. Since each injector supplies fuel to a specific cylinder, the ECU can optimize the injection for varying engine conditions, such as load and speed.
   - The ECU adjusts the timing based on the engine's operating cycle, injecting methanol during the intake stroke when the intake valve is open. This synchronization ensures that methanol mixes effectively with the intake air for each cylinder.

3. Fuel Injection:
   - In port fuel injection, methanol is injected into the intake port near the intake valve. The high-pressure injector atomizes the methanol into a fine mist, which mixes with the incoming air. The proximity to the intake valve ensures that the methanol-air mixture is drawn directly into the cylinder when the valve opens.
   - In direct injection systems, methanol is injected directly into the combustion chamber during the intake or compression stroke. Direct injection allows for even finer control of the air-fuel mixture and can lead to more efficient combustion and lower emissions.

4. Air-Fuel Mixing:
   - The injected methanol mixes with the intake air as it flows through the intake manifold or directly into the cylinder. Methanol's low viscosity and high volatility facilitate mixing, but the injection system must ensure a homogeneous mixture to prevent uneven combustion or knocking.
   - The MPFI system's ability to inject methanol close to each cylinder's intake valve improves the consistency of the air-fuel ratio in each cylinder, leading to more stable and efficient combustion across all cylinders.

5. Compression and Ignition:
   - After the methanol-air mixture enters the cylinder, the piston compresses it during the compression stroke. Methanol's high auto-ignition temperature can make compression ignition challenging, so the engine may employ pilot ignition. A small quantity of diesel is injected to ignite the methanol, or ignition-assist devices such as glow plugs are used.
   - The precise control offered by the MPFI system allows for fine adjustments to the injection timing and volume, ensuring reliable ignition and efficient combustion, even with methanol's challenging properties.

6. Combustion and Power Generation:
   - The compressed air-methanol mixture is ignited (either through compression ignition or pilot diesel ignition), resulting in combustion that drives the piston downward and generates power.
   - Methanol burns cleaner than diesel, producing fewer particulates and lower NOx emissions. However, methanol's lower energy density means that more fuel must be injected to achieve the same power output as diesel, which is managed by the MPFI system.

7. Exhaust and Emission Control:
   - The combustion of methanol produces exhaust gases that are expelled through the exhaust system. While methanol combustion reduces emissions like NOx, SOx, and particulates, it may produce other emissions, such as formaldehyde, which requires specific after-treatment systems.
   - The multi-point injection system contributes to more complete combustion, reducing unburned methanol and associated emissions, thereby improving overall engine efficiency and reducing the environmental impact.

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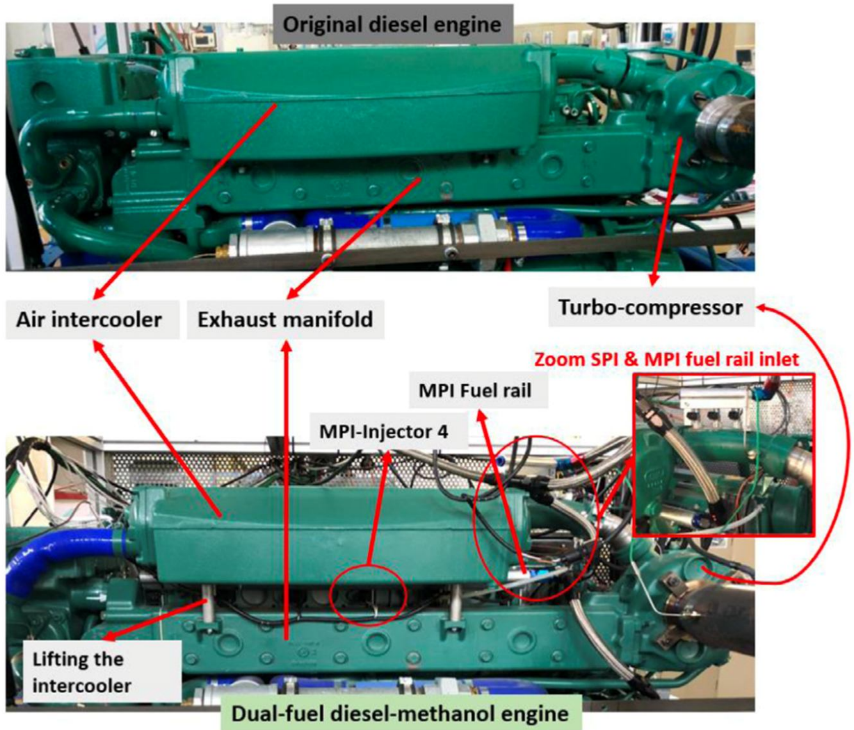

