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Development of Hybrid CNG/Diesel Dual-Fuel Engine in High Load Condition for Marine Debris Vessel

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Abstract

Greenhouse gas (GHG) emissions are the most influential issue in the transportation sector in recent years due to their impact on the environment. Thus, the design of transportation power plants is necessary to ensure the lowest GHG emissions. However, the development of a small vessel power plant is discussed in this study. The small vessel is a marine debris working vessel that has the purpose of collecting marine debris on the water surface with a conveyor. This vessel is designed with a dual-fuel engine fueled by natural gas from CNG and diesel fuel in high load conditions. Furthermore, the power system is designed with a systematical assessment condition based on the operational condition. Moreover, an experiment was conducted to study the performance and emissions of the engine. The hybrid system is designed with several operational conditions, such as sailing, collecting, and maneuvering. Most of the operations can be used in the hybrid dual-fuel system with nearly similar engine torque to diesel mode. The dual-fuel hybrid system has a significantly low engine fuel consumption with low CO2 emissions, especially at 3 kW and 2200 rpm about 3,2%. However, relatively high NO2 and CO emissions are still considerable. The NO2 emissions are low at 4 kW and 2200 rpm by about 21 ppm but are still 38% higher than at the 3 kW. Moreover, the CO emissions are low at 4 kW and 2100 to 2200 rpm about until 14,2% reduction.

1. Introduction

Marine vessels have been observed for GHG emissions contribution, which is harmful to the environment. The GHG emissions produced on the vessel are mainly from the propulsion engine, with most of the vessel using a diesel engine. Most of the diesel engines on marine vessels generate NOx (Nitrogen Oxides), SOx (Sulfur Oxides), COx (Carbon Oxides), and PM (Particulate Matter) emissions depending on the main fuel used [1], [2]. These emissions should be reduced significantly to decrease the risk to human health and climate change [3]. Besides, the diesel engine is difficult to replace on the marine vessel due to the high efficiency and higher-power output than other internal combustion engines [4]. Thus, a diesel engine's existence is still more considerable on the vessel than environmentally friendly power sources such as solar and wind power are proposed in terms of low GHG emissions. However, the high capital cost and low efficiency of renewable energy devices are still being studied to ensure their high feasibility [5].

Reducing the GHG emissions on vessels with diesel engines is still considered to lower the environmental impact rather than converting to another power source. At least the IMO (International Maritime Organization) mandated new ships with EEDI (Energy Efficiency Design Index) and SEEMP (Ship Energy Efficiency Management Plan) [6]. The EEDI and SEEMP are efficiency strategies for a ship′s design and operation, respectively, that can be useful to increase the energy efficiency of the shipswhich can reduce GHG emissions. Moreover, the existing vessel can be retrofitted using an after-treatment device on the engine exhaust gas system, for example, an engine scrubber [7] and EGR (Exhaust Gas Recirculation) [8]. The engine scrubber can reduce SOx emissions significantly on diesel engine exhaust gas emissions. Furthermore, EGR can recirculate the exhaust gas to be mixed with fuel and air and re-combusted for a cleaner exhaust gas with lower NOx emissions. Nevertheless, attaching the after-treatment device is still feasible only on large ship tonnage, especially for scrubbers. Moreover, most of the EGR is already packaged with the engine system when purchased for new shipbuilding. Thus, an after-treatment device is quite optional based on the cost even from capital cost or operational cost [9]. Another option to reduce GHG emissions is converting or blending the diesel fuel to other alternative fuel for the combustion process [10-12]. Many alternative fuels have their characteristics on the combustion then affect the emissions produced. The diesel engine can use bio-diesel, methanol, ammonia, or natural gas as the main fuel in a single or dual-fuel mode. Combined natural gas and diesel fuel as dual-fuel in the diesel engine can be a solution to develop a vessel propulsion system due to an abundant source of natural gas fuel which has a main fuel composition of methane [13-15]. Natural gas can be stored as LNG (Liquid Natural Gas) or CNG (Compressed Natural Gas). The LNG is stored in very low-temperature conditions in the liquid phase at atmospheric pressure and the CNG is stored in a high-pressure gas tank at room temperature.

The dual-fuel engine utilization on vessels has been implemented and continuously will be improved for several years later. The dual-fuel engine is very attractive on emissions with high engine performance at high load conditions compared with diesel fuel [16]. The NOx and PM emissions are reduced significantly on dual-fuel engines than the dedicated diesel engine [17]. It leads to producing cleaner combustion and lowers the emissions contribution from the marine vessel to improve the environment. However, the CO and HC emissions need to improve in the dual-fuel engine, both in low and high load conditions [18]. Besides, it can be lowered in the engine as mentioned in several studies [18-20]. The high amount of CO and HC emissions in dual-fuel engines can be reduced with higher diesel fuel substitution [21], advancing the diesel injection timing [22], or attaching an after-treatment device to the engine [8]. The dual-fuel engine can be used in high load conditions with less modification on the system compared with the dedicated diesel engine. Although, several studies mentioned that the knocking phenomenon should be considered on the high load dual-fuel engine operation [2]. However, a proper diesel/natural gas fuel ratio can be attractive for the engine operated in high load conditions with less knocking [23]. Most marine vessels avoid engine operation in low-load conditions thus dual-fuel engine is more applicable in high loads condition.

In the case of a small vessel, it also contributes to GHG emissions even in a small amount, but it can be equivalent if it is built in a large number. However, reducing GHG emissions on small vessels is also challenging due to the cost and environmental issues [24]. A marine debris vessel is mostly a small-sized vessel that has the purpose of collecting water surface debris such as plastic garbage. In recent years, the popularity has increased due to the high concentration of marine debris in the ocean from the shore and river flow [25-27]. The production of it is in high demand for small and large capacities, thus it should be designed carefully considering the emissions that can be produced. A marine debris vessel has at least three main operational conditions, sailing, collecting, and maneuvering [27]. Collecting debris on the water surface dynamically is the main purpose of the marine debris vessel. Thus, it has more priority on the system developed, the system should support the performance of collecting the debris flexibly. Moreover, it only needs a small power source in a high load condition for the operational condition, the operational condition is mostly in low-speed dynamic propulsion. Hybrid propulsion is compatible with dynamic propulsion which has superior characteristics in the power, propulsion mode, and cost than fully operated in an electric mode [28-30].

