Internal Combustion Engines MMME4066

Pollutant and Emissions control

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Content

- Emissions from shipping
- Exhaust emissions limits from marine engines
- Emission–control legislations
- Routes to engine fuel economy and CO2 reductions
- Emission control - aftertreatment

Student Evaluation of the Module

Advanced Powertrain Engineering (MMME4066),
Can you to take a few moments to complete the SEM Survey for our module.
You can access the survey using the following link:

Students can access the survey at https://bluecastle-uk-surveys.nottingham.ac.uk

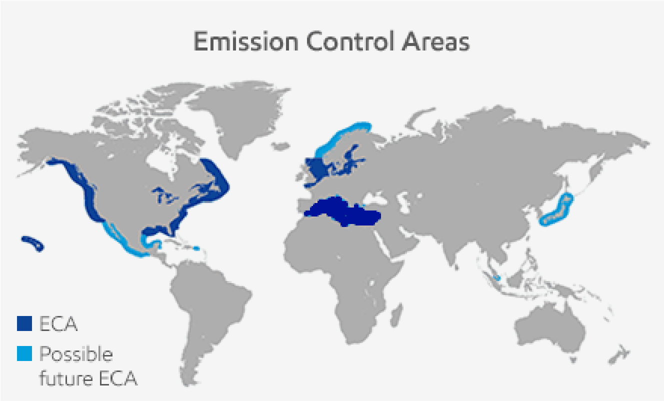
Survey Starts	**01/12/2025 07:00**
Survey Ends	12/12/2025 23:00

Your feedback is incredibly important to me, and I'd love to see a good number of responses. Last week, I was pleased to receive some great feedback regarding the course, particularly about uploading lecture materials in advance and making lecture recordings available promptly afterward. I'm happy to confirm that this will now be implemented moving forward!
I truly hope you've found the module interesting and enjoyable this year.

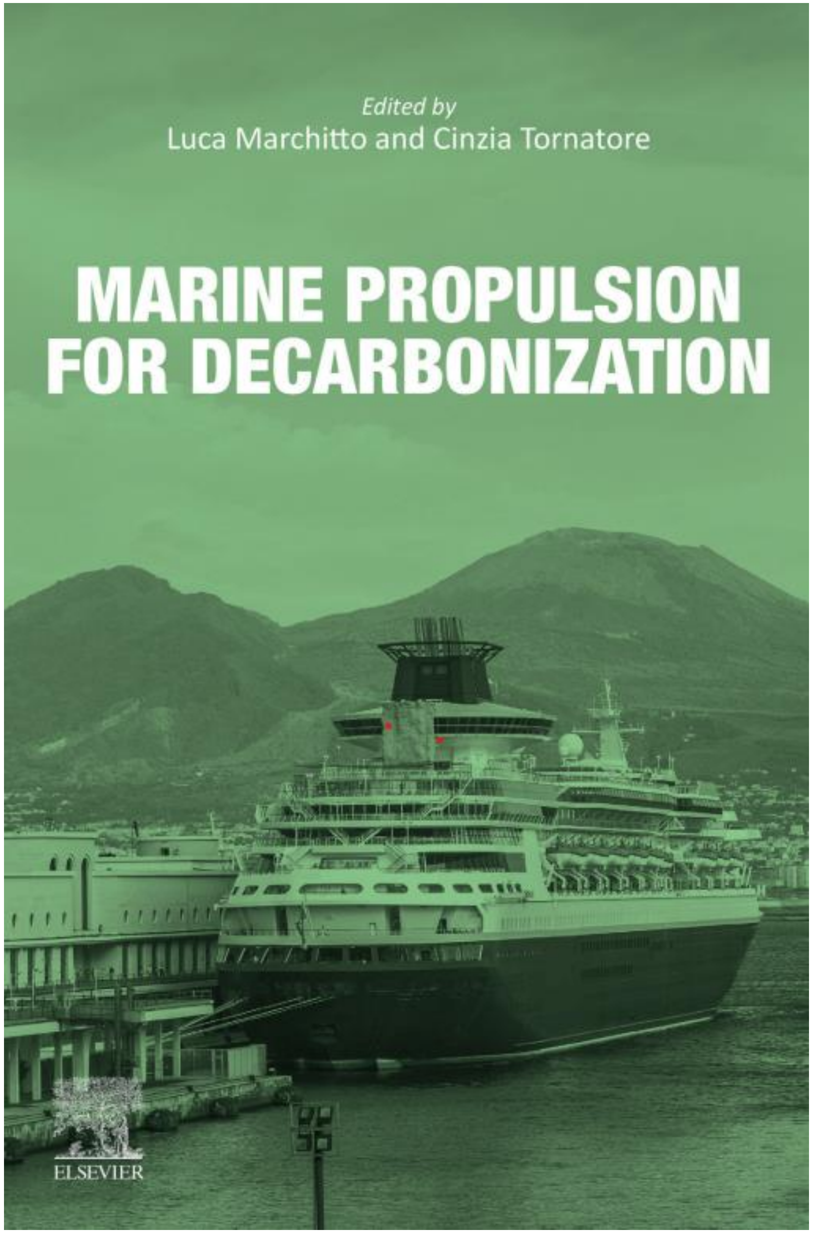
Ship: larger, ocean-going vessel, especially those designed for transporting cargo or passengers over long distances

