Methane slip from LNG engines – review and on-board study

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Introduction

Following the regulations set by the International Maritime Organization for emissions of nitrogen oxides (NO_x) and fuel sulphur content, the use of liquefied natural gas (LNG) as shipping fuel has increased in recent years. According to a recent report, about 20% of the total vessel orders in 2021 were LNG-fuelled (Plevrakis et al., 2022). Vessels using LNG as fuel enable one transition pathway from fossil to non-fossil fuels and utilization in dual-fuel engines fuel flexibility for the ship operators. Compared to conventional liquid fuels, LNG has direct effects, namely benefits, on air quality and human health. The use of LNG as marine fuel can also reduce the emissions of NO_x and particulate matter including black carbon, relative to operation on marine gas oil.

LNG is mainly composed of methane (CH_4) which has higher hydrogen-carbon ratio and energy content compared to liquid fuels, leading to lower emissions of carbon dioxide (CO_2). However, unburned methane is a greenhouse gas (GHG) with a global warming potential of 28-30 times higher than CO_2. Thus, while the use of LNG has benefits in terms of CO_2 emissions and local air pollutants, slip of unburnt methane to atmosphere remains a concern. Currently, the European Union is in the process of issuing amendments for directives that regulate maritime transport as part of the Green Deal and Fitfor55 environmental packages. Two specific regulations will affect methane emissions from ships: the Emissions Trading System and the FuelEU Maritime, which both will include CO_2, CH_4, and nitrous oxide GHG emissions. Currently, the emission data of methane slip from vessels utilizing LNG is limited. In this study, results from a review considering methane slip and other emissions from LNG engines are presented, together with comparison to new results collected during on-board campaign on a modern RoPax ferry.

Methods

A literature review was conducted to collect emission factors of brake-specific methane slip and other emissions from LNG engines from published literature and from ship owner data for engines from recent years. From the literature, published methane emission results could be found for engines from years 2010 (and older / newer), 2012, 2013 (and newer), 2016, 2016 (retrofitted), and 2021. In addition, ship owner data was received, including results for engines designed and constructed in the recent years (2019-2022).

The LNG engines could be divided to four categories according to the engine technology they apply. Lean Burn Spark Ignited (LBSI) engines are typically 4-stroke (4-S) high or medium-speed engines which use only natural gas with spark plug ignition. Low Pressure Dual Fuel engines include both 4-stroke (4-S) and 2-stroke (2-S) engines, in which natural gas is injected in low pressure during compression stroke and injection of small quantity of pilot fuel is used for ignition. Fourth engine type are 2-S High Pressure Dual Fuel engines where natural gas is injected in high pressure at the end of the compression stroke, simultaneously with the liquid pilot fuel injection. The choice of engines for a vessel is dependent at least on the ship type, size, and operational parameters. Large container ships often use 2-stroke engines and mainly operate in deep-sea regions where they may apply constant engine load for long periods after exiting the harbour. On the other hand, ferries or cruise ships are typically equipped with 4-stroke engine and operate on coastal areas where engine load changes may be more frequent (Schuller et al., 2021). To consider these varying operational patterns with different engine types, the methane slip values are presented as function of engine load percentage.

To complement the review, emission measurements on a state-of-the-art LNG ferry were conducted on-board Aurora Botnia, Wasaline's RoPax ferry while it was operating on its route between Vaasa (Finland) and Umeå (Sweden), in December 2022. The vessel's construction was finalized in 2021 and its operation started in the autumn 2021. Aurora Botnia is equipped with four Wärtsilä 31DF 4-S medium-speed dual-fuel engines with 8 cylinders and power of 550 kW per cylinder. Exhaust was sampled from one of the engines with normal 31DF setup (ME4) and an engine which was piloting a new combustion concept (ME3). Both engines were operated at load points of 10%, 25%, 50%, 75% and 90% and the loadings were realized with the accuracy of ±2 %-units. The engines used LNG with high methane content of 95.1% and marine diesel oil (MDO) with very low sulphur content of 0.01% was used as pilot fuel. The contribution of pilot fuel to the total fuel flow depended on the engine (3-13% with ME4) and (10-28% with ME3) and load condition with higher shares of MDO utilization at the lowest load conditions.