However, there are only a few studies on small vessel propulsion systems such as marine debris vessels which also contribute to GHG emissions. Moreover, most of the studies about marine debris technology have a low identification of the system on the marine debris vessel. This study developed the design of a hybrid dual-fuel engine with several operation conditions which also identified the performance and emissions. A hybrid diesel power system with natural gas and diesel fuel for the main propulsion on the small vessel was developed based on the operational condition. The operational condition is based on the working condition of the specific engine loads. Sailing, collecting, and maneuvering are the main working conditions that are assessed on the system equipment used. The propulsion system design is focused on power system development. The energy efficiency is calculated based on the system requirements of the operations. Furthermore, an experiment was also conducted to study the hybrid diesel engine performance and emissions in several variables.

2. Methods

The development of the dual-fuel hybrid system is focused on the power system which is driven by a small marine debris vessel. Moreover, the design is combined with a static experiment on the high load condition. The experiment is conducted in non-operational conditions and hence projected based on workload at high energy demand. The vessel which is projected for energy utilization is a small marine debris vessel that is described in this section.

2.1. System Design Development

The developed system is a hybrid system that combines a diesel generator with other electric energy power sources. However, this study is focused on diesel generator development and another electric energy source using batteries that are designed for partial power output. Besides, the vessel design and working conditions are briefly described.

2.1.1. Vessel Specification

The vessel used in this study is a small marine debris vessel that is also under development. The specification is described briefly and it has already been discussed extensively in another study [31]. Table 1 shows the specification of the vessel which has been developed. The vessel is a catamaran vessel that has two main hulls with a very low block coefficient. Moreover, the vessel has a conveyor in the front of the vessel at a 20° angle and is precisely attached in the middle with a wing rack in the front of it to collect the debris on the water's surface. Moreover, the vessel is propelled by two propellers which are powered by an electrical motor. However, the dimension and specification of the propulsion system (electrical motor to the propeller) will be discussed in future studies. A further detailed specification of the vessel is reported in another study [31].

Table 1. Vessel Main Dimension

Parameter	Symbol	Details	Unit
Hull type	-	Catamaran	-

Hull dimension			
Length perpendicular	Lpp	3.95	m
Length of water line	Lwl	3.85	m
Length overall	Loa	4.00	m
Draft	T	0.30	m
Height	H	0.60	m
Block coefficient	Cb	0.25	-
Conveyor dimension			
Conveyor length	Lc	1.63	m
Conveyor angle	La	20.0	deg

2.1.2. Machineries System

In this study, the discussed system machinery is focused on the power plant of the vessel. Figure 1 depicts the power system design on the vessel with the equipment support. The diesel generator is the main power source in the system, it is projected to be adequate for the whole energy of the whole operation. Besides, the battery is mainly used as a standby system for propulsion in case of emergency while operating in uncontrolled conditions and for electronic control units (ECU) with very low energy requirements. However, the battery can be charged by the generator while the generator is operating. The diesel generator is used in dual-fuel mode using CNG fuel as the main fuel combined with diesel fuel. A gas and diesel tank is prepared for the vessel with the outfitting arrangement. The gas tank system is connected to the engine with a regulator valve, pressure gauge, flowmeter, and emergency safety device. The gas flow is also regulated by an ECU thus the injection timing is used in a proper configuration on the load condition. Meanwhile, the diesel tank is attached to the engine and the flow is regulated by a governor with a fixed injection timing.

