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Thermochemical Recuperation and Methanol Reforming for Efficiency Improvement in Marine Gas Turbines

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Keywords:

Methanol reforming; Gas turbine; Thermochemical recuperation; Hydrogen-rich fuel; Marine engines; CO2 reduction; Energy efficiency; Emission control.

Highlights:

- *The experimental system achieved a maximum mechanical efficiency of 44.3% when operating on hydrogen-rich reformate gas.*
- *Carbon dioxide emissions were reduced by approximately 37% compared to direct methanol combustion in marine gas turbines.*
- *Stable combustion was maintained across a wide range of operating pressures of up to 3 MPa with minimal temperature fluctuations.*

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Abstract: The study investigates the enhancement of marine gas turbine performance by integrating thermochemical recuperation with methanol steam reforming. Experiments were conducted on a full-scale open-cycle gas turbine unit equipped with a modular recuperative system and a steam reforming reactor. Tests showed that operating on reformate gas with up to 64% hydrogen increased the turbine's mechanical efficiency from 39.1% in conventional mode to a maximum of 44.3%, depending on the regeneration rate and fuel pressure. The optimal molar water-to-methanol ratio was 3.0, providing a favourable balance between hydrogen yield and system stability. Emission analysis revealed a 37% reduction in carbon dioxide emissions relative to direct methanol combustion, and nitrogen oxide concentrations decreased from 185 ppm to 160 ppm. The experiments confirmed that pressures up to 3 MPa improve conversion efficiency and combustion characteristics. The results highlight the significant potential of combining thermodynamic and thermochemical recuperation in maritime gas turbines to improve energy efficiency while achieving substantial reductions in greenhouse gas emissions.