On-board, raw exhaust gas sample was drawn through a sonde installed in the exhaust duct few meters downstream the engine and then divided to separate gaseous and particulate instruments applying different sample conditioning. A gas chromatograph (Agilent MicroGC) was applied to study methane concentrations. Additionally, methane was measured with Fourier transform infrared spectroscopy (FTIR, Gasmet DX4000) together with water, NO, NO_2, and formaldehyde. The FTIR as well as the sampling line and the filter prior to the FTIR spectrometer were heated to 180°C. NO_x was also measured by standard method with chemiluminescence detector (CLD). CO_2 and carbon monoxide (CO) were measured with a nondispersive infrared (NDIR) analyzer. For particle emissions, particle number (PN) was studied according to the procedure mandated by EU Stage V regulation for inland waterway vessels which considers non-volatile particles with a diameter greater than 23 nm ($PN_{>23nm}$). In addition, smaller particles with a diameter exceeding 10 nm ($PN_{>10nm}$) were studied with same methodology applying a Dekati Engine Exhaust Diluter (DEED) for sample conditioning. The system consists of two ejector diluters, providing a total dilution ratio of 1000:1. The temperature of the first ejector was ∼200 °C, and the temperature at the outlet of the DEED unit was below 35 °C. Condensation particle counters (Airmodus A23 CPC and Airmodus A20 CPC) were used to determine $PN_{>23nm}$ and $PN>_{10nm}$ concentrations, respectively. Measurements were conducted similarly for both engines and carbon balance method (described e.g., in ISO 8178 and NOx technical code) was used to calculate emission factors in kWh^{-1} basis. The fuel consumption measured during the onboard studies was provided by the vessel operator together with the engine loading data (power in kW) and LNG bunkering report including fuel composition. Pilot fuel sample was received from the vessel and was further analysed for C, H and N, to include in the calculation of the exhaust gas mass flow rate by the carbon balance method.

Results & discussion

The methane slip data regarding LNG engines is limited and relies largely on measurement data from test-bed (Lehtoranta et al., 2019; Ushakov et al., 2019) or data provided by engine manufacturers (Lindstad et al., 2020; Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022; Pavlenko et al., 2020; Rolls-Royce, 2012; Schuller et al., 2021; Stenersen & Thonstad, 2017) although a handful of studies (Anderson et al., 2015; Balcombe et al., 2022; Corbin et al., 2020; Peng et al., 2020; Sommer et al., 2019; Stenersen & Thonstad, 2017; Ushakov et al., 2019, Rochussen et al. 2023) which report original research data collected during on-board measurements could be recognized. For the purposes of this study, ship owner data from 6 LPDF 2-S and 5 LPDF 4-S engines from years 2019-2022 were received to complement the data with methane slip information from recently build engines.

Majority of the found data considers methane slip from 4-stroke and 2-stroke LPDF engines, except few studies which also included measurements of LBSI engines. For HPDF engines, the results originate from engine manufacturers and no data including dependence of engine load was found, however, methane slip from HPDF engines is generally considered small due to the injection and combustion strategy of the engines (0.2-0.28 g/kWh estimated for load ranges between 25-85% (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022).

Figure 1 shows brake specific methane slip emission factors for 19 LPDF 4-S engines, 8 LPDF 2-S engines, and 8 LBSI engines for which data was available. For LPDF 4-S engines, the methane slip ranged between 2.1-10 g/kWh at 100%, 3.1-10.1 g/kWh at 75% load, 2.6-16.7 g/kWh at 50% load, 6.1-70.2 at 25% load and 12.2-123 g/kWh at 10% load. Respectively, for LBSI engines, corresponding values were 2.5-4.2 g/kWh at 100% load, 3.3-5 g/kWh at 75% load, 4.1-7.2 g/kWh at 50% load, and 6.4-42 g/kWh at 10% load. In the case of LPDF 2-S engines, methane emissions ranged between 1.9-2.5 g/kWh for operation at 100% load, 2.4-2.9 g/kWh at 75% load, 2.4-5.1 g/kWh at 50% load and 2.8-7.2 g/kWh at 25% load.