Figure 6: Original diesel engine & converted engine to dual fuel diesel methanol operation.
(Source: researchgate.net)

- **Advantages of MPI (Methanol Port Injection) Dual-Fuel Systems:**

1. Lower Carbon Dioxide (CO_2) Emissions: Methanol has a higher hydrogen-to-carbon (H/C) ratio compared to diesel. This leads to lower CO_2 emissions during combustion, making it more environmentally friendly.
2. Reduced Nitrogen Oxides (NO_x) Emissions: The cooling effect of methanol due to its high latent heat of evaporation helps lower combustion temperatures (T_comb↓), which in turn reduces the formation of nitrogen oxides (NO_x).
3. Particulate Matter (PM) Reduction: Methanol improves the mixing of the diesel spray in the combustion chamber, which reduces the formation of rich zones (fuel-rich areas) that typically produce particulate matter (soot). This can result in significantly lower PM emissions.
4. Increased Ignition Delay: The cooling effect from methanol's evaporation increases the ignition delay, allowing better mixing of air and fuel, which may result in more complete combustion under certain conditions.
5. Better Premixed Combustion: Methanol burns in the premixed phase of combustion, leading to a faster combustion process. This premixed combustion can improve engine responsiveness and reduce harmful emissions.

- **Disadvantages of MPI Dual-Fuel Systems:**

1. Increased Carbon Monoxide (CO) Emissions: Due to the cooler combustion process, incomplete combustion can occur, leading to an increase in CO emissions. This is a significant drawback since CO is a harmful pollutant.
2. Higher Nitrogen Dioxide (NO_2) Emissions: Although total NO_x emissions are reduced, there may be an increase in NO_2, a specific form of nitrogen oxide that can have more adverse health effects than NO.
3. Efficiency Reduction (η↓): While methanol has environmental benefits, the overall thermal efficiency of the engine can decrease. This may be due to the lower energy density of methanol compared to diesel, as well as the cooling effect that can reduce combustion temperatures too much, affecting engine performance.

4. Complexity of Dual-Fuel Systems: Managing the injection, combustion, and timing of two fuels requires more complex engine control systems, which can increase the cost of both manufacturing and maintenance.
5. Fuel Storage and Handling Challenges: Methanol is corrosive and can be more difficult to store and transport compared to diesel. It also requires modifications to the fuel system to handle its different chemical properties.
6. Increased CO_2 Emissions During Production: While the CO_2 emissions from methanol combustion are lower, methanol is typically produced from natural gas, which involves CO_2 emissions. If renewable sources are not used, this can offset some of the environmental benefits.

The MPI dual-fuel system offers significant benefits in terms of reduced CO_2, PM, and NO_x emissions, making it a cleaner option for reducing certain types of emissions in diesel engines. However, it also comes with trade-offs like increased CO and NO_2 emissions and reduced engine efficiency. These advantages and disadvantages must be carefully balanced depending on the priorities of fuel economy, emissions regulations, and engine performance.

- **Comparison of MPI dual-fuel operation in comparison to diesel- only operation:**