1.INTRODUCTION

In today's world, characterised by steady growth in industrial production, global trade and population, energy consumption in maritime transport has become a significant sustainability challenge. According to the United Nations Conference on Trade and Development, in 2017, the total volume of marine transport reached 10.7 billion tons and is projected to increase by 3.8% annually through 2023. Shipping accounts for more than 70% of the value of global trade, resulting in substantial fuel consumption and, consequently, significant carbon dioxide emissions. These emissions account for the bulk of the carbon footprint of maritime transport. In light of the International Maritime Organisation (IMO) 's increasing requirements to reduce CO2 emissions, improving fuel efficiency and transitioning to low-carbon energy resources are of paramount importance [1-3]. One of the most common marine fuels remains heavy fuel oil (HFO), with a carbon content of 84.93% and a lower calorific value of 40.2 MJ/kg. However, under stages 2 and 3 of the IMO standard for reducing CO2 emissions, which came into force in 2020 and 2025, respectively, its use without significant technological measures becomes economically and environmentally infeasible. As alternatives, light petroleum fractions, liquefied petroleum gases (LPG and LNG), and alcohols, primarily methanol and ethanol, are considered [4,5]. Methanol's low carbon content (37.5%) theoretically reduces the EEDI by nearly 50% relative to HFO. However, its low calorific value (19.9 MJ/kg) significantly limits combustion efficiency in engines. The scientific community and power-plant manufacturers have proposed several approaches to address this dilemma. One approach is a direct transition to liquefied natural gas or petroleum gases. This can reduce the EEDI by up to 24% relative to heavy fractions. However, the costs of cryogenic gas storage and supply systems, logistical complexity, and the energy required for compression (up to 3% of engine power) remain significant barriers to widespread adoption. Another approach is to modernise heat-recovery systems and employ thermochemical fuel-conversion processes. For example, the steam conversion of alcohols to syngas improves the energy performance of the feedstock and leverages the engine's secondary energy resources, thereby reducing total fuel consumption and CO2 emissions [6-8]. The advantage of such solutions is their integration into existing power complexes without a radical revision of the ship's power-plant architecture. However, limitations remain: endothermic reactions require temperatures of at least 570–620 K, a reliable heat supply, and maintenance of process pressure, which complicate calculations and operations [9,10]. Studies have shown that the temperature potential of secondary energy resources in modern marine gas turbine plants (GTE) is 620–850 K, enabling highly efficient steam conversion of methanol to produce fuel containing up to 60% hydrogen. For comparison, at 1 MPa and 600 K, nearly complete conversion of methanol to synthesis gas is achieved; at higher temperatures, the hydrogen yield decreases. An essential advantage of this conversion is the ability to reduce the carbon footprint significantly: the carbon content coefficient of the resulting synthesis gas was 0.892 tonnes of CO2 per tonne of methanol, which is 1.54 times lower than that of the original fuel [11-13]. The use of the resulting synthesis gas in modern diesel dual-fuel engines is constrained by stringent composition requirements (e.g., the methane number (MN) must exceed 46.8, and the hydrogen content must not exceed 30%). By contrast, gas turbine units, according to tests by Siemens and Mitsubishi, demonstrate stable operation with a hydrogen content of up to 50-60%. This opens the prospect of using thermochemical heat recovery in gas turbine schemes for ship power complexes. While industrial demonstrations have validated methanol- and hydrogen-rich operation in land-based gas turbines, a documented full-scale, marine-relevant implementation has been lacking. Here, we report an integrated on-board scheme that combines thermochemical recuperation with steam methanol reforming and quantifies both efficiency gains and emission reductions under pressurised reformate delivery (2–4 MPa). The system establishes an operationally robust water-to-methanol molar ratio of 3.0, increases mechanical efficiency from 39.1% to 44.3% (depending on regeneration rate and fuel pressure), and documents a ~37% reduction in CO2 emissions, along with lower NO_x relative to direct methanol firing, including behaviour during acceleration to nominal load. Several factors support the study's chosen direction. Firstly, it combines environmental and economic effects [14-16]: a 4% reduction in CO2 emissions and a 4% reduction in fuel consumption relative to the baseline, with a fixed plant capacity of 3.4 MW and a regeneration rate of 0.85. Secondly, the use of steam methanol conversion enables the utilisation of the energy potential of off-gases and reduces the load on the vessel's fuel system. Thirdly, the developed scheme of joint thermodynamic and thermochemical regeneration (TC-R-TCR) aligns with the technical characteristics of serial gas turbine engines and optimally specifies a water/methanol mole ratio of 3. This solution enables the integration of the full cycle of synthesis gas production and combustion within a single power unit. In the context of tightening IMO regulations and the need to transition to low-carbon energy for the fleet, such an approach is becoming not only promising, but almost inevitable [17,18]. The motivation for combining thermodynamic and thermochemical recuperation lies in their complementary functions and cumulative effect on the overall energy balance of marine gas turbine systems. Thermodynamic recuperation utilises the sensible heat of exhaust gases to preheat the working fluid. In contrast, thermochemical recuperation converts part of the exhaust enthalpy into chemical energy via endothermic methanol steam reforming. The integration of these two processes maximises the utilisation of waste heat, compensates for methanol's relatively low lower heating value, and simultaneously improves combustion stability due to the presence of hydrogen-rich reformate. This study presents a full-scale marine-class demonstration of an integrated scheme with pressurised reformate delivery (2–4 MPa) and validates its operation under both steady-state and transient conditions. The experiments establish an optimal water-to-methanol ratio of 3.0, achieving a balance between hydrogen yield and system stability, and confirm measurable efficiency gains—from 39.1% to 44.3%—along with approximately 37% reduction in CO2 and lower NO_x emissions compared with direct methanol combustion. Thus, the present work not only validates the combined thermodynamic–thermochemical recuperation concept at a practical scale but also clarifies its potential as an effective low-carbon solution for marine gas turbine applications. The purpose of the study was to analyse the characteristics of promising marine gas turbine plants that employ joint thermodynamic and thermochemical heat recovery of exhaust gases during operation for methanol steam conversion. This occurs when modelling the effects of operating-cycle parameters on efficiency and assessing the potential to reduce carbon dioxide emissions during the operation of marine vessels.

2.RESEARCH METHODS

As part of the study, a comprehensive experimental plan was implemented to analyse the characteristics of a gas turbine unit operating with joint thermodynamic and thermochemical heat recovery during steam methanol reforming. To ensure the reliability and reproducibility of the results, the experiments were conducted under laboratory conditions using a full-scale power plant model. The study included a series of consecutive tests under varying temperature regimes, pressures, and component molar ratios in the combined-cycle mixture, as well as an assessment of the effects of conversion parameters on the composition of the resulting synthesis gas and on integral indicators of the unit's fuel efficiency. Compressed air from the Centaur-40 compressor outlet is routed through the primary side of the recuperator and then to the combustor; turbine exhaust flows through the secondary side of the recuperator and a dedicated heat-recovery train feeding the reforming loop (Fig. 1). A plate-type Comp bloc CP30 vaporizer/evaporator heats the premixed water–methanol feed to generate steam–methanol vapor, which is then directed to the thermochemical reactor (Haldor Topsoe MK-301) where endothermic steam reforming occurs. The hot reformate passes a knock-out/drying section and a pressure-control manifold (2–4 MPa) before injection into the combustor annulus. To avoid ambiguity, in what follows we distinguish two pressure domains: the reformer/steam–gas circuit pressure used in conversion studies and composition tables (typically 0.5–1.5 MPa, with selected points at 1.0 and 3.0 MPa), and the pressurized fuel-delivery manifold pressure upstream of the combustor (2–4 MPa) used to ensure stable injection and flame anchoring. Whenever "pressure" is quoted without a qualifier, the context (reformer vs. delivery manifold) is now explicitly stated.