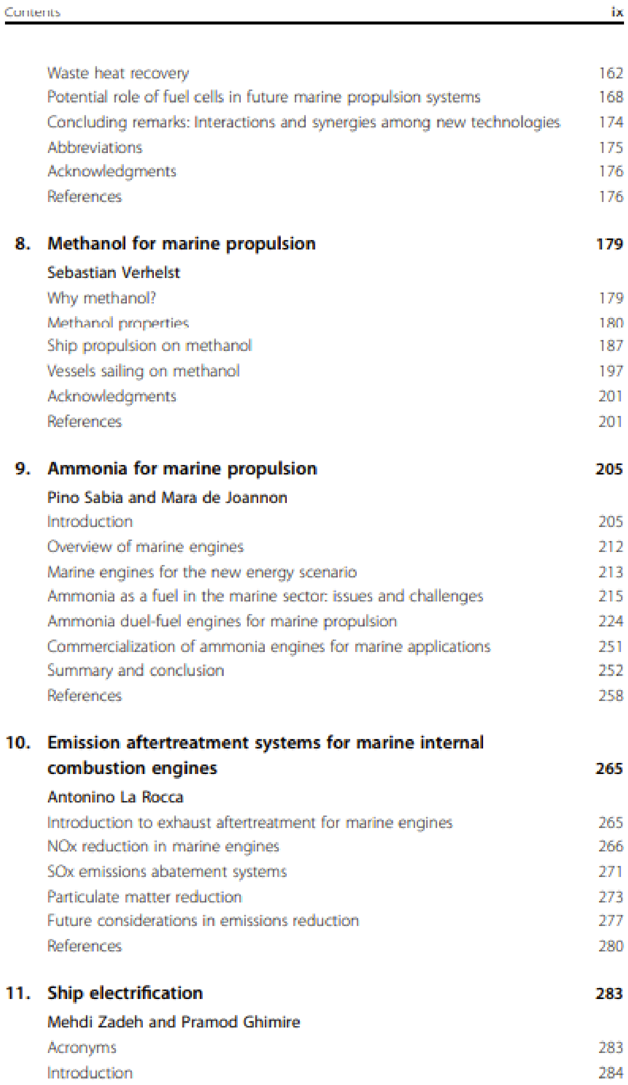
Ships, carry over 80% of global trade by volume, are responsible for approximately 2.5%–3% of total global emissions.

Several types of ships are used in global trade today to carry various types of cargo demanded by consumers and industries worldwide. Ship travel in and out of Emission Control Areas (ECAs)