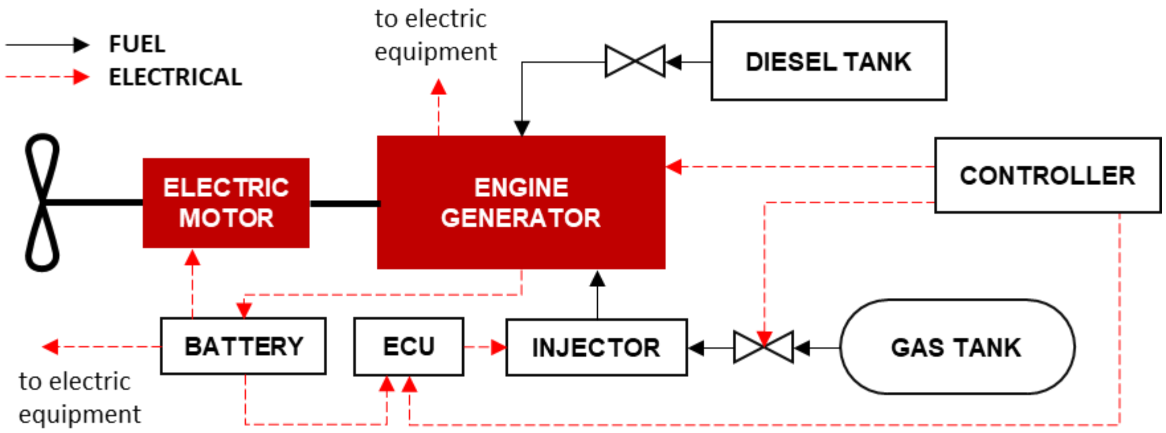

Figure 1. Power System Design on The Vessel

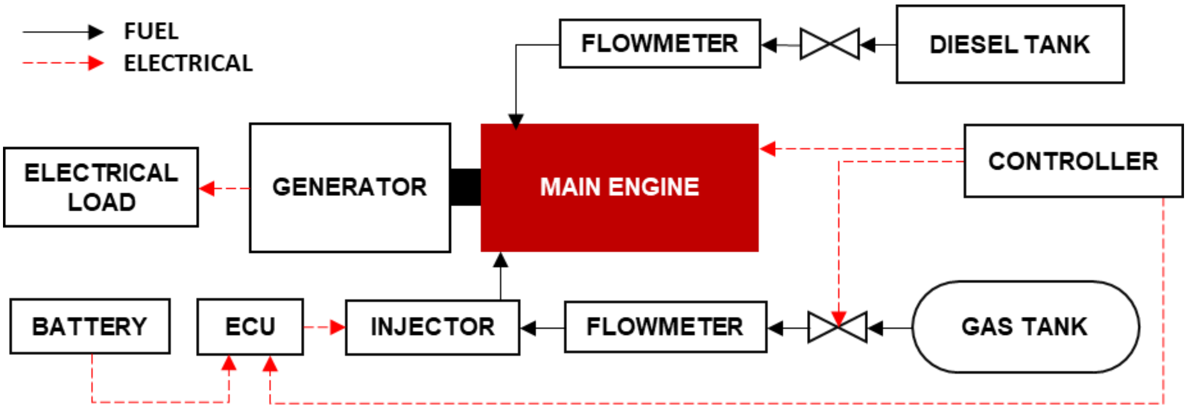

Figure 2. Engine Test Arrangement

2.2. Experiment Setup

This study also experimented with the hybrid dual-fuel engine to evaluate the engine performance and emissions. The experiment is necessary since the engine is developed with separate equipment to ensure all of the components work properly. It is conducted in the experiment setup adjustment which includes the required test equipment.

Table 2. Engine Specification

Parameters	Specification	Unit
Engine Type	Diesel Engine	-
Cooling System	Water Cooling System	-
Number of Cylinders	Single Cylinder	-
Injection Type	Direct Injection Diesel	-
Air Flow	Naturally Aspirated	-
Diesel Injection Pressure	120	MPa
Compression Ratio	18:1	-
Maximum Power Output	5.96	kW

An experiment is conducted with an engine setup and test arrangement as Figure 2. However, there is main equipment is used such as the main engine which is connected to the electric generator, the fuel system, and the test acquisitions. The main engine used in this experiment is a converted diesel engine to a dual-fuel engine using CNG and diesel fuel, the detailed engine specification is shown in Table 2. The engine is a single-cylinder diesel engine with a natural aspirated flow, direct injection diesel, and water-cooled. Diesel injection is about 120 MPa, maximum engine power output is 5.96 kW, and the engine compression ratio is 18:1. The engine is connected to a generator and it is also connected to the electric load for the loading condition test. The diesel fuel is injected into the diesel engine directly into the combustion chamber. Besides, the CNG is injected into the intake port on the engine and controlled by the ECU. Moreover, flow meters are attached to the fuel lines to measure the fuel flow. The engine is tested at several engine speeds and it is measured with an independent tachometer. The engine performance which is tested is the engine torque and engine fuel consumption or specific fuel consumption (SFC). Furthermore, the engine emissions tested in the experiment are carbon dioxide (CO2), carbon monoxide (CO), and nitrogen dioxide (NO2). However, the engine equipment detail was reported in another study [12]. However, the test is conducted in high load conditions, 3 kW and 4 kW.

3. Results and Discussion

A small vessel power plant system is developed, especially on a small marine debris vessel type using a hybrid dual-fuel engine. The system is mainly designed with the highest engine load requirement thus it can be operated in any working condition with a certain operation procedure. However, in this section, the design of the system operation and experiment are discussed.

3.1. Design of The System Operation

The vessel power plant development is based on the highest power requirement for the operation. Table 3 shows the operational condition of the vessel with the working load specification. Moreover, it shows the energy source options which are needed for the operation. At least, there are three operational conditions are proposed for this vessel such as sailing, collecting, and maneuvering. Sailing is an operation in which the vessel goes to the target area at a specific distance before the debris-collecting process. A propeller work is a dominant load required during the sailing operation with a medium load requirement from the power plant and it can be used for the dual-fuel diesel generator only. Afterward, the operation in the target area is collecting which is the main operational design of the vessel. In this operation condition, the propeller and conveyor are working independently at the same time thus high power is required. With high power output, the dual-fuel diesel generator is the main power source for the operation to achieve high efficiency. Furthermore, the vessel has a maneuvering operation condition which is additional vessel movement other than sailing and collecting which is necessary. This condition only uses the propeller for the operation and it only requires a low power load thus it can be operated with a dual-fuel diesel generator or battery.

Table 3. Vessel Operational Conditions

Operational	Main Equipment	Load	Energy Source
Sailing	Propeller	Medium	Hybrid engine
Collecting	Propeller Conveyor	High	Hybrid engine
Maneuvering	Propeller	Low	Hybrid engine Battery

Nevertheless, low load conditions on the operational condition should be avoided due to multiplier consequences for the power plant system, especially when using the dual-fuel engine [32-34]. It is reported in another study that low-load engine operation lowers thermal efficiency which implies that the combustion is dominantly incomplete [35]. Thus, it increases fuel consumption and leads to higher GHG emissions concentrations. Another study also stated that the methane slip or the unburned hydrocarbon significantly increases in low-load conditions [20]. However, many options can be applied to overcome those conditions such as regulating the fuel-energy ratio, applying an injection strategy, or attaching an after-treatment device. Increasing the diesel fuel mass in low-load conditions increases thermal efficiency and lowers methane emissions [36]. Moreover, certain injection strategies such as perfect injection timing, injection duration, and split injection also increase thermal efficiency [37]. Also, adding the after-treatment such as exhaust gas recirculation (EGR) can re-combust the methane slip and lowers the unburned methane emissions [8]. Besides, this strategy is difficult to adjust if the engine is unpacked with self-response control and it is complicated in the case of the in-field application.