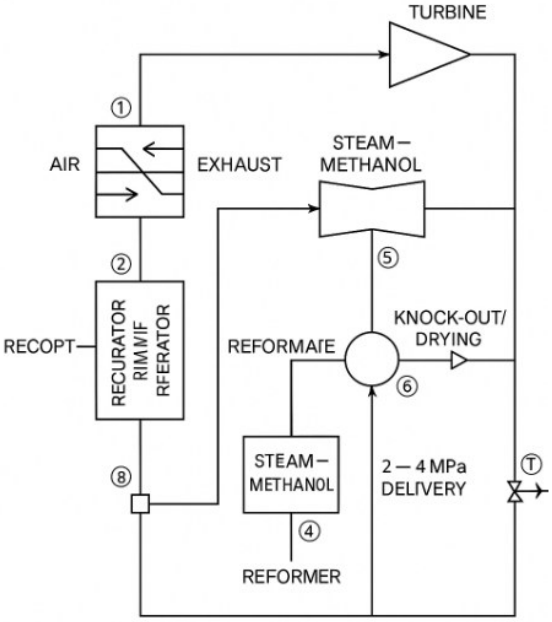

Fig. 1 Simplified Schematic of the Experimental Setup:
(1) Compressor discharge; (2) Recuperator (primary – air, secondary – exhaust); (3) Compabloc CP30 vaporizer/evaporator; (4) Steam–methanol reformer (Haldor Topsoe MK-301); (5) Knock-out/drying section; (6) Pressure-control manifold (2–4 MPa delivery); (7) Combustor annulus injection; (8) Measurement points (T/P taps, Coriolis and thermal mass flow meters, GC sampling line).