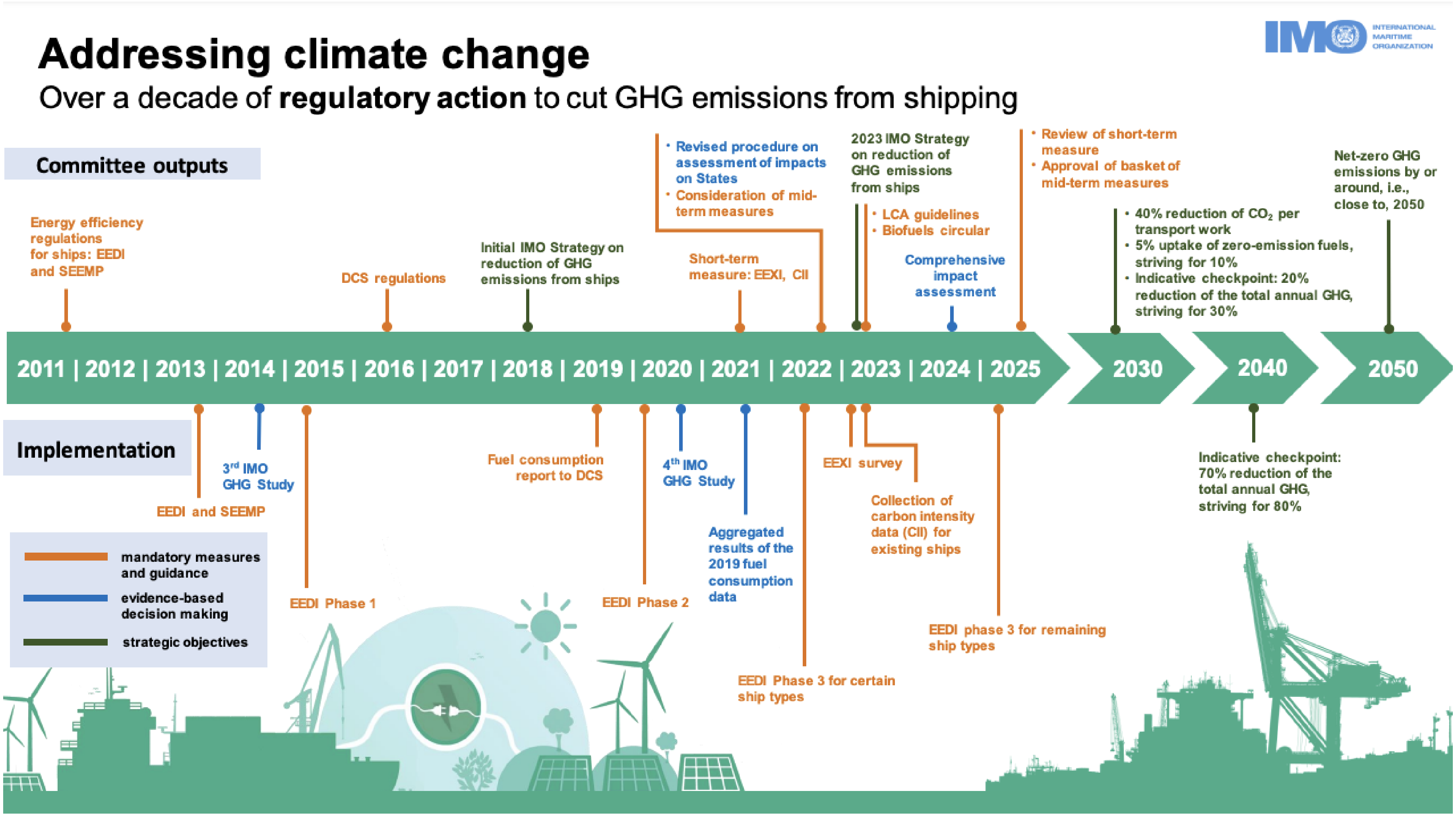


Book focusing on technologies, policies, and strategies that are reshaping the propulsion systems of today's marine vessels





Shipping and emissions: Net-zero GHG by 2050



Addressing climate change

Over a decade of **regulatory action** to cut GHG emissions from shipping

INTERNATIONAL MARITIME ORGANIZATION

Committee outputs

Energy efficiency regulations for ships: EEDI and SEEMP

DCS regulations

Initial IMO Strategy on reduction of GHG emissions from ships

Short-term measure: EEXI, CII

- Revised procedure on assessment of impacts on States
- Consideration of mid-term measures

2023 IMO Strategy on reduction of GHG emissions from ships

- LCA guidelines
- Biofuels circular

Comprehensive impact assessment

- Review of short-term measure
- Approval of basket of mid-term measures

- 40% reduction of CO_2 per transport work
- 5% uptake of zero-emission fuels, striving for 10%
- Indicative checkpoint: 20% reduction of the total annual GHG, striving for 30%

Net-zero GHG emissions by or around, i.e., close to, 2050

2011 | 2012 | 2013 | 2014 | 2015 | 2016 | 2017 | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 2030 2040 2050

Implementation

EEDI and SEEMP

3rd IMO GHG Study

EEDI Phase 1

Fuel consumption report to DCS

EEDI Phase 2

4th IMO GHG Study

Aggregated results of the 2019 fuel consumption data

EEDI Phase 3 for certain ship types

EEXI survey

Collection of carbon intensity data (CII) for existing ships

EEDI phase 3 for remaining ship types

Indicative checkpoint: 70% reduction of the total annual GHG, striving for 80%

🟧 mandatory measures and guidance
🟦 evidence-based decision making
🟩 strategic objectives

The International Maritime Organization (IMO) implemented guidelines to reduction in carbon intensity of international shipping and other harmful emissions

Prevention of Air Pollution from Ships

Key pollutants from the combustion of fossil fuels in marine compression ignition engines:

Carbon dioxide (CO_2),
Nitrogen oxides (NO_x),
Sulphur oxides (SO_x)
Particulate matter (PM),
Small fraction of unburned hydrocarbons (UHC), carbon monoxide (CO), and other by-products may also be generated depending on combustion and fuel characteristics.