3.2. Experiment with The System on High-Load Operation

The engine performance and emissions are reported in this study such as engine torque, fuel consumption, NO2 emissions, CO2 emissions, and CO emissions. The experiment was conducted in dedicated diesel mode and dual-fuel mode. The engine was tested with an experiment at several engine speeds from 1800 rpm to 2200 rpm. Moreover, it was also tested at high load conditions of 3 kW and 4 kW. Diesel 1 and diesel 2 represent dedicated diesel modes at 3 kW and 4 kW, respectively. DF 1 and DF 2 are the dual-fuel modes at 3 kW and 4 kW, respectively.

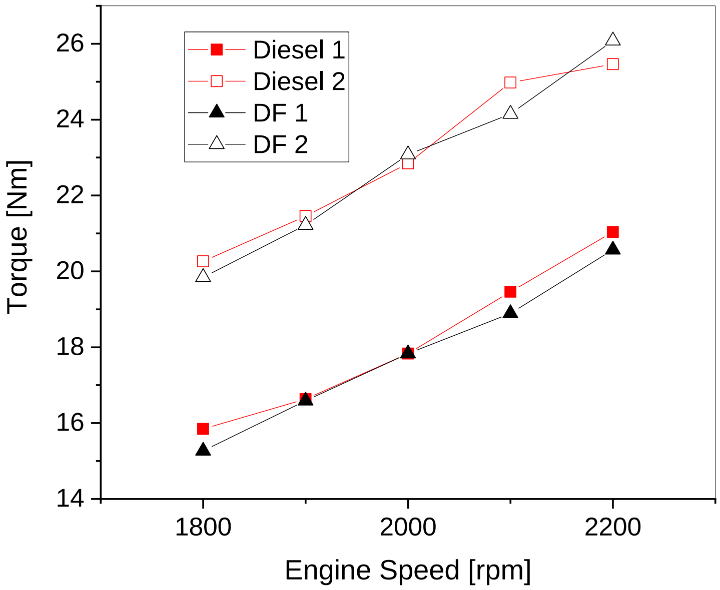

Figure 3. Engine Torque on High Load Condition

Figure 3 shows the engine torque in several modes, speeds, and loads. The engine torque at 4 kW is higher than at 3 kW with the highest and lowest torque at dual-fuel mode about 26 Nm at 4 kW loads and 15 Nm at 3 kW loads, respectively. The 3 kW load shows that dedicated diesel has a higher torque at most of the engine speeds than dual-fuel mode. However, the torque is nearly similar in both dedicated diesel and dual-fuel modes at 1900 rpm and 2000 rpm. Moreover, it is 3% higher at 1800 rpm and 2100 rpm. The 4 kW load shows that diesel mode has a higher engine torque at most of the engine speeds but at 2000 rpm and 2200 rpm the dual-fuel has slightly higher torque than dedicated diesel mode. This phenomenon indicates that proper engine speeds are required to improve the torque [38], hence the difference is insignificant thus it can be neglected. The engine torque decreases at dual-fuel mode significantly by about 3,3%. Lower engine torque in dual-fuel mode than in dedicated diesel mode is normal. It is reported in several studies that dual-fuel combustion has a longer ignition delay than dedicated diesel mode thus the engine torque lowers as a consequence [39], [40]. It can be normalized with higher engine torque with several settings such as adjusting the injection timing [22]. However, the difference remains insignificant thus additional setting is unnecessary in terms of operational efficiency.

The engine fuel consumption is reported in Figure 4 in several loads, engine speeds, and operation modes. The dual-fuel mode has a significant reduction in the engine fuel consumption at both engine loads than the dedicated diesel. However, the lower engine fuel consumption with dual-fuel mode than dedicated diesel is due to the CNG fuel addition in the diesel engine. The CNG fuel has a higher lower heating value (LHV) than diesel fuel thus the lower total fuel consumption for the combustion [41]. In the dual-fuel mode, the higher engine speeds have a lower engine fuel consumption. It is due to higher engine power at higher engine speeds thus the fuel consumption is more efficient. The lowest engine fuel consumption is at dual-fuel mode with 2200 rpm and 3 kW loads of about 107 g/kWh. Furthermore, in a dedicated diesel mode, the engine fuel consumption both at 3 kW and 4 kW loads has the lowest engine fuel consumption at 2000 rpm. Higher engine speeds in dedicated diesel mode have higher engine fuel consumption. It indicates that the combustion is more efficient at 2000 rpm due to the diesel fuel spray quality. The highest engine fuel consumption is at 4 kW loads and 2200 rpm with a dedicated diesel mode of about 339 g/kWh.

Figure 5 depicts the NO2 emissions in the experiment at 3 kW and 4 kW load conditions with dedicated diesel and dual-fuel modes at several engine speeds. It shows that the NO2 emissions in diesel mode have higher concentration at low load conditions than the dual-fuel mode as a consequence of low fuel injection mass in low load conditions. In low fuel injection mass, the combustion temperature tends to be low thus increasing the NO2 emissions. Higher engine speeds decrease the NO2 emissions both in dedicated diesel and dual-fuel modes in all engine loads. It is due to the more efficient combustion at high engine speeds. However, most of the dual-fuel mode conditions have a significantly higher NO2 emissions concentration than the dedicated diesel mode. Meanwhile, it also has the potential to lower NO2 emissions at 2200 rpm with a 4 kW engine load in dedicated diesel mode. In that condition, the NO2 emissions are about 21 ppm which is nearly the same as the lowest NO2 emissions concentration in the dual-fuel mode about 13 ppm. The high NO2 emissions concentration in dual-fuel mode is due to the severe knock in high load conditions, as reported in several studies [16], [23], [42]. The air/fuel mixture is too rich due to lower air concentration which is replaced in volume by the natural gas fuel and severe knock is difficult to avoid. Thus, the high combustion temperature from the knock phenomenon produces significant NOx emissions.