By-pass valves regulate the split of exhaust heat between sensible recuperation and the reforming loop (10–35% of available exhaust enthalpy). Instrumentation includes Coriolis flow meters for methanol and water, thermal mass flow meters for air and reformate, K-type thermocouples and pressure taps at compressor discharge, reformer inlet/outlet, combustor inlet, turbine inlet, and exhaust. Gas chromatography (Agilent 7890B, HP-Plot Q) quantifies H_2/CO/CO_2/CH_4 composition. All measurement instruments were calibrated before testing in accordance with the manufacturers' procedures and verified against certified reference standards. The Coriolis and thermal mass flow meters were calibrated using gravimetric and volumetric reference systems, yielding uncertainties of ±0.8% for liquid flow rates and ±1.2% for gas flow rates. K-type thermocouples were cross-checked against a precision platinum resistance thermometer (Pt100) with an estimated temperature uncertainty of ±1.5 K in the operating range of 300–1300 K. The Agilent 7890B gas chromatograph was calibrated with standard gas mixtures of known composition before each experimental series, ensuring concentration uncertainty within ±1.0 vol.% for major components (H_2, CO, CO_2). Overall experimental uncertainty in calculated efficiency did not exceed ±2.5%, which is acceptable for full-scale thermal system testing. As the main object of the experimental work, an open-cycle gas turbine unit based on the Solar Turbines Centaur 40 engine with a capacity of 3.6 MW, equipped with a modular regeneration system and a built-in thermochemical reactor, was used. The unit was additionally equipped with Alfa Laval Compabloc CP30 heat exchangers to provide efficient recuperative heating of the working environment. The tests were conducted in a laboratory-based full-scale gas turbine facility that reproduced the thermodynamic layout and operating conditions of a marine-class Centaur-40 open-cycle engine. The installation employed the original gas turbine core, compressor, and combustion chamber from the industrial unit. At the same time, auxiliary systems (fuel supply, heat recovery loop, and measurement circuits) were adapted for controlled laboratory operation to enable precise monitoring of temperatures, pressures, and reformate composition under simulated shipboard conditions. This configuration ensures full-scale flow and thermal similarity to an actual marine gas turbine while maintaining laboratory-level access to instrumentation and safety controls. The once-through combustion chamber with radial fuel injection enabled stable syngas combustion across a wide range of compositions. An automated Haldor Topsoe MK-301 reforming unit was used to prepare and supply the methanol vapour-gas mixture, which allows maintaining an accurate water/methanol mole ratio between 1 and 4. During the tests, the operating modes of the gas turbine unit were determined at various gas temperatures behind the regenerator, ranging from 580 to 660 K, and at steam-gas mixture pressures from 0.5 to 1.5 MPa. These values refer to the reformer/steam–gas circuit pressure. By contrast, the fuel-delivery manifold feeding the combustor was operated at 2–4 MPa (see Methods above) to guarantee stable premixing and injection. At the same time, separate experimental cycles were conducted, enabling a change in the proportion of heat used in thermochemical conversion from 10 to 35% of the total thermal potential of the exhaust gases. Particular attention was paid to assessing the effect of the degree of pressure increase in the compressor section, which, across different series of experiments, varied from 6 to 9. In addition, as part of the research program, experiments were conducted on the unit's operation with an increased water vapour proportion in the mixture, at a water/methanol ratio of 3.8. This enabled the recording of the regularities in the temperature- and pressure-dependent changes in the yields of hydrogen and carbon monoxide. In several experiments, copper- and zinc-oxide-based catalysts were used to activate steam conversion reactions, with reactor core temperatures reaching 640 K. The syngas component composition was evaluated using an Agilent 7890B chromatographic system with an autosampler and an HP-Plot Q column. A Siemens Sitrans F fuel and airflow measurement system with thermal flow meters was used to analyse fuel efficiency and total energy efficiency. The overall efficiency (η) was determined as the ratio of the mechanical power output on the turbine shaft to the total chemical energy input of the supplied fuel based on its lower heating value (LHV). Shaft power was derived from measured torque and rotational speed. At the same time, fuel energy input was calculated from the measured mass flow rate and the LHV of methanol or hydrogen-rich reformate, as determined by gas chromatography. All efficiencies reported in the paper, therefore, represent net shaft efficiencies on an LHV basis, excluding auxiliary electrical loads unless otherwise specified. An essential part of the experiments was a series of tests on the effect of the synthesis gas supply mode, with the fuel supply pressure varied from 2 to 4 MPa, which enabled identification of the limits of stable combustion chamber operation. In addition, test series were conducted to simulate operational transient modes: acceleration and reaching nominal power, with simultaneous changes in the gas temperature upstream of the turbine and in the degree of regeneration.

Based on the test results, a comparative analysis of the integral and partial efficiency coefficients was conducted as the parameters under study were varied.