The MARPOL convention (main international treaty) designed to prevent and minimize pollution from ships.

Annex VI Prevention of Air Pollution from Ships (May 2005): Sets limits on sulphur oxide and nitrogen oxide emissions from ship exhausts and prohibits deliberate emissions of ozone depleting substances; designated emission control areas set more stringent standards for SOx, NOx and particulate matter.

Future trends in fuels for marine vessels

Significant developments in maritime fuels are being driven by environmental concerns and the IMO's stringent emission requirements.

The amount of sulphur in marine fossil fuels is being drastically decreased (e.g. lower sulphur fuel <0.10%).

New fuels: To reach aggressive decarbonisation goals, the sector is moving away from conventional heavy fuel oil and towards cleaner substitutes.

Liquefied natural gas, or LNG, is becoming a popular transitional fuel as it cuts local air pollutants (SOx, NOx, PM) and reduces CO2 emissions (around 20-25%).

Long-term priorities, however, centre on creating and deploying zero-emission fuels such advanced biofuels, hydrogen, and ammonia.

By 2050, e-ammonia and other such fuels may account for 20% to 60% of all shipping fuels.

Methanol and biofuels are also anticipated to become more popular in the near to medium future. It cuts emissions SOx by up to 99% and nitrogen oxides (NOx) by up to 80%. Green methanol, can achieve a nearly carbon-neutral lifecycle, aligning with the IMO's net-zero emissions targets for 2050

Shipping and emissions

Emission control can be achieved through engine design and control, fuel and lubricant appropriate selection and formulation or using exhaust gas aftertreatment.

The heavy fuel oil used in international shipping contains on 2700 times more sulphur that road fuel.

IMO guidelines mandate a global sulphur reduction in fuels with even stricter regulation in specific areas.

The IMO requires the application of low-sulphur fuel (0.1% sulphur content)

Marine engines must have efficient exhaust aftertreatment systems.

Vessels operating in the Emission Control Areas (ECAs) need emission reduction equipment installed in accordance with IMO Tier III requirements.

NOx reduction in marine engines

NOx are generated by the high temperature reactions during combustion, that is, above 1800K.

The nitrogen (N_2) present in the intake air oxidizes forming the so-called thermal NOx. However, marine fuel may also contain organic compounds with nitrogen atoms (e.g., C_4H_5N, C_5H_5N, and C_9H_7N) with a nitrogen mass content in these fuels that can be as much as 0.4% particularly for the heavy oils (referred to as fuel NOx).

The most established aftertreatment method for reducing NOx in marine engines is the SCR systems.

A reducing agent, typically a urea solution, is injected into the exhaust stream; a catalyst then promotes the chemical reactions that convert the NOx into harmless components such as nitrogen and water.

The amount of sulphur in the fuel impacts on the SCR system set up and influences the catalyst life.

NOx reduction in marine engines

Urea, NH2CONH2, consists of two amine groups (-NH2) connected to a carbonyl group (C]O). In marine applications, typically, a urea water solution, containing 40% by weight, is injected in the exhaust stream just before the catalyst.

The high temperature of the exhaust gasses, vaporizes the water and decomposes the urea into isocyanic acid (HNCO) and ammonia (NH3). The newly formed isocyanic acid reacts with the water vapor and, through hydrolysis, forms CO2 and an additional ammonia molecule.

$$NH_2CONH_2 \xrightarrow{heat} NH_3 + HNCO$$

$$HNCO + H_2O \rightarrow NH_3 + CO_2$$

the presence of ammonia in the exhaust stream could contribute to the formation of N2O.

SOx emissions abatement systems

Target: A global sulphur reduction in fuels with even stricter regulation in specific areas.

These guidelines focus on reducing air acid rain and health issues directly related not only to the sulfuric oxides (SOx) but also to enable other aftertreatment systems to function avoiding catalyst poisoning associated with the sulphur.

However, fuels with the higher sulphur content may still be used outside the Emission Control Areas (ECAs)

SOx forms during combustion when sulphur and oxygen react rapidly forming sulphur dioxide and then sulphur trioxide through further oxidation.

The most straightforward way to ensure compliance with the MARPOL emission restrictions is indeed to use low-sulphur fuels in ECAs.

SOx emissions abatement systems

Scrubbers, are used to remove SO_x from engine exhaust by spraying water or an alkaline solution through the exhaust stream.