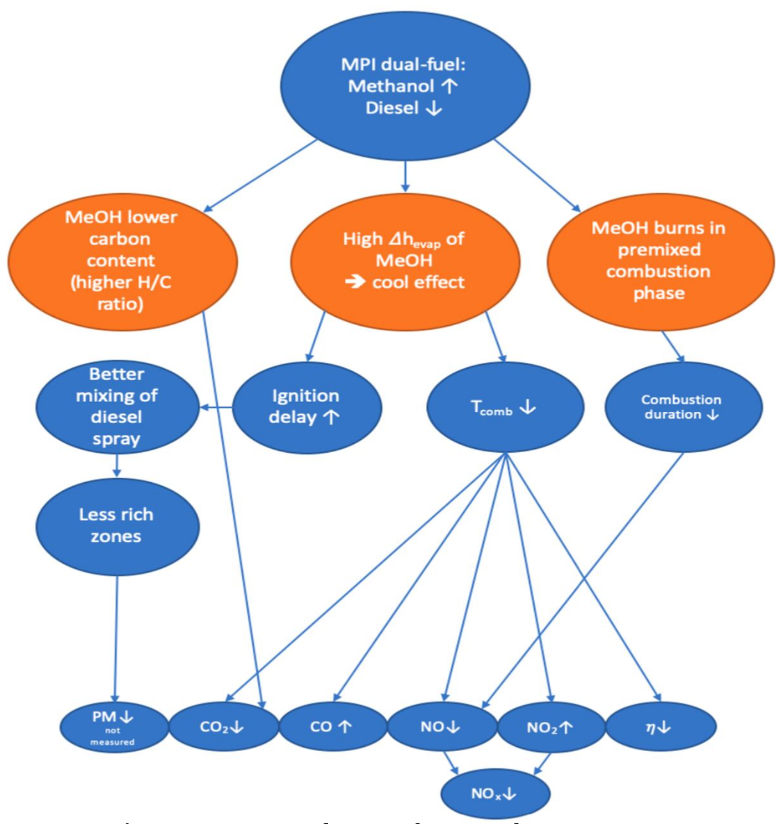

Figure 7: MPI conclusive schematic diagram

Key Considerations in the Multi-Point Injection System:

1. Injector Design:
- Methanol-specific injectors are required due to methanol's lower viscosity and different spray pattern needs compared to diesel. These injectors must be designed to handle methanol's corrosiveness and ensure consistent atomization across all cylinders.
- The injector nozzles are optimized for methanol, ensuring that the fuel is sprayed in a fine mist that mixes easily with the intake air.

2. Injection Pressure and Timing:

- The injection pressure for methanol is carefully controlled to achieve the required atomization and mixture. Higher injection pressures may be needed compared to diesel to ensure proper atomization, especially in direct injection systems.
- The timing of methanol injection is important for efficient combustion. The ECU must account for methanol's higher auto-ignition temperature and adjust the timing to ensure complete combustion, preventing issues like knocking or misfiring.

3. Material Compatibility:

- Due to methanol's corrosive nature, all components in contact with the fuel, including injectors, fuel lines, and seals, are made from methanol-compatible materials. Stainless steel and specialized rubber compounds are commonly used to prevent degradation and leaks.

4. Safety Considerations:

- Methanol's low flashpoint and toxicity require additional safety features in the injection system. Flame arrestors, leak detection systems, and proper ventilation are necessary to prevent accidents and ensure safe operation.

5. Combustion Assistance:

- Depending on the engine design, combustion assistance such as pilot diesel injection or ignition-assist technologies may be required to initiate methanol combustion reliably. The MPFI system's precise control of injection timing allows for smooth integration of these systems.

6. Dual-Fuel Capabilities:

- Some retrofitted marine engines may operate as dual-fuel systems, using both methanol and diesel. The MPFI system allows for seamless switching between fuels or simultaneous use of both, optimizing fuel efficiency and performance under varying conditions. The multi-point fuel injection system offers precise control over methanol injection in a retrofitted marine diesel engine, optimizing combustion efficiency and reducing emissions. By delivering methanol directly to each cylinder's intake port or combustion chamber, the system ensures consistent air-fuel mixing and combustion across all cylinders. However, methanol's unique properties require careful management of injection timing, pressure, and materials to ensure reliable operation and safety. The MPFI system, with its individualized cylinder control, plays a crucial role in overcoming these challenges and enabling the efficient use of methanol as a marine fuel.

IV. TECHNICAL CHALLENGES AND CONSIDERATIONS

A. Corrosive Nature of Methanol and Material Compatibility

Methanol, although a highly efficient fuel, has certain corrosive properties that pose challenges when it comes to material compatibility in fuel systems. Its corrosive nature can affect metals, rubbers, plastics, and other materials used in fuel storage, transportation, and engine components.

1. Corrosive Effects on Metals

- Aluminium: Methanol can cause pitting and corrosion in aluminium. It forms aluminium methoxide, which can degrade the integrity of aluminium components over time.
- Steel: Both carbon steel and stainless steel can corrode when in contact with methanol, particularly if water is also present. Methanol can form acidic by-products (such as formic acid) when it degrades, accelerating the corrosion process.
- Copper: Methanol reacts strongly with copper, forming salts that can pollute the fuel and potentially harm engine components. Magnesium and Zinc: These metals are particularly vulnerable to methanol, undergoing rapid corrosion when exposed to it.