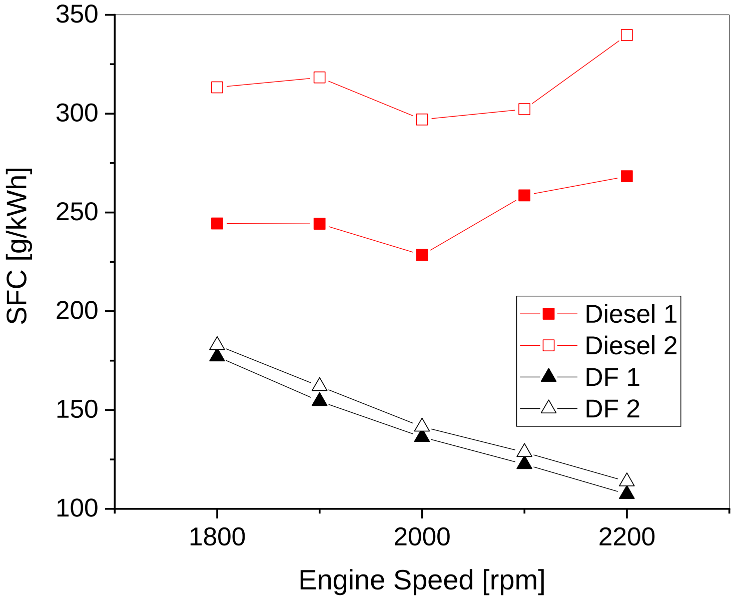

Figure 4. Engine Fuel Consumption on High Load Condition

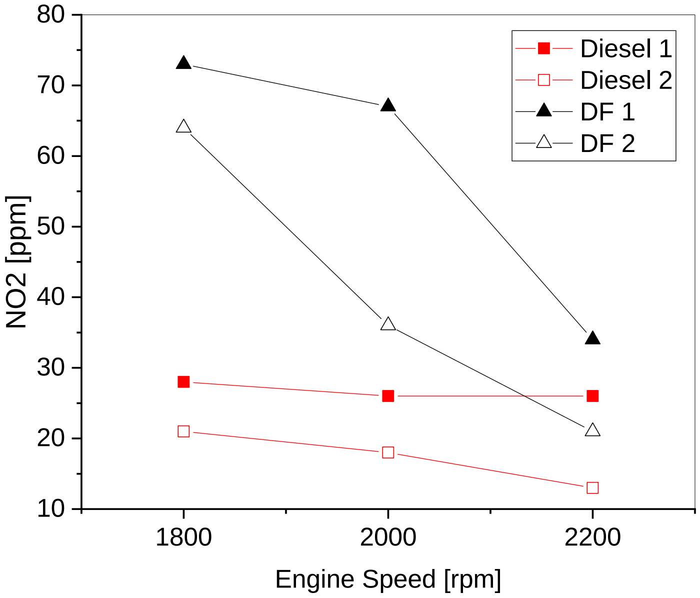

Figure 5. Engine NO2 Emissions on High Load Condition

Figure 6 shows the CO2 emissions of the engine with dedicated diesel and dual fuel. The CO2 emissions indicate perfect combustion in the chamber which means the fuel is completely burned. It depicts that the CO2 emissions in diesel mode are higher at high load conditions as in the dual-fuel mode. It is due to the fuel mass burned in the high load being higher than the low load condition as a consequence of the higher fuel mass injected into the combustion chamber. The CO2 concentration at low engine speed (1800 rpm) increases with higher engine speed (2000 rpm) and then decreases at the highest engine speed (2200 rpm). However, it shows that the dual-fuel mode at 3 kW has a lower CO2 emissions concentration in the experiment at each engine speed than other variations with the lowest CO2 achieved at 2200 rpm at about 3.2% concentration. In this condition, it means that a lot of the combustion zone has not reached the minimum temperature for perfect combustion thus decreasing the CO2 emissions [43]. However, this condition can be advantageous due to the stringent regulations to reduce CO2 emissions [44]. Meanwhile, the consequence is higher NOx emissions which can be reduced with another strategy. Besides, the highest CO2 emissions are in dual-fuel mode with a 4 kW load at 2000 rpm about 5.7% concentration. At that condition, at 2200 rpm, the CO2 emissions significantly decrease. It is due to the combustion at the lower engine speed being supported with a proper diesel fuel injection spray. The larger diesel injection mass at the highest engine speed at 2200 rpm worsened the injection spray characteristic thus lowering the CO2 emissions.

Furthermore, the CO2 emissions in each mode remain to be high at most engine speeds due to more perfect combustion generated by the process.