Fresh or sea water passes through the scrubber and interacts with the exhaust gases. Spray nozzles geometry can be optimized according to the application. Objective of the spray nozzles is to generate a droplet cloud so that a larger surface is available for the diffusion of sulphur compounds in water

The sulphur oxides dissolve and react to form harmless compounds, mainly sulphates.

$$SO_2 + H_2O \rightarrow H_2SO_3$$

$$2H_2SO_3 + O_2 \rightarrow 2H_2SO_4$$

The resulting acidic water is neutralised before discharge or recycled, depending on the system type. Scrubbers can reduce SO_x emissions by over 90–95%, enabling ships to continue using high-sulphur fuel oil while meeting IMO limits.

SOx emissions abatement systems – SOx Scrubbers

Open-loop systems:

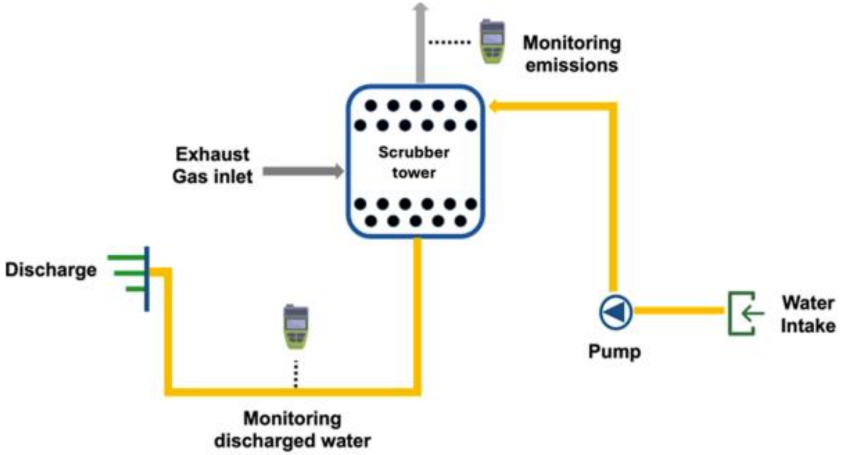


Figure 10.1 An open-loop setup for a SOx scrubber. *Modified from Solutions, M.E., 2024. MAN B&W Two-stroke Marine Engines Emission Project Guide for Marpol Annex VI Regulations.*

Key working principle:
Use seawater (naturally alkaline) to neutralise SO_x.
Wash water is treated and discharged back to sea
Simple and cost-effective but restricted in some ports due to seawater discharge regulations

Closed-loop systems:

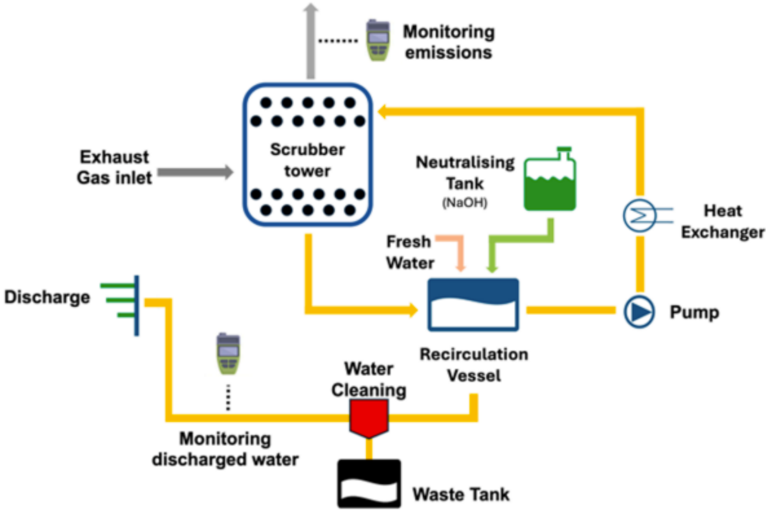


Figure 10.2 SOx scrubber in a closed-loop configuration. *Modified from Solutions, M.E., 2024. MAN B&W Two-stroke Marine Engines Emission Project Guide for Marpol Annex VI Regulations.*

Key working principle:
Use freshwater with an alkaline additive (e.g., sodium hydroxide).
Wash water is recirculated, with minimal discharge.
Suitable for areas with discharge bans but requires more maintenance and chemical handling.

Shipping and emissions aftertreatment for PM

Particulate matter: Sulphates, metallic elements, carbon-based particles, and a variety of organic and inorganic materials make up the complex mixture of PM produced by ships. These particles have a very wide size distribution, with diameters ranging from a few nanometres to several microns.