2. Non-Metallic Material Compatibility

- Elastomers (Rubber Components): Certain elastomers, such as natural rubber, nitrile rubber (NBR), and polyurethane, are highly susceptible to methanol-induced swelling, softening, and degradation. These materials can lose flexibility, become brittle, and ultimately fail, leading to leaks or malfunction in fuel systems.
- Plastics: Many plastics, like nylon and polyethylene, can be weakened by methanol exposure over time. Polymers such as polyvinyl chloride (PVC) and certain types of polyesters are known to degrade in methanol environments.

3. Hydroscopic Nature of Methanol

Methanol is hygroscopic, which means it easily draws in moisture from the surrounding air. Water content in methanol accelerates corrosion, especially in metals like aluminium and steel. The presence of water can also cause phase separation, leading to poor fuel combustion and engine problems.

B. Material Compatibility with Methanol Fuel

Due to methanol's corrosiveness, specific materials must be selected for use in fuel systems.

1. Metallic Materials

- Stainless Steel (304, 316 grades): Although methanol can corrode metals, certain grades of stainless steel, particularly those with higher chromium and nickel content (e.g., 316 stainless steel), offer better resistance.
- Nickel Alloys: Nickel-based alloys, such as Monel or Hastelloy, exhibit strong resistance to methanol corrosion.
- Titanium: Titanium is an excellent material for methanol fuel systems due to its high corrosion resistance.

2. Non-Metallic Materials

- Fluoropolymers (e.g., PTFE): Polytetrafluoroethylene (PTFE, or Teflon) and other fluoropolymers offer excellent resistance to methanol and are commonly used in fuel seals and gaskets.
- FKM (Viton): Viton is a fluoroelastomer that provides good resistance to methanol and is often used for seals and hoses in methanol-compatible systems.
- Polypropylene: Certain thermoplastics, such as polypropylene, can also withstand methanol exposure, though their long-term durability should be verified in specific conditions.

C. Mitigation Techniques

To minimize corrosion and material degradation, the following practices can be employed:

- Use of corrosion inhibitors: Additives can be used to prevent or slow down the corrosive effects of methanol on metals.
- Material selection: Choosing materials specifically designed for compatibility with methanol (e.g., using stainless steel instead of aluminum or copper).
- Water separation: Implementing water separation systems to reduce the water content in methanol fuel, which decreases corrosion rates.

D. Cold Start Challenges and Its Solution:

The cold start issues with methanol fuel are primarily due to its unique physical and chemical properties, which make it challenging for the fuel to ignite and combust efficiently in low temperatures. Here are the main reasons for cold start difficulties in methanol engines:

1. Low Vapor Pressure

Evaporation Issues at Low Temperatures: Methanol has a much lower vapor pressure than gasoline, particularly in cold conditions. Vapor pressure is essential for fuel to evaporate and mix with air, forming a combustible air-fuel mixture. In cold environments, methanol struggles to vaporize, making it harder for the engine to ignite the fuel.

2. High Latent Heat of Vaporization

Significant Cooling During Evaporation: Methanol absorbs a large amount of heat from its surroundings when it evaporates due to its high latent heat of vaporization. In cold weather, this cooling effect can further lower the intake air temperature, making it even harder for methanol to vaporize and ignite. This often results in incomplete combustion or no ignition at all during startup.

3. High Ignition Energy Requirement

Higher Ignition Temperature: Methanol has a higher auto-ignition temperature (around 470°C) compared to gasoline (280°C), meaning more energy is required to ignite the fuel. In cold weather, the engine and fuel may not reach the required ignition temperature easily, leading to starting difficulties.

4. Low Energy Content
Lower Combustion Energy: Methanol has about half the energy content of gasoline per unit volume. This means more methanol is required to achieve the same power output. During a cold start, when the engine is already struggling to form a proper air-fuel mixture, the lower energy content compounds the problem by providing less energy for ignition and sustaining combustion.

5. Water Absorption (Hygroscopic Nature)
Moisture Absorption: Methanol is hygroscopic, meaning it readily absorbs moisture from the air. In cold conditions, the absorbed water can form ice crystals within the fuel system, potentially clogging fuel lines, injectors, or carburetors. This further exacerbates cold start issues by disrupting fuel delivery.

6. Fuel Condensation in Intake Manifold
Condensation at Low Temperatures: As methanol cools the intake air during evaporation, it can condense back into liquid form in the intake manifold, leading to uneven distribution of fuel and air. This causes improper combustion or no combustion during engine start-up, especially when the engine is cold.