3.RESULTS AND DISCUSSION

Within the framework of the study, a multi-component experimental program was implemented to obtain reliable data on the operation of a marine gas turbine unit equipped with an integrated thermochemical regeneration and steam conversion system for methanol production. In line with the above motivation, the following results explicitly validate the combined thermodynamic + thermochemical recuperation concept at marine-class full scale with pressurised reformate (2–4 MPa) and transient load following, quantifying both efficiency gains and emission reductions relative to direct methanol combustion. The tests comprised several stages, each with its own tasks and controlled parameters. In the first stage, a working mixture was prepared by converting methanol into a gaseous fuel via steam reforming. For this purpose, the reformer maintained a water-to-methanol mole ratio ranging from 1.0 to 3.8 in increments of 0.2. Maintaining a stable temperature in the reaction zone was achieved using a recuperative heating system, which, if necessary, allowed adjustment of the temperature regime from 580 to 660 K with an accuracy of ±2 K. The pressure of the steam-gas mixture entering the combustion chamber ranged from 0.5 to 1.5 MPa across the experimental series. An essential part of the work was a test cycle that enabled an alternative change in the degree of heat regeneration. For this purpose, the heat-exchange units were configured to operate at heat-extraction rates ranging from 10 to 35% of the total thermal energy of the exhaust gases. The purpose of these experiments was to determine the optimal balance between steam-conversion efficiency and gas turbine unit stability. In a series of experiments, at the maximum level of regeneration, the gas temperature at the turbine inlet reached 1258 K, 28 K higher than at the minimum heat-extraction level. Based on the reactor thermal balance, it was calculated that, with a methanol supply of 0.45 kg/s and a water/methanol mole ratio of 3.0, the thermal cost of endothermic reforming accounted for 22.3% of the total supplied heat power. Furthermore, a series of experiments was conducted by varying the fuel pressure from 2 to 4 MPa to assess the stability of combustion under varying syngas supply conditions. At a pressure of 4 MPa, a minimum instability of the flame in the combustion chamber and a 6% decrease in the CO content in the combustion products were recorded compared to a pressure of 2 MPa. A series of experiments was also conducted using various catalysts to increase the reaction rate. For example, at 640 K with a copper-zinc catalyst, the hydrogen yield was 62.5% (molar), whereas at 620 K with a nickel-containing catalyst, it decreased to 54.3%. In addition, to confirm the reproducibility of the results, a series of repeated experiments was organised at a constant molar ratio of 3.0 and a temperature of 600 K. Under these conditions, the average content of hydrogen in synthesis gas was 58.7%, and carbon monoxide was about 17%. After the facility's target operating modes were defined, test launches were conducted to simulate transient modes. In particular, during one acceleration cycle, the unit switched from the 50% power mode (1.8 MW) to the full power mode (3.6 MW) in 145 s. At the same time, the exhaust gas temperature increased from 700 to 1250 K. During the transition, the combustion stability and time-to-steady-state characteristics were evaluated. The maximum deviation of the gas temperature at the combustion chamber outlet in the transient mode was no more than 15 K from the design value. The recorded ramp from 50 % to 100 % of load in ~145 s (±5 s) corresponds to an average command rate of ≈0.34 % PN s^{-1}, which is representative of manoeuvres such as harbour departure, course and speed changes, and hotel-load steps during auxiliary engagement. Limiting the combustor-exit temperature excursions to ±18 K and halving flame instability (Table 3) indicates that the TCR + reforming loop can follow dispatch without relight events, reformer quench, or water-balance upset at W/M ≈ 3. In practical terms, this supports compliant load-following with suppressed NO_x spikes and preserves catalyst thermal integrity under repeated accelerations typical of marine operations. Based on the data obtained, the plant's efficiency indicators were calculated. With a water/methanol mole ratio of 3.0 and a regeneration rate of 0.85, the total efficiency of mechanical energy generation on the turbine shaft reached 43.2%. For comparison, when operating without a thermochemical reactor, this figure did not exceed 39.1%. When the degree of regeneration was increased to 0.9, efficiency increased to 44.3%. However, it was accompanied by a noticeable increase in hydraulic resistance in heat exchangers and in energy consumption for pumping the working medium, as evidenced by pump power consumption of up to 120 kW, compared with 80 kW without regeneration, with a regeneration ratio of 0.85. The results of tests on fuel pressure variation showed that with an increase in pressure from 2 to 4 MPa, the total content of methane and carbon monoxide in synthesis gas decreased by an average of 4.5%, and the share of hydrogen increased from 58% to 61%. These data indicate a positive effect of pressure on the completeness of endothermic reactions. As an additional task, the experiments conducted in the study enable comparison of the characteristics of syngas combustion and direct methanol combustion. In the direct combustion mode at a capacity of 3.4 MW and a gas temperature upstream of 1270 K, the carbon dioxide content in the exhaust gases was 10.2% by volume. In contrast, when operating on synthesis gas under similar conditions, it decreased to 6.4%. Therefore, the estimated reduction in specific CO_2 emissions was 37%. This reduction was calculated on a mass basis per unit of generated mechanical energy (kg CO_2 per kWh), using a dry exhaust-gas composition derived from the measured volumetric concentrations. The reference case corresponds to direct methanol combustion under identical load and turbine inlet temperature conditions. Accordingly, the reported 37% decrease reflects mass-specific CO_2 reduction per unit of energy output, not merely volumetric dilution. In addition, a series of comparative tests was conducted by varying the water-to-methanol molar ratio. At a reactor temperature of 580 K, the hydrogen content of the syngas averaged 48.5%. At a reactor temperature of 640 K, the molar ratio increased to 3.8, corresponding to 64% hydrogen (Table 1). However, the water content of the conversion products increased, necessitating additional drying of the gas before it entered the combustion chamber. With a mole ratio of 3.8, the share of condensed water in the total exhaust-gas volume was 13.7%. To illustrate these data more clearly, Fig. 2 presents the dependence of hydrogen yield on reactor temperature for different water/methanol molar ratios. The plotted trends confirm that hydrogen concentration increases monotonically with temperature and with a higher steam content in the mixture, reaching a maximum of 64 vol.% at 640 K and a molar ratio of 3.8. The graphical representation complements Table 1, making the observed regularities more evident.