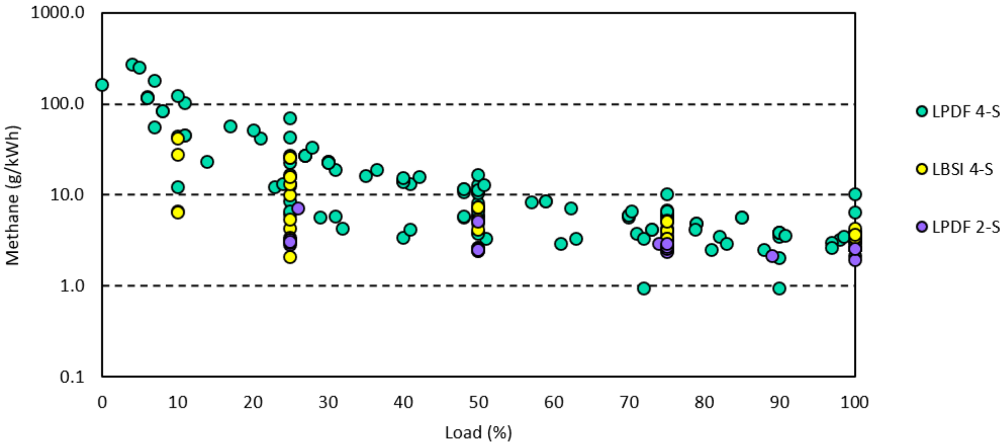

Figure 1. Break-specific emission factors as function of engine load for LPDF 4-S, LBSI 4-S, and LPDF 2-S engine. Figure includes data from reviewed literature as well as ship owner data. (Data sources: LPDF 4-S engines (Anderson et al., 2015; Balcombe et al., 2022; Corbin et al., 2020; Lehtoranta et al., 2019; Peng et al., 2020; Sommer et al., 2019; Ushakov et al., 2019; Rochussen et al. 2023; ship owner data), LBSI engines (Rolls-Royce, 2012; Ushakov et al., 2019); LPDF 2-S engines (Balcombe et al., 2022; WinGD according to Pavlenko et al., 2020; ship owner data). For details of data sources, see Kuittinen et al. (2023).

Increase in brake specific methane emissions as function of decreasing engine load could be observed for all engine types. In case of LPDF 2-S engines, the load dependency was suppressed, although it should be noted that data was limited to load conditions of 25% or above. In the case of LPDF 2-S engines all data originates from relatively new engines (~2018-2021), whereas for LBSI engines, newest published data could be found for engine from 2015. Largest amount of data was found for LPDF 4-S engines with results available for engines from 2012 until 2021. For LPDF 4-S engines, it could be noted that methane emission results for engines from 2016-2019 were equal or higher than those from engines built earlier at all engine loads. For the newest engines, emission factors obtained from ship owner data measured at test-bench show decreased values compared to engines from 2016-2019, especially at 50% load and below. For on-board studies, results from two on-board studies indicate higher values (especially below 50% load) whereas in one case (Rochussen et al. 2023) where engine from 2016 was tested with new engine control calibration, methane slip values were among the lowest and agreed with test-bed values for the new engines.

Taking a closer look to the on-board results from LPDF 4-S engines (Figure 2), 8 studies conducted on 5-6 vessels were found, covering methane and, in some cases, additional gaseous and particle emissions. These results could be complemented with recent on-board results where two engines ME4 (standard engine setup build in 2021) and ME3 (engine piloting a novel combustion concept) (see Lehtoranta et al., 2023 for details) were studied. Including the recent on-board results shows that methane slip from recently build engines can exhibit lower values than majority of the currently available literature suggests, especially at the low engine loads. At loads exceeding 25%, similar methane levels were observed for ME4 that in the case of 2016 engine fitted with new engine calibration. For the ME4 engine, methane slip varied between 3.3-3.6 g/kWh at 50-85% loads, and methane slip of 7.6 g/kWh was observed at 25% load and 12.4 g/kWh at 10% load. In the case of ME3, employing the new combustion concept, corresponding values of 1.4-1.6 g/kWh were seen at 50-85% loads, 1.5 g/kWh at 25% load, and 3.9 g/kWh at 10% load. From the previous studies, very low values of 0.9 g/kWh at 70 and 90% loads have been reported for a 7.6MW engine with larger cylinder (Anderson et al., 2015).