It is also far more difficult to develop a single, globally applicable aftertreatment solution for maritime applications, and the range of particle sizes necessitates a more advanced approach to emissions management.

Electric precipitators (EP), diesel oxidation catalysts (DOC), diesel particulate filters (DPF), and wet and venturi scrubbers are some of the technologies that have the highest particle removal efficiency, ranging from 85 to 95%.

Exam paper 2024-2025

A 9-litre, port-injected, ammonia-powered four-stroke engine operates at a steady-state condition of 2000 rpm and full torque of 1500 Nm for 100 hours to evaluate the impact of ammonia on the lubricant oil. The gross indicated specific fuel consumption is 410 g/kW·h. For this 4-cylinder engine, the power required to overcome friction is 0.9 kW, and the ancillary mean effective pressure is 1 bar. The intake manifold pressure is 0.95 bar, while the exhaust back pressure is 1.2 bar.

Calculate the brake mean effective pressure, *BMEP*. [5]

Calculate the gross indicated power, $\dot{W}_{c,ig}$.
[10]

Calculate the mass of fuel required to run the engine for 100 hours, assuming it operates on 100% ammonia (NH_3).
[5]

Solutions

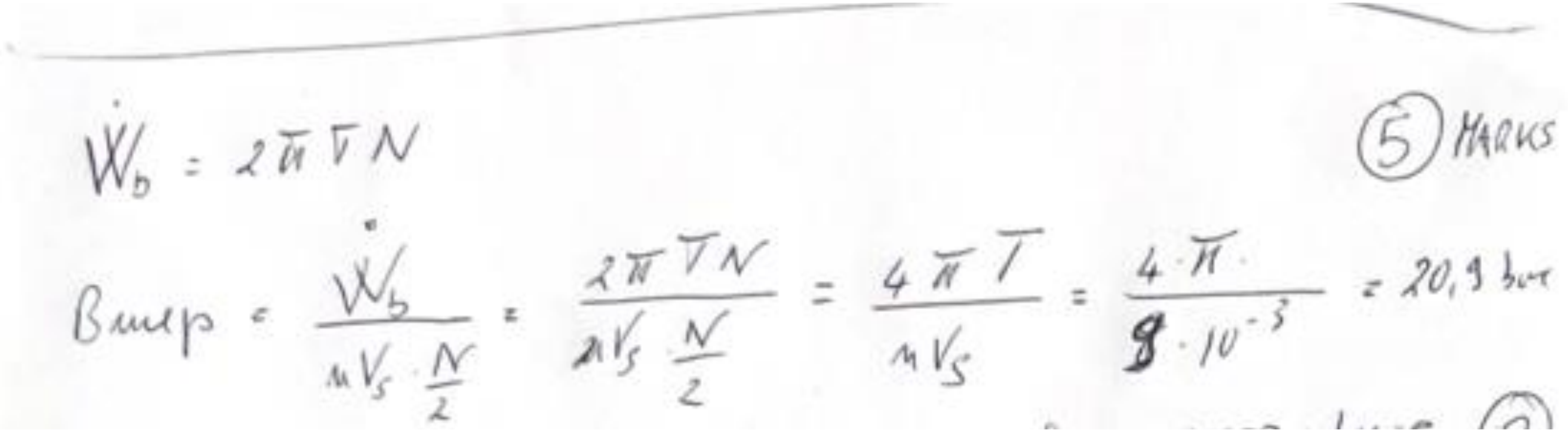
Given data:

- Engine type: 9-litre, port-injected, 4-cylinder, ammonia-powered four-stroke engine
- Engine speed: 2000 rpm
- Torque: 1500 Nm
- Operating time: 100 hours
- Gross indicated specific fuel consumption (ISFC): 210 g/kW·h
- Frictional power: 0.9 kW
- Ancillary mean effective pressure (MEP): 1 bar
- Intake manifold pressure: 0.96 bar
- Exhaust back pressure: 1.2 bar

Calculate

- brake mean effective pressure, *BMEP*
- gross indicated power, $\dot{W}_{c,ig}$
- mass of fuel required to run the engine on 100% NH3 for 100 hours