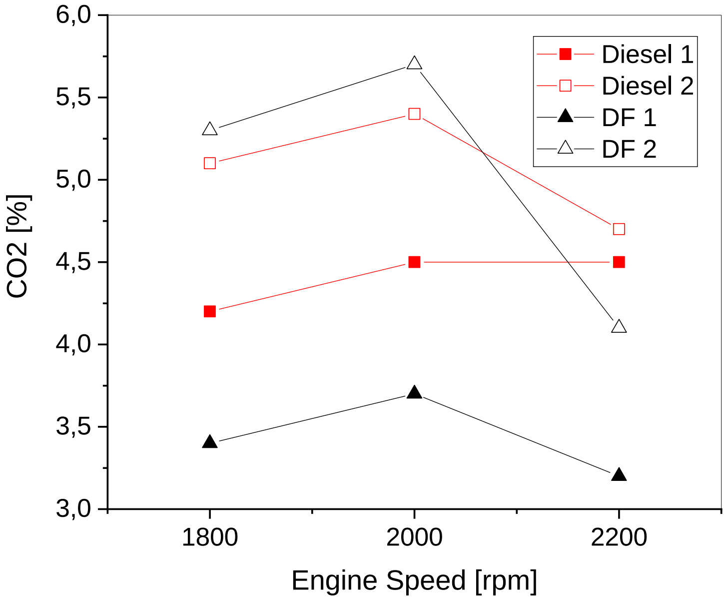

Figure 6. Engine CO2 Emissions on High Load Condition

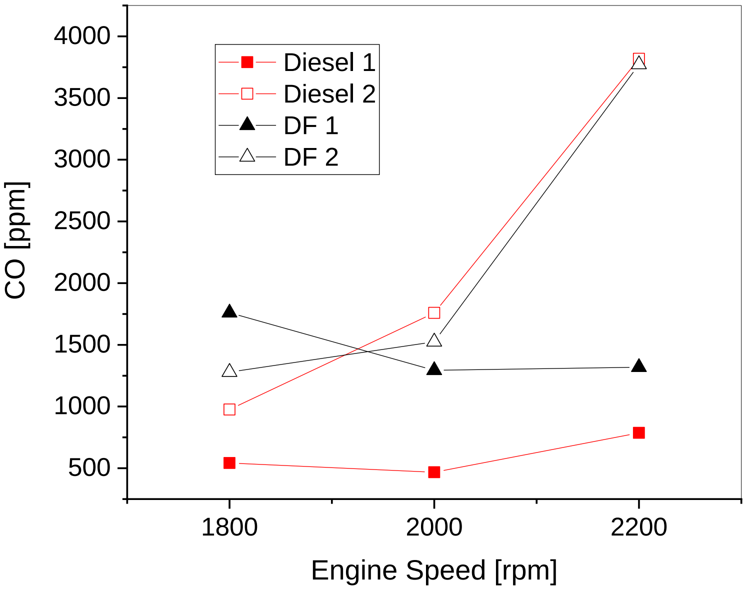

Figure 7. Engine CO Emissions on High Load Condition

The CO emissions in the experiment are reported in Figure 7 with several engine speeds, engine modes, and engine loads. It shows that the CO emissions in diesel mode have higher concentrations at high load conditions. The higher engine load leads to higher diesel fuel mass injection thus increasing CO emissions. Besides, the CO emissions in dual-fuel mode have different characteristics. The CO emissions at high loads with low engine speeds have a lower concentration than low load conditions. It indicates that the combustion quality increases in the high load with low engine speeds thus decreasing the CO concentration. The CO emissions on the 3 kW load have a different characteristic than the 4 kW load condition in both of the engine modes. At a 3 kW load, the CO emissions decrease at 2000 rpm from 1800 rpm and then slightly increase at 2200 rpm. At a 4 kW load, the CO emissions increase at 2000 rpm and then significantly increase at 2200 rpm. The higher CO emissions indicate that several combustion zones have a lower temperature than the ideal temperature for combustion [18]. However, Figure 7 shows that the CO emissions concentration mostly occurred due to the engine loads. Higher engine loads increase the diesel injection mass thus it affects the injection spray characteristic which also affects the combustion quality. Moreover, it indicates that CO emissions are also affected by engine speeds. The higher the engine speeds the higher the air intake mass into the combustion chamber thus the higher oxygen concentration is imperfectly burned with lower diesel spray characteristics and increases the CO emissions.

4. Conclusion

A marine debris hybrid dual-fuel engine system is developed which is fueled by CNG and diesel with the operational condition focused on high load conditions. A power system design and experimental works on the power system occurred. However, the following are several conclusions from this study regarding the design.

a. The power system which is mainly used a hybrid CNG/diesel dual-fuel engine is conditionally operated based on an operational conditions such as sailing, collecting, and maneuvering. Most of the operational conditions can be fully operated with the hybrid engine. In the maneuvering, the battery power source can be used which needs only low load conditions.
b. The hybrid system is can be operated in both diesel mode or dual-fuel mode in high load conditions, 3 kW to 4 kW. The dual-fuel mode has a promising engine torque output which is nearly the same as diesel mode in over-engine speeds. The dual-fuel mode can reduce engine fuel consumption significantly with high engine speeds. Diesel mode operation has a relatively higher engine fuel consumption than the dual-fuel mode.
c. The hybrid system with dual-fuel mode has high NO2 emissions than the diesel mode. However, the CO2 emissions are significantly reduced in dual-fuel mode at 3 kW engine load than the other conditions. Moreover, the CO emissions are mostly dependent on the engine loads. The dual-fuel mode still has higher CO than the diesel mode at a 3 kW engine load and relatively similar concentration at 4 kW engine loads.

Nevertheless, the hybrid system in this study is still in the preliminary design and it will be detailed in future work such as the engine-propeller matching, power management system, and instrumentation. However, other fuel and system combinations are desirable in terms of low environmental impact.

References

[1] C. A. Reusser and J. R. Pérez Osses, " Challenges for Zero-Emissions Ship," *Journal of Marine Science and Engineering 2021, Vol. 9, Page 1042*, vol. 9, no. 10, 2021, doi: 10.3390/JMSE9101042.

[2] A. Iswantoro, I. M. Ariana, and M. Syuhri, " Analysis of Performance, Emission, Noise and Vibration on Single Cylinder Diesel Engine After Installing Dual Fuel Converter-Kit Based on ECU," *Kapal: Jurnal Ilmu Pengetahuan dan Teknologi Kelautan*, vol. 19, no. 1, pp. 42– 49, 2022, doi: 10.14710/KAPAL.V19I1.44126.

[3] S. Kose, D. M. Sekban, and M. Ozkok, " Determination of port-induced exhaust gas emission amounts and investigation of environmental impact by creating emission maps: Sample of Trabzon port," *https://doi.org/10.1080/15568318.2020.1871130*, vol. 16, no. 3, pp. 258– 268, 2021, doi: 10.1080/15568318.2020.1871130.

[4] F. M. Felayati, B. Cahyono, U. Prayogi, and A. Winarno, " Future perspective of the ship alternative fuels in Indonesia," in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 2022, p. 12024.

[5] F. Diab, H. Lan, and S. Ali, " Novel comparison study between the hybrid renewable energy systems on land and on ship," *Renewable and Sustainable Energy Reviews*, vol. 63, pp. 452– 463, 2016, doi: 10.1016/J.RSER.2016.05.053.