7. Slow Flame Propagation
Slower Combustion Process: Methanol burns more slowly than gasoline. This slower flame propagation can lead to incomplete combustion in the initial phases of cold starts, where the engine needs quick and efficient ignition to reach operating temperatures.

8. Fuel System Compatibility Issues
Material Sensitivity to Methanol: Methanol can be corrosive to certain metals and rubber components used in traditional fuel systems. In cold environments, deterioration of fuel system components can further disrupt proper fuel delivery and atomization, making cold start issues more severe.

E. Solutions to Cold Start Challenges

To mitigate the cold start issues associated with methanol fuel, several strategies have been developed:
- Pre-heating Intake Air or Fuel: This can help vaporize methanol more effectively by providing the necessary heat for vaporization before it enters the combustion chamber.
- Dual-Fuel Systems: Some engines use a small amount of gasoline or another high-volatility fuel during startup to ensure proper combustion and then switch to methanol once the engine has warmed up.
- Higher Compression Ratios: To improve the ignition of methanol, engines can be designed with higher compression ratios, helping achieve the necessary ignition temperature.
- Fuel Blending: Methanol can be blended with other fuels (e.g., ethanol or gasoline) to improve its cold-weather volatility and reduce starting issues.

F. Combustion characteristics of Methanol :

1. High Octane Rating
Methanol has a high octane number (around 105-110), which means it resists knocking (pre-ignition) better than many conventional fuels like gasoline. A higher octane rating enables engines to run at increased compression ratios, enhancing thermal efficiency and overall performance. Engines running on methanol can be designed with higher compression ratios, leading to more power output and better efficiency.

2. High Heat of Vaporization
Methanol has a higher latent heat of vaporization than gasoline, meaning it absorbs more heat when it vaporizes. This cools the intake charge, resulting in denser air and an increase in the air-fuel mixture's density. This cooling effect can enhance volumetric efficiency, potentially improving power output, especially in turbocharged or supercharged engines.

3. Lower Energy Density
Methanol has a lower energy content than gasoline (around 19.9 MJ/kg vs. 44 MJ/kg for gasoline). This means more methanol fuel is required to produce the same amount of energy. Engines running on methanol require a higher fuel flow rate to compensate for the lower energy density, which can affect fuel system design and necessitate larger fuel injectors or fuel pumps.

4. Wide Flammability Range

Methanol has a broader flammability range compared to gasoline, making it easier to ignite over a wide range of air-fuel ratios. This wide range allows for more flexible combustion strategies and can help optimize fuel efficiency at various engine loads and speeds.

5. Fast Flame Speed

Methanol shows a relatively high flame speed compared to gasoline. This characteristic allows for more complete combustion and can reduce combustion duration. Faster flame speeds can lead to better thermal efficiency and lower cycle-to-cycle variability in engine performance, improving power and fuel economy.

6. Cleaner Combustion

Methanol burns with fewer carbon-based emissions (such as CO_2, CO, and hydrocarbons) compared to gasoline. It produces lower particulate matter and NO_x emissions under most operating conditions. The cleaner combustion of methanol can result in lower exhaust emissions and reduced engine deposits, potentially extending engine life and reducing maintenance requirements.

7. Oxygen Content

Methanol contains oxygen within its molecular structure (about 50% by weight), which helps promote more complete combustion of the fuel and reduces the formation of carbon monoxide (CO) and unburnt hydrocarbons. The oxygen-rich nature of methanol enables leaner combustion, which improves fuel efficiency and reduces pollutant emissions, especially in lean-burn engine designs.

G. Impact of Methanol on Engine Performance

The combustion characteristics of methanol significantly affect various aspects of engine performance, including power output, efficiency, and emissions:

1. Power Output

- Higher power potential: Methanol’s high octane rating and cooling effects allow for more aggressive tuning of the engine (higher compression ratios, advanced ignition timing). This can lead to higher power output compared to engines using gasoline, especially in turbocharged or supercharged applications.
- Lower energy content offset: Despite methanol’s lower energy density, engines can make up for it with increased volumetric efficiency and higher compression ratios, enabling comparable or superior power output.