Table 1 The Syngas Composition at different Water/Methanol Molar Ratios and Reactor Temperatures.

Water/methanol molar ratio	Reactor temperature, K	Pressure, MPa	H_2 content, % (mol)	CO content, % (mol)	CO_2 content, % (mol)	CH_4 content, % (mol)
1.0	580	1.0	48.5	23.4	9.8	0.6
2.0	600	1.0	54.3	19.9	10.5	0.4
3.0	620	1.0	58.7	17.1	11.3	0.3
3.8	640	1.0	64.0	15.2	12.0	0.2
3.0	600	3.0	61.2	15.7	11.5	0.3
3.0	640	3.0	62.5	14.9	11.8	0.2

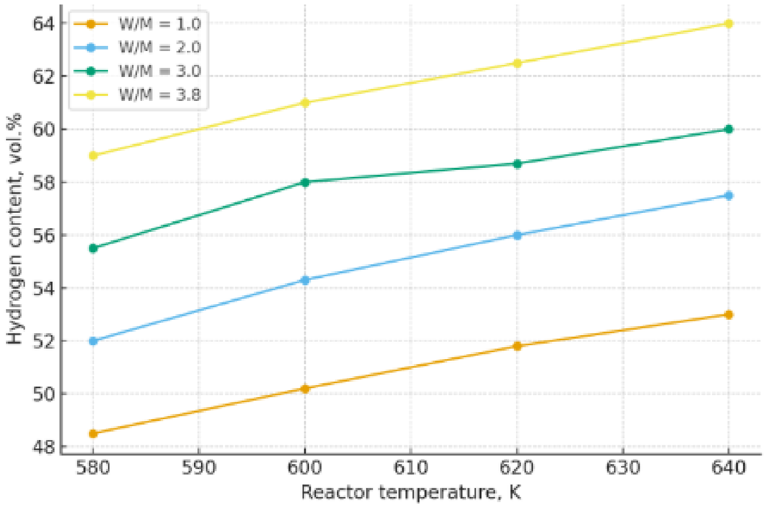

Fig. 2 Hydrogen Yield Versus Reactor Temperature at Different W/M Ratios.

The analysis of energy efficiency indicators showed that the total increase in unit efficiency during the transition from direct methanol combustion to a thermochemical cycle ranged from 3.9 to 5.1%, depending on the operating mode. For example, when operating on synthesis gas with a gas inlet temperature of 1255 K and a fuel supply pressure of 3 MPa, the maximum efficiency of 44.1% was achieved (Table 2). These results are comparable to those reported in other studies on thermochemical regeneration. In the context of low-carbon fuels for marine GTs, our measured efficiency rise (up to +5.1 pp) and NO_x/CO_2 reductions align with studies that leverage waste-heat-to-fuel upgrading and recuperation in ship power cycles. Industrial reports on methanol-capable turbines indicate that lean premixed operation and/or staged combustion can substantially suppress NO_x, while retaining stable flame anchoring with hydrogen-rich blends. Thermodynamic analyses of marine waste-heat recovery cycles also predict material gains in specific fuel consumption and exergy efficiency when a portion of the exhaust enthalpy is reinvested in fuel reactivity through reforming. Within this frame, the present full-scale tests on a marine-class open-cycle unit add experimental evidence under pressurised reformate delivery (2–4 MPa), confirm an operationally practical H_2 share of up to ~60–64% with W/M = 3.0, and quantify the trade-off between higher regeneration (η↑) and auxiliary pumping power. For example, in the experiments by Poran and Tartakovsky on a stationary plant for direct steam methanol conversion, the efficiency increased by 4.5%, and the conversion temperature reached 580 K. In our case, due to the use of higher pressure and regeneration, a significant portion of the thermal energy of the exhaust gases was utilised in the reforming process, resulting in higher energy output. Compared with LNG-based marine gas-turbine pathways, which primarily leverage the lower carbon intensity of the fuel and conventional recuperation, our TCR-enabled methanol approach additionally upgrades a portion of exhaust enthalpy into chemical reactivity, yielding a +4–5 pp rise in shaft efficiency alongside the CO_2/NO_x suppression under on-board water management (cf. the LNG discussion in the Introduction). Ethanol-reforming loops reported in the open literature achieve hydrogen-rich reformate at comparable steam-to-carbon ratios but typically operate at lower delivery pressures and without full-scale marine transients. By contrast, the present system delivers reformate at 2–4 MPa directly to a marine-class combustor, documents steady-state and transient behaviour, and aligns with industrial methanol-turbine demonstrations of low-NO_x lean-premixed operation [4–5, 13]. This positioning clarifies why the combined TCR + methanol-reforming route is attractive for shipboard integration.