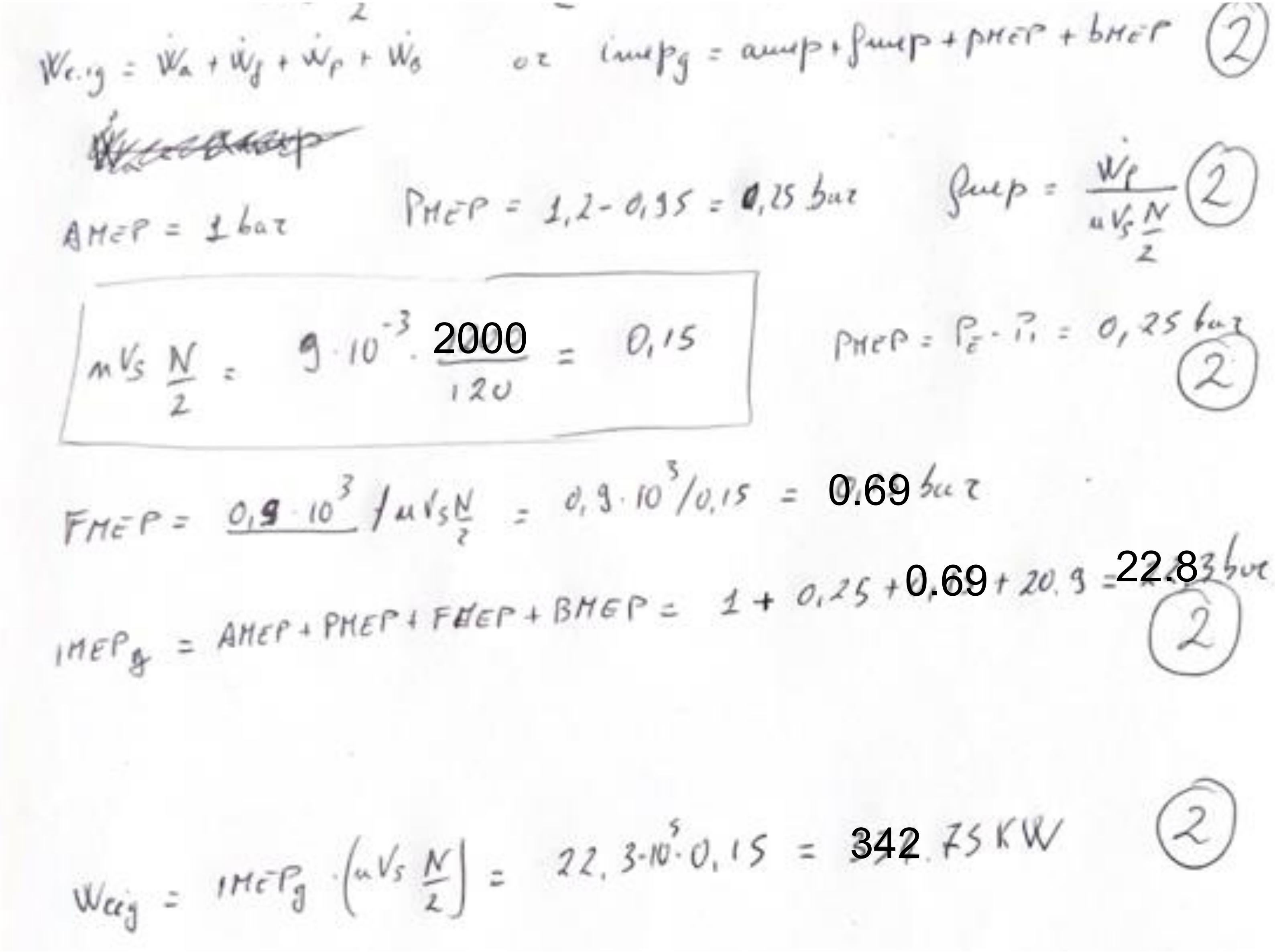
Solutions - brake mean effective pressure, *BMEP*



$\dot{W}_b = 2\pi T N$ ⑤ MARKS

$$Bmep = \frac{\dot{W}_b}{n V_s \cdot \frac{N}{2}} = \frac{2\pi T N}{n V_s \frac{N}{2}} = \frac{4\pi T}{n V_s} = \frac{4\cdot\pi\cdot}{8\cdot 10^{-3}} = 20{,}9 \text{ bar}$$

gross indicated power, $\dot{W}_{c,ig}$



$\dot{W}_{c,ig} = \dot{W}_a + \dot{W}_f + \dot{W}_p + \dot{W}_B$ or $imep_g = amep + fmep + pmep + bmep$ ②