2. Fuel Efficiency

- Lower thermal efficiency: Methanol has a lower energy density, so engines consume more fuel by volume to travel the same distance compared to gasoline-powered engines. However, methanol's ability to allow higher compression ratios can improve thermal efficiency, partly offsetting its lower energy content.
- Potential for lean-burn operation: The oxygen content and wide flammability limits of methanol can enable lean-burn strategies, which improve fuel economy under certain operating conditions.

3. Emissions

- Reduced harmful emissions: Methanol combustion results in lower emissions of harmful pollutants such as hydrocarbons (HC), carbon monoxide (CO), and nitrogen oxides (NO_x). Methanol engines can also produce lower levels of soot and particulate matter.
- Formaldehyde formation: A potential downside of methanol combustion is the formation of formaldehyde (CH_2O), a toxic compound. Proper engine management and aftertreatment systems (e.g., catalytic converters) are required to mitigate this issue.

4. Engine Cooling and Durability

- Better cooling: The high heat of vaporization of methanol provides enhanced cooling of the engine’s combustion chamber, reducing the likelihood of knocking and enabling higher performance without engine damage.
- Reduced wear and tear: Methanol’s cleaner combustion results in fewer carbon deposits in the engine, which can reduce wear on engine components and extend the life of the engine. However, methanol is corrosive to certain materials (e.g., aluminum, rubber), so engine components must be designed or treated to resist corrosion.

5. Cold Start and Vaporization Issues

- Cold-start challenges: Methanol has a higher heat of vaporization and lower vapor pressure compared to gasoline, which can cause difficulties in vaporizing the fuel at low temperatures. This makes cold starting more challenging without auxiliary systems like preheaters.
- Special fuel handling: The hygroscopic nature of methanol (it absorbs water from the air) can lead to fuel contamination and corrosion in the fuel system. This requires careful fuel management and materials resistant to corrosion.

V. CONCLUSION

As the global shipping industry grapples with tightening environmental regulations and the urgent call for decarbonization, methanol has gained significant traction as a clean, scalable, and future-ready marine fuel. Retrofitting existing marine diesel engines to operate on methanol is emerging as a practical bridge between today's fossil-fueled operations and tomorrow's sustainable maritime landscape. This approach allows for substantial emissions reductions without requiring a complete overhaul of ship propulsion systems—a major advantage in terms of cost and feasibility.

Throughout this paper, the technical, economic, and environmental dimensions of methanol retrofitting have been explored in depth. Two main fuel system configurations—low-pressure and high-pressure—were compared, each offering distinct benefits. Low-pressure systems stand out for their simplicity, lower initial cost, and operational safety, while high-pressure systems deliver higher thermal efficiency, reduced fuel consumption, and significantly lower emissions, albeit at the cost of added complexity and higher maintenance requirements.

Dual-fuel strategies, including Single-Point Injection (SPI) and Multi-Point Injection (MPI), provide further adaptability. SPI systems are easier to implement but may pose challenges like engine knock and increased emissions at higher loads. MPI, while more complex, offers greater combustion control, reduced soot formation, and improved overall engine efficiency.

Several key observations emerged from this study that highlight both the potential and the limitations of methanol retrofitting:

1) Methanol significantly reduces harmful emissions, including SOx, NOx, and particulate matter, making it compliant with IMO standards.
2) Retrofitting is technically viable, with necessary modifications focused on injectors, fuel lines, and combustion strategies.
3) Low-pressure systems are simpler and safer, while high-pressure systems offer better performance and fuel efficiency.
4) Dual-fuel operation balances ignition reliability and emissions control, especially in cold climates.
5) SPI is cost-effective but may lead to knocking and higher NOx, while MPI provides more precision and cleaner combustion.
6) Cold start challenges remain, due to methanol's low vapor pressure and high ignition temperature, requiring additional systems for reliable ignition.
7) Material compatibility is critical, as methanol is corrosive and demands the use of resistant alloys and specialized components.
8) Fueling infrastructure is still developing, but progress is being made as methanol becomes more widely adopted in global ports.

In conclusion, while retrofitting marine engines for methanol use is not without its challenges—such as corrosiveness, cold start issues, and infrastructure gaps—it represents a powerful and attainable step toward decarbonizing maritime transport. By embracing the right combination of injection systems, materials, and safety measures, the shipping industry can leverage methanol's strengths to meet both regulatory demands and environmental responsibilities. As production of renewable methanol scales and bunkering capabilities expand, retrofitting will become not just a transitional solution—but a cornerstone in the sustainable evolution of marine propulsion.

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