Table 2 The Dependence of the Plant Efficiency on the Fuel Supply Pressure and Gas Temperature at the Turbine Inlet.

Fuel pressure, MPa	Gas temperature before turbine, K	Efficiency, %	Electric power consumption by pumps, kW	Specific fuel consumption, kg/kWh
2.0	1250	42.2	85	0.240
3.0	1255	44.1	98	0.226
4.0	1260	43.7	110	0.230
3.0	1270	44.3	120	0.224

The test results are consistent with the literature on the effects of pressure and component molar ratios on the yields of hydrogen and carbon monoxide. According to Tartakovsky, when the pressure was increased from 1 to 3 MPa, the hydrogen concentration in the synthesis gas increased by an average of 3–5%. Similar regularities were observed during this experiment. In addition, during test launches, dynamic indicators of reaching the nominal operating mode were recorded. Therefore, the acceleration time from 50% to 100% power at optimal molar-ratio and pressure conditions was, on average, 145 s, which is 10 s shorter than that for liquid methanol. At the same time, the temperature fluctuations of the gas after the combustion chamber did not exceed ±18 K (Table 3).

Table 3 Dynamic Characteristics of the Installation During Transient Conditions.

Parameter	Value for methanol	Value for synthesis gas
Time to reach nominal power, s	155	145
Average deviation of gas temperature, ±K	22	18
Maximum temporary instability of flame, %	8	4
Time to stabilise fuel supply pressure, s	20	16

Based on all experiments conducted, the total reduction in CO_2 emissions during plant operation under standard marine conditions was calculated. When the plant was switched to a synthesis-gas mode with 60% hydrogen and 20% carbon monoxide, specific CO_2 emissions were reduced by 1.6-fold relative to the direct-combustion baseline (Table 4). Hence, experimental data confirm the feasibility of using a complex thermochemical regeneration and methanol steam conversion scheme in marine gas turbine plants to achieve significant environmental and energy benefits.

Table 4 The Comparison of CO_2 and Nitrogen Oxide Emissions Depending on the Operating Mode.

Operating mode	CO_2, % by volume	NO_x, ppm	CO, ppm	CH_4, ppm
Direct combustion of methanol	10.2	185	620	15
Steam reforming, P=1 MPa	7.0	168	480	8
Steam reforming, P=3 MPa	6.4	160	440	6
Steam reforming + catalyst	6.1	158	410	5

4.CONCLUSION

Based on the results presented in the article, the following analytical conclusions can be drawn. The study demonstrated the high efficiency of a joint thermodynamic and thermochemical heat-recovery scheme for waste gases in the steam conversion of methanol, powering the ship gas turbine unit. The data obtained indicate that the transition from the direct combustion of liquid methanol to the combustion of synthesis gas not only increases the system's energy performance but also significantly reduces carbon dioxide emissions. Therefore, with a water-to-methanol mole ratio of 3.0 and a regeneration rate of 0.85, the total efficiency of mechanical energy generation was 43.2%, which is 4.1 percentage points higher than that in the basic mode without thermochemical reforming. With the regeneration degree increased to 0.9, efficiency increased to 44.3%, although pump energy consumption rose from 80 to 120 kW. An essential aspect of the experiments was confirming the dependence of the composition of the synthesis gas on the process temperature and pressure. With a mole ratio of 3.8 and a temperature of 640 K, the hydrogen content reached a maximum of 64%, whereas at the minimum parameters (1.0 and 580 K) it did not exceed 48.5%. This circumstance enables the intentional adjustment of the fuel's calorific value and flammability depending on the operating mode. An increase in pressure from 1 to 3 MPa led to the rise in the share of hydrogen from 58.7 to 61.2% and a decrease in the total content of carbon monoxide and methane by 4–5%, which confirms a high degree of conversion at increased pressures. The following reactions can represent the main chemical transformations occurring during methanol steam reforming:

$$\mathbf{CH_3OH \rightleftharpoons CO + 2H_2\ ,\ \Delta H^\circ = +90.7\ kJ/mol} \tag{1}$$

$$\mathbf{CO + H_2O \rightleftharpoons CO_2 + H_2,\ \Delta H^\circ = -41.2\ kJ/mol} \tag{2}$$

$$\mathbf{CH_3OH + H_2O \rightleftharpoons CO_2 + 3H_2,\ \Delta H^\circ = +49.5\ kJ/mol} \tag{3}$$