[6] S. Nguyen, " Development of an MCDM framework to facilitate low carbon shipping technology application," *The Asian Journal of Shipping and Logistics*, vol. 34, no. 4, pp. 317– 327, 2018, doi: 10.1016/J.AJSL.2018.12.005.

[7] J. Yang *et al.*, " Controlling emissions from an ocean-going container vessel with a wet scrubber system," *Fuel*, vol. 304, p. 121323, 2021, doi: 10.1016/J.FUEL.2021.121323.

[8] Y. Chen *et al.*, " Study of Injection Pressure Couple with EGR on Combustion Performance and Emissions of Natural Gas-Diesel Dual-Fuel Engine," *Fuel*, vol. 261, p. 116409, 2020, doi: 10.1016/j.fuel.2019.116409.

[9] D. Wijayanto and G. B. D. S. Antara, " Comparison Analysis of Options to Comply with IMO 2020 Sulphur Cap Regarding Environmental and Economic Aspect," *IOP Conf Ser Earth Environ Sci*, vol. 1081, no. 1, p. 012051, 2022, doi: 10.1088/1755-1315/1081/1/012051.

[10] N. R. Ammar, " An environmental and economic analysis of methanol fuel for a cellular container ship," *Transportation Research Part D: Transport and Environment*, vol. 69, pp. 66– 76, 2019, doi: 10.1016/J.TRD.2019.02.001.

[11] B. Yang, L. Ning, B. Liu, G. Huang, Y. Cui, and K. Zeng, " Comparison study the particulate matter characteristics in a diesel/natural gas dual-fuel engine under different natural gas-air mixing operation conditions," *Fuel*, vol. 288, p. 119721, 2021, doi: 10.1016/j.fuel.2020.119721.

[12] F. M. Felayati, Semin, B. Cahyono, R. A. Bakar, and M. Birouk, " Performance and emissions of natural gas/diesel dual-fuel engine at low load conditions: Effect of natural gas split injection strategy," *Fuel*, vol. 300, p. 121012, 2021, doi: 10.1016/j.fuel.2021.121012.

[13] I. Ø. Tvedten and S. Bauer, " Retrofitting towards a greener marine shipping future: Reassembling ship fuels and liquefied natural gas in Norway," *Energy Research & Social Science*, vol. 86, p. 102423, 2022, doi: 10.1016/J.ERSS.2021.102423.

[14] P. Balcombe, I. Staffell, I. G. Kerdan, J. F. Speirs, N. P. Brandon, and A. D. Hawkes, " How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis," *Energy*, vol. 227, p. 120462, 2021, doi: 10.1016/J.ENERGY.2021.120462.

[15] C. Wang, Y. Ju, and Y. Fu, " Comparative life cycle cost analysis of low pressure fuel gas supply systems for LNG fueled ships," *Energy*, vol. 218, p. 119541, 2021, doi: 10.1016/J.ENERGY.2020.119541.

[16] S. Chu, J. Lee, J. Kang, Y. Lee, and K. Min, " High Load Expansion with Low Emissions and The Pressure Rise Rate By Dual-Fuel Combustion," *Applied Thermal Engineering*, vol. 144, pp. 437– 443, 2018, doi: 10.1016/J.APPLTHERMALENG.2018.08.027.

[17] R. Sindhu, G. Amba Prasad Rao, and K. Madhu Murthy, " Effective Reduction of NOx Emissions From Diesel Engine Using Split Injections," *Alexandria Engineering Journal*, vol. 57, no. 3, pp. 1379– 1392, 2018, doi: 10.1016/J.AEJ.2017.06.009.

[18] E. Shim, H. Park, and C. Bae, " Intake Air Strategy for Low HC and CO Emissions in Dual-Fuel (CNG-Diesel) Premixed Charge Compression Ignition Engine," *Applied Energy*, vol. 225, pp. 1068– 1077, 2018, doi: 10.1016/j.apenergy.2018.05.060.

[19] B. Ariani, I. M. Ariana, and M. A. Fathallah, " Effect of natural gas injection timing on combustion performance & methane slip emission of diesel – NG dual fuel engine: An experimental study," *AIP Conf Proc*, vol. 2187, no. 1, p. 020003, 2019, doi: 10.1063/1.5138258.

[20] B. Ariani, I. M. Ariana, and A. Z. Fathallah, " Experimental Investigation on Natural Gas Injection to Minimize Abnormal Combustion and Methane Slip in the Diesel - Natural Gas Dual Fuel Engine at Low Load," *International Review of Mechanical Engineering (IREME)*, vol. 14, no. 9, pp. 599– 606, 2020, doi: 10.15866/IREME.V14I9.19821.

[21] J. Liu, Q. Guo, J. Guo, and F. Wang, " Optimization of a diesel/natural gas dual fuel engine under different diesel substitution ratios," *Fuel*, vol. 305, 2021, doi: 10.1016/j.fuel.2021.121522.

[22] Z. Wang, F. Zhang, Y. Xia, D. Wang, Y. Xu, and G. Du, " Combustion phase of a diesel/natural gas dual fuel engine under various pilot diesel injection timings," *Fuel*, vol. 289, p. 119869, 2021, doi: 10.1016/j.fuel.2020.119869.

[23] A. Yousefi, H. Guo, and M. Birouk, " Split Diesel Injection Effect on Knocking of Natural Gas/Diesel Dual-Fuel Engine at High Load Conditions," *Applied Energy*, vol. 279, p. 115828, 2020, doi: 10.1016/j.apenergy.2020.115828.

[24] V. Ruggiero, " The future developments of Hybrid and electrical propulsion for small vessel, according to new possibilities offered by Industry 4.0.," *Procedia Comput Sci*, vol. 200, pp. 962– 968, 2022, doi: 10.1016/J.PROCS.2022.01.294.

[25] C. Y. Ji, J. T. Guo, R. C. Ye, Q. L. Yin, W. Y. Xu, and Z. M. Yuan, " Experimental study of an ocean surface cleaning system," *Ocean Engineering*, vol. 249, p. 110937, 2022, doi: 10.1016/J.OCEANENG.2022.110937.