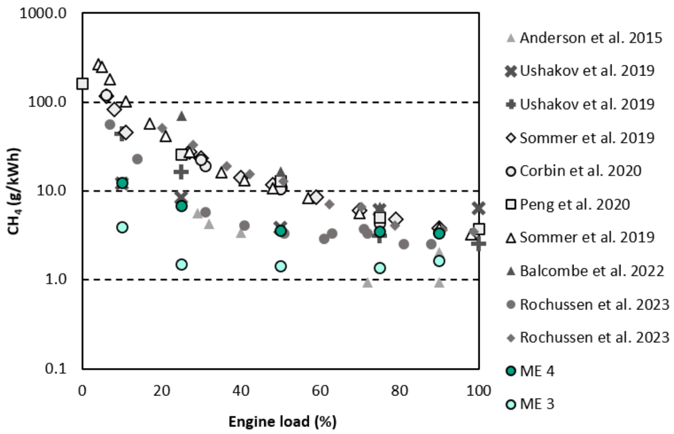

Figure 2: Methane slip emission factors for LPDF 4-S engines studied on-board from literature and recent on-board measurements (Lehtoranta et al., 2023).

Considering other gaseous emissions (Figure 3), the results obtained from the on-board study add to the current data of CO_2, nitrogen oxides (NO_x), carbon monoxide (CO), and formaldehyde (HCHO) emission factors.

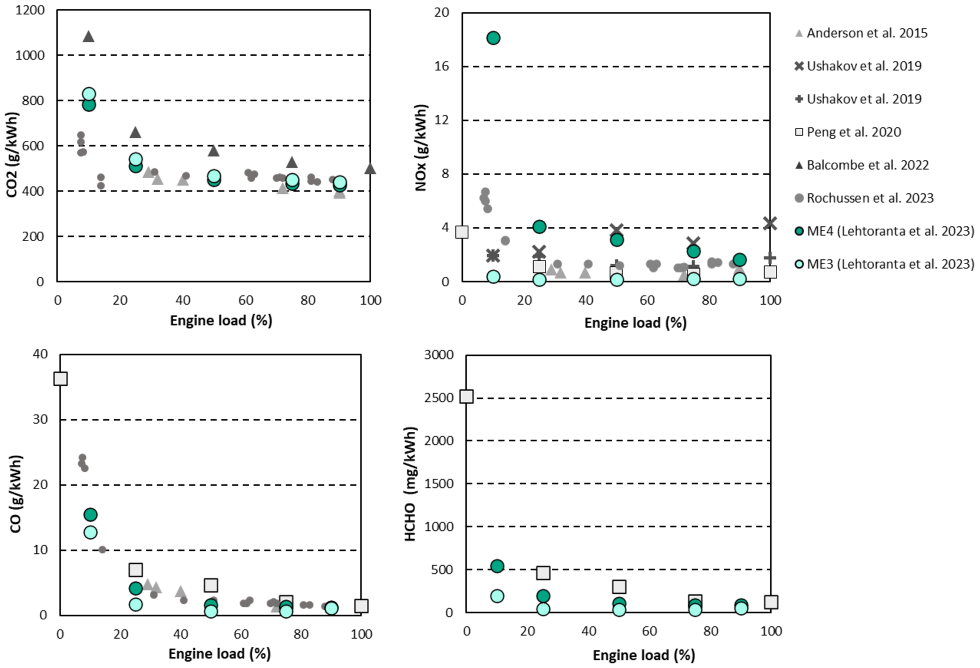

Figure 3: Emission factors of CO_2, NO_x, CO, and HCHO for LPDF 4-S engines studied on-board from literature and recent on-board measurements (Lehtoranta et al., 2023).