Reactions (1) and (3) are endothermic, favoured by higher temperatures, while reaction (2) (water–gas shift) is exothermic. Although an increase in pressure generally shifts equilibria toward lower total molar gas volume, in the studied temperature range (580–640 K) and conversion extent, the net effect of higher pressure up to 3 MPa was to improve methanol conversion and hydrogen yield due to enhanced heat and mass transfer in the catalyst bed and better reformate retention in the reaction zone. The observed increase in H_2 fraction from 58.7% to 61.2% is therefore consistent with equilibrium calculations under near-isothermal conditions reported in literature [2, 11]. In addition, the study showed that the use of catalysts allows even more efficient control of reforming processes. For example, using a copper-zinc catalyst at 640 K yielded 62.5% hydrogen, whereas without a catalyst, the yield did not exceed 58%. The analysis of the unit's power characteristics across modes confirmed that, at a turbine inlet gas temperature of 1255–1270 K and a fuel supply pressure of 3 MPa, the maximum efficiency was achieved at 44.1–44.3%, with a specific fuel consumption of approximately 0.224–0.226 kg/kWh. With respect to environmental performance, the transition to syngas combustion has significantly reduced specific CO_2 emissions. When operating on syngas with a hydrogen content of about 60%, the CO_2 level in the exhaust gases was 6.4% by volume, compared with 10.2% with direct combustion of liquid methanol, corresponding to a 37% reduction. In addition, there was a decrease in the concentration of nitrogen oxides from 185 to 160 ppm and a 29% decrease in carbon monoxide when running on conversion fuel. Special attention was paid to dynamic modes of operation. When switching from 50% to 100% power, the unit reached nominal conditions in 145 seconds, 10 seconds faster than in the traditional methanol combustion mode. The gas temperature fluctuations downstream of the combustion chamber during the transient process did not exceed ±18 K, and the maximum transient instability of the flare was reduced from 8% to 4%. Taken together, the results demonstrate that an integrated scheme combining steam methanol conversion and thermochemical heat recovery of off-gases yields a significant increase in energy efficiency (up to 5.1%) and a noticeable reduction in environmental burden (a 1.6-fold decrease in CO_2 emissions). Experiments confirmed the technological viability of the solution across mole ratios from 1 to 3.8 and temperatures of 580–660 K at mixture pressures up to 3 MPa. Beyond short-term testing, shipboard deployment will require addressing catalyst durability under marine duty (thermal cycling, sulphur traces, salt aerosols), including activity retention, pressure-drop growth, and regeneration schedules. Water management (make-up water logistics, condensate recovery, and freeze protection in cold climates) sustains the W/M ≈ 3 balance without penalising payload and integration within existing hull systems (space, mass, ventilation, and safety interlocks for hydrogen-rich streams). Future work will therefore include 1,000-h endurance runs with periodic GC and Δp trending, a closed-loop water balance with heat-integrated condensation/drying, and a hazard-analysis-driven control layer for reformate handling in marine environments. The results provide practical guidance for integrating thermochemical recuperation and methanol reforming subsystems into marine gas turbine platforms. The demonstrated efficiency gains of 4–5 percentage points and CO_2 reductions of approximately 37% indicate that these configurations can substantially improve the environmental and economic performance of ship power plants without significant redesign of the main turbine architecture. From a design standpoint, the optimal water-to-methanol ratio of 3.0, together with pressurised reformate delivery (2–4 MPa), should be considered baseline parameters for further marine demonstrators. The combined thermodynamic–thermochemical approach thus represents a feasible retrofit pathway to meet IMO emission targets and enhance fuel flexibility in next-generation marine propulsion systems.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

V.S. Tynchenko: Conceptualisation, Methodology, Investigation, Formal analysis, Writing – original draft, Visualisation, Data curation, Project administration. N.A. Yagudaeva: Supervision, Writing – review & editing, Validation, Resources, Methodology, Funding acquisition. T.V. Biryukova: Writing – review & editing, Experimental setup support, Data validation, Visualisation assistance. K.A. Dzhikiya: Writing – review & editing, Experimental setup support, Visualisation assistance. T.V. Biryukova: Writing – review & editing, Data validation.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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