[26] M. Compa, D. March, and S. Deudero, " Spatio-temporal monitoring of coastal floating marine debris in the Balearic Islands from sea-cleaning boats," *Marine Pollution Bulletin*, vol. 141, pp. 205– 214, 2019, doi: 10.1016/J.MARPOLBUL.2019.02.027.

[27] G. Duan and K. Zhang, " Optimization on hybrid energy vessel routing and energy management for floating marine debris cleanup," *Transportation Research: Part C*, vol. 138, p. 103649, 2022, doi: 10.1016/J.TRC.2022.103649.

[28] B. Jeong, E. Oguz, H. Wang, and P. Zhou, " Multi-criteria decision-making for marine propulsion: Hybrid, diesel electric and diesel mechanical systems from cost-environment-risk perspectives," *Applied Energy*, vol. 230, pp. 1065– 1081, Nov. 2018, doi: 10.1016/J.APENERGY.2018.09.074.

[29] A. Bordianu and G. Samoilescu, " Electric and Hybrid Propulsion in the Naval Industry," *2019 11th International Symposium on Advanced Topics in Electrical Engineering, ATEE 2019*, 2019, doi: 10.1109/ATEE.2019.8725022.

[30] N. Bennabi, J. F. Charpentier, H. Menana, J. Y. Billard, and P. Genet, " Hybrid propulsion systems for small ships: Context and challenges," *Proceedings - 2016 22nd International Conference on Electrical Machines, ICEM 2016*, pp. 2948– 2954, Nov. 2016, doi: 10.1109/ICELMACH.2016.7732943.

[31] E. Sugianto, J. H. Chen, and N. V. A. Permadi, " Effect of Monohull Type and Catamaran Hull Type on Ocean Waste Collection Behavior Using OpenFOAM," *Water 2022, Vol. 14, Page 2623*, vol. 14, no. 17, p. 2623, 2022, doi: 10.3390/W14172623.

[32] A. Yousefi, H. Guo, and M. Birouk, " Effect of Diesel Injection Timing on The Combustion of Natural Gas/Diesel Dual-Fuel Engine at Low-High Load and Low-High Speed Conditions," *Fuel*, vol. 235, pp. 838– 846, 2019, doi: 10.1016/j.fuel.2018.08.064.

[33] H. Park, E. Shim, and C. Bae, " Expansion of Low-Load Operating Range By Mixture Stratification in A Natural Gas-Diesel Dual-Fuel Premixed Charge Compression Ignition Engine," *Energy Convers Manag*, vol. 194, pp. 186– 198, 2019, doi: 10.1016/J.ENCONMAN.2019.04.085.

[34] J. You, Z. Liu, Z. Wang, D. Wang, and Y. Xu, " Impact of Natural Gas Injection Strategies on Combustion and Emissions of A Dual Fuel Natural Gas Engine Ignited with Diesel at Low Loads," *Fuel*, vol. 260, p. 116414, 2020, doi: 10.1016/J.FUEL.2019.116414.

[35] H. Guo, B. Liko, and W. S. Neill, " Effect of Diesel Injection Split on Combustion and Emissions Performance of a Natural Gas– Diesel Dual Fuel Engine at a Low Load Condition," in *Proceedings of the ASME 2017 Internal Combustion Engine Division Fall Technical Conference*, 2017. doi: 10.1115/ICEF2017-3584.

[36] Z. Zhu, Y. Li, and C. Shi, " Effect of natural gas energy fractions on combustion performance and emission characteristics in an optical CI engine fueled with natural gas/diesel dual-fuel," *Fuel*, vol. 307, 2022, doi: 10.1016/j.fuel.2021.121842.

[37] H. Park, E. Shim, and C. Bae, " Injection Strategy in Natural Gas– Diesel Dual-Fuel Premixed Charge Compression Ignition Combustion Under Low Load Conditions," *Engineering*, 2019, doi: 10.1016/j.eng.2019.03.005.

[38] A. Yousefi, H. Guo, and M. Birouk, " Effect of diesel injection timing on the combustion of natural gas/diesel dual-fuel engine at low-high load and low-high speed conditions," *Fuel*, 2019, doi: 10.1016/j.fuel.2018.08.064.

[39] G. A. Karim, *Dual-fuel diesel engines*. CRC Press, 2015.

[40] G. Theotokatos, S. Stoumpos, I. Lazakis, and G. Livanos, " Numerical Study of A Marine Dual-Fuel Four-Stroke Engine," 2016.

[41] A. García, J. Monsalve-Serrano, D. Villalta, and R. Sari, " Fuel Sensitivity Effects on Dual-Mode Dual-Fuel Combustion Operation for Different Octane Numbers," *Energy Conversion and Management*, vol. 201, p. 112137, 2019, doi: 10.1016/J.ENCONMAN.2019.112137.

[42] M. Y. E. Selim, " Sensitivity of Dual Fuel Engine Combustion and Knocking Limits to Gaseous Fuel Composition," *Energy Conversion and Management*, vol. 45, no. 3, pp. 411– 425, 2004, doi: 10.1016/S0196-8904(03)00150-X.

[43] A. Gholami, S. A. Jazayeri, and Q. Esmaili, " A detail performance and CO2 emission analysis of a very large crude carrier propulsion system with the main engine running on dual fuel mode using hydrogen/diesel versus natural gas/diesel and conventional diesel engines," *Process Safety and Environmental Protection*, vol. 163, pp. 621– 635, Jul. 2022, doi: 10.1016/J.PSEP.2022.05.069.

[44] M. A. Budiyanto, M. R. Habibie, and T. Shinoda, " Estimation of CO2 emissions for ship activities at container port as an effort towards a green port index," *Energy Reports*, vol. 8, pp. 229– 236, 2022, doi: 10.1016/J.EGYR.2022.10.090.