Together with the current literature values, it is seen that CO_2 levels observed from ME4 and ME3 somewhat align with Anderson et al. (2015) and Rochussen et al. (2023), together showing 390-550 gCO_2/kWh when load decreases from 90% to 25%. Similar trend of increased emissions at 10% load is seen as in Balcombe et al. (2022) while their study shows generally higher CO_2 level between 500-660 gCO_2/kWh (25-100% load) and 1100 g/kWh (at 10% load). NO_x emissions were covered for six different engines in the included literature, showing generally low values of 0.5-4.3 gNO_x/kWh over the load range from 25% to 100% and 1.9-6.7 gNO_x/kWh at loads below 25%. The results from ME4 mainly align with these values, except at 10% load when 18.2 gNO_x/kWh was observed. For ME3, NO_x emission factors were on a low level of 0.2-0.4 gNO_x/kWh for all load conditions between 10-100%. In case of CO, the results from ME3 (0.7-1.2 gCO/kWh) and ME4 (1.3-1.4 gCO/kWh) aligned with emission levels of 1.4-2.1 gCO/kWh at 75-100% loads from three on-board studies. At 25-50% loads, ME3 and ME4 showed somewhat lower values (0.7-1.8gCO/kWh and 1.7-4.2gCO/kWh) than previous studies (2.1-7 gCO/kWh). In the literature, formaldehyde was included in one on-board study where 120-470 mgHCHO/kWh were reported at 25-100% loads and significantly increased value of 2500 mgHCHO/kWh at idle. Results from ME4 (90-550 mgHCHO/kWh) and ME3 (50-210 mgHCHO/kWh) indicate lower formaldehyde emissions from the modern engine, especially in the case of the new combustion concept.

Non-volatile particle number (PN$_{nv}$) has been reported earlier from two on-board studies, where PN (>6nm) emission factors of 1.0-3.1×10^{12} 1/kWh (25-90% loads) together with 2.3-3.0×10^{12} 1/kWh (53-90% loads) and 1.4×10^{14}-3.0×10^{15} 1/kWh (6-50% loads) were reported. The results from recent on-board measurements showed lower values of 0.14-3.4×10^{12} 1/kWh (>23nm) and 0.39-26×10^{12} 1/kWh (>10nm) for ME4 with increase towards low load conditions. For ME3, the results were 0.65-23×10^{12} 1/kWh and 2.6-43×10^{12} 1/kWh, aligning with the previous results at high loads but remaining one to two orders of magnitude lower than the observations by Corbin et al., 2020. Different cut-points of the measurement instruments however complicate the comparison and instead of differences between engines may indicate high number of smallest particles in the exhaust.

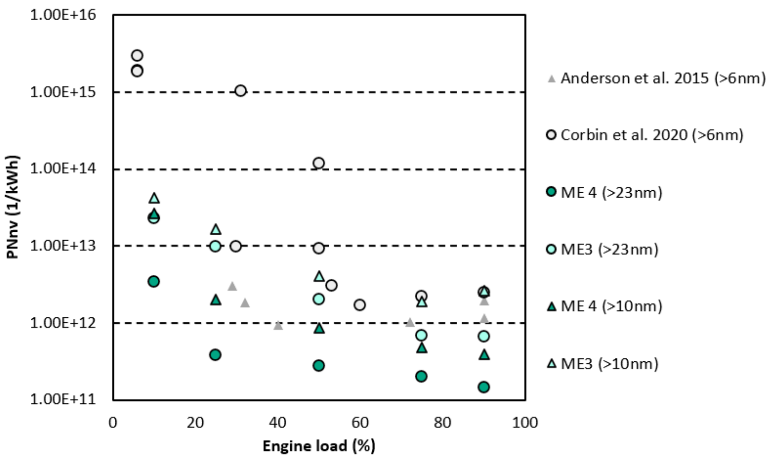

Figure 4: Non-volatile PN emission factors for LPDF 4-S engines studied on-board from literature and recent on-board measurements (Lehtoranta et al., 2023).

Conclusions

Review of literature presenting methane slip emission factors for LNG engines showed limited amount of available data for different LNG engine types. For HPDF engines, methane slip is considered low (0.2-0.3 g/kWh) and no load-dependent data was found. For other engine types, brake specific emissions increased towards low load conditions and varied between 2-26 g/kWh for LBSI, 2-70 g/kWh for LPDF 4-S, and 2-7 g/kWh for LPDF 2-S at 25-75% loads. In addition to NO$_x$, other gaseous and particle emissions were reported for LPDF 4-S engines. These emissions from on-board studies were complemented with recent measurements of two recently build engines on-board a modern RoPax ferry. Together they showed that reduced methane slip levels can be achieved with state-of-the-art LNG engine (3-7 g/kWh at 25-90% loads) and especially new combustion concept (1.4-1.6 g/kWh at 25-90% loads). NO$_x$, CO, CO$_2$, formaldehyde, and PN results from on-board studies show generally low levels for LPSF 4-S engines, but increased concentrations of especially PN and formaldehyde at low loads were shown.

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