~~$\dot{W}_a$ amep~~

$AMEP = 1\ bar$ $\quad PMEP = 1,2 - 0,95 = 0,25\ bar$ $\quad fmep = \frac{\dot{W}_f}{\eta V_s \frac{N}{2}}$ ②

$$\boxed{\eta V_s \frac{N}{2} = 9 \cdot 10^{-3} \cdot \frac{2000}{120} = 0,15}$$

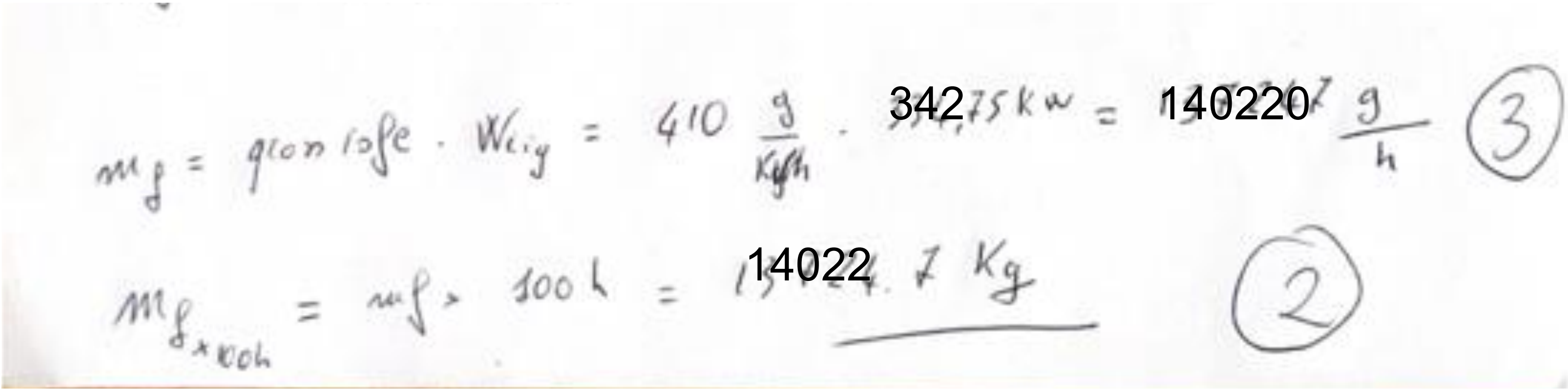
$PMEP = P_E - P_I = 0,25\ bar$ ②

$FMEP = \underline{0,9 \cdot 10^3} / \eta V_s \frac{N}{2} = 0,9 \cdot 10^3 / 0,15 = 0.69\ bar$

$IMEP_g = AMEP + PMEP + FMEP + BMEP = 1 + 0,25 + 0.69 + 20,9 = 22.83\ bar$ ②

$W_{c,ig} = IMEP_g \cdot \left(\eta V_s \frac{N}{2}\right) = 22,3 \cdot 10^5 \cdot 0,15 = 342.75\ KW$ ②

mass of fuel required to run the engine on 100% NH3 for 100 hours



$$m_f = g_{con\,lofe} \cdot W_{c,iy} = 410\,\frac{g}{kWh} \cdot 342,75\,kW = 140220\,\frac{g}{h}$$ ③

$$m_{f \times 100h} = m_f \times 100\,h = \underline{14022.7\ Kg}$$ ②

Exam paper 2024-2025

The net Heat Release Rate (HRR), ($dQ_n/d\theta$), is calculated from measured cylinder pressure data using the equation for the net HRR:

$$\frac{dQ_n}{d\vartheta} = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\vartheta} + \frac{1}{\gamma - 1} V \frac{dp}{d\vartheta}$$

Explain the significance of each term of the net HHR equation.

[6]

Discuss two sources of error in calculating the HRR from experimental data and how they might affect the results.

[6]

Solutions

a) The equation for net Heat Release Rate (HRR) is:

$$\frac{dQ_n}{d\vartheta} = \frac{\gamma}{\gamma - 1} p \frac{dV}{d\vartheta} + \frac{1}{\gamma - 1} V \frac{dp}{d\vartheta}$$

Where:

γ = ratio of specific heats
P = cylinder pressure
V = cylinder volume
θ = crank angleSignificance of terms:

- First term represents work done on the piston. (2marks)
- Second term represents the change in internal energy (2marks)
- Together, they account for the energy released by combustion(2marks)

Two sources of error in calculating net HRR:

1. Pressure measurement errors: (3marks). For example, oressure transducers may have inaccuracies or drift over time. This directly affects both terms in the net HRR equation. Can lead to over or underestimation of heat release.
2. Assumption of constant γ: (3marks) γ actually varies with temperature and composition during combustion. Using a constant value can lead to inaccuracies, especially near the start and end of combustion. This typically results in an overestimation of net HRR early in combustion and underestimation later.

These errors can affect the magnitude and timing of the calculated heat release, potentially leading to misinterpretation of combustion characteristics.