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Propulsion of VLCC

Introduction
This paper evaluates the options when selecting an engine for a VLCC (very large crude carrier) on the basis of vessel speed, propeller diameter and CO₂ emissions. The influence of the various parameters is illustrated by two case studies.

The size of VLCCs, see Fig. 1, is normally within the deadweight range of 250,000-320,000 dwt, and the overall length is typically 315-335 m, making these vessels some of the largest vessels in commercial trade.

One of the goals in the marine industry today is to reduce the impact of CO₂ emissions from ships and, therefore, to reduce the fuel consumption for the propulsion of ships to the widest possible extent at any load.

This also means that the inherent design CO₂ index of a new ship, the energy efficiency design index (EEDI), will be reduced. Based on an average reference CO₂ emission from existing tankers, the CO₂ emission from new tankers in gram per dwt per nautical mile must be equal to or lower than the reference emission figures valid for the specific tanker.

This drive for lower CO₂ emissions may often result in operation at lower-than-normal service ship speeds compared to earlier, which results in reduced propulsion power. The design ship speed at normal continuous rating (NCR), including 15% sea margin, used to be as high as 16.0-16.5 knots. Today, the ship speed may be 15.5 knots, or even lower.

A more technically advanced solution is to optimise the aftbody and hull lines of the ship, thereby making it possible to fit propellers with a larger diameter and achieve a higher propeller efficiency at a lower optimum propeller speed.
For vessels that cannot accommodate a larger propeller, an improved propeller design such as the Kappel propeller can offer an increased efficiency of about 2-4% without increasing the propeller diameter.

As the two-stroke main engine is directly coupled to the propeller, the "green" ultra-long-stroke G80ME-C engine with an even lower-than-usual shaft speed will meet this drive and target goal. The main dimensions for this engine type, and for other existing VLCC engines, are shown in Fig. 2.

EEDI and Major Ship and Main Engine Parameters

Energy efficiency design index (EEDI)
The EEDI guidelines are a mandatory instrument adopted by the International Maritime Organization (IMO) that ensures compliance with international requirements on CO₂ emissions of new ships. The EEDI represents the amount of CO₂ in gram emitted when transporting one deadweight tonnage of cargo for one nautical mile.

The EEDI value is calculated on the basis of cargo capacity, propulsion power, ship speed, SFOC and fuel type. However, certain correction factors are applicable, e.g. for installed waste heat recovery systems (WHRS). To evaluate the calculated EEDI value, a required reference value for the specific ship type and the cargo capacity specified is used for comparison. The achieved EEDI value shall not exceed the required EEDI value.

As the standard, the main engine's 75% SMCR (specified maximum continuous rating) power is applied in the calculation of the EEDI value.

According to the EEDI guidelines implemented on 1 January 2013, the EEDI reference value for new ships is reduced in three steps leading to a final EEDI reduction of 30% for a vessel built after 2025.

There are a number of methods that can be applied to lower the EEDI value. By derating the engines, the specific fuel oil consumption (SFOC) is lowered due to lower mean effective pressure (MEP). Engine tuning methods such as exhaust gas bypass (EGB) can optimise the fuel curve at part load operation, thus reducing SFOC at 75% load.

The power installed is also a parameter that can be reduced to achieve a lower EEDI value. This can be achieved by either lowering the vessel speed, improving the hull design or by optimising the propeller design. Installation of green technologies, WHRS or changing fuel to liquid natural gas (LNG) will also lower the EEDI value.

Minimum propulsion power

While lowering the vessel's installed power has been acknowledged as a method to obtain a lower EEDI value, it has also created a concern that it could result in underpowered vessels with reduced manoeuvrability in rough weather. As a result of this, IMO has published an assessment method for determining the minimum propulsion power required to maintain the manoeuvrability of ships in adverse conditions.

The method for determining minimum propulsion power can be carried out by assessment level 1 or assessment level 2. Assessment level 1 allows one to calculate minimum propulsion power value based on vessel type and deadweight. If the total propulsion power installed is above this limit value, no further assessment is needed. However, if the propulsion power installed is below the given minimum propulsion power value of assessment 1, then an evaluation based on the vessel's design, and possibly a tank test can be performed as part of assessment level 2.

It should be noted that, at present, this assessment method is valid for phase 0 and phase 1 of EEDI. It is expected that it would also be incorporated for EEDI phase 2 which will come into force on 1 January 2020.

Major propeller and engine parameters

In general, the larger the propeller diameter, the higher the propeller efficiency and the lower the optimum propeller speed referring to an optimum ratio of the propeller pitch and propeller diameter.

When increasing the propeller pitch for a given propeller diameter with optimum pitch/diameter ratio, the corresponding propeller speed may be reduced and the efficiency will also be slightly reduced, of course depending on the degree of the changed pitch. The same is valid when reducing the pitch, but here the propeller speed may increase.

The efficiency of a two-stroke main engine depends particularly on the ratio of the maximum (firing) pressure and the mean effective pressure. The higher the ratio, the higher the engine efficiency, and the lower the SFOC.

Furthermore, the higher the stroke/bore ratio of a two-stroke engine, the higher the engine efficiency. This means, for example, that an ultra long stroke engine type, as the G80ME-C9.1, has a higher efficiency compared with a shorter stroke engine type, such as a 570ME-C9.1.

Based on a case study of a 320,000 dwt VLCC, this paper shows the influence on fuel consumption when choosing engine layout, vessel speed and propeller diameter. The focus of this paper is on the 880ME-C9.1 engine, a widely applied engine for the tanker segment, compared with the 570ME-C9.1 engine with a longer stroke and higher L1 mean effective pressure. The layout ranges from 6 to 8 cylinder engines of the S and G types, as shown in Fig. 3.

As for the EEDI evaluation, the case studies in this paper are based on high-load tuned engines, without taking into account the tuning methods, alternative fuels, WHRS or shaft generators. Consequently, the resulting EEDI values are considered to be conservative.
320,000 dwt VLCC

For a 320,000 dwt VLCC tanker, the following case study illustrates the potential for reducing fuel consumption by increasing the propeller diameter and applying the 8G80ME-C9.5 as main engine.

Based on the average ship particulars given in Table I, a power prediction can be calculated (by Holtrop & Mennen’s method) for the different design ship speeds and propeller diameters. Based on these predictions, the corresponding SMCR power and speed, point M, for propulsion of the VLCC can be found, see Fig. 3. The propeller diameter change corresponds approximately to the constant ship speed factor:

\[ \alpha = 0.24 \]  

\[ p_{M2} = p_{M1} \times \left( \frac{n_2}{n_1} \right)^\alpha \]

Referring to the two ship speeds of 15.8 knots and 15.0 knots, respectively, Fig. 3 illustrates four potential main engine types with the pertaining layout diagrams and SMCR points. The main engine operating costs have been calculated and described individually for each ship speed case.

Table 1: Average ship particulars

<table>
<thead>
<tr>
<th>Average ship particulars</th>
<th>22.5 m</th>
<th>21.0 m</th>
<th>333.0 m</th>
<th>319.0 m</th>
<th>60.0 m</th>
<th>15%</th>
<th>10%</th>
<th>15.8 and 15.0 Kn</th>
<th>4 blades</th>
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<tbody>
<tr>
<td>Scantling draught</td>
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<td>Design draught</td>
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<td>Sea margin</td>
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<td>Engine margin</td>
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<tr>
<td>Design ship speed</td>
<td>15.8</td>
<td>15.0</td>
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<td>Type of propeller</td>
<td>FPP</td>
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<td>No. of propeller blades</td>
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<tr>
<td>Propeller diameter</td>
<td>9.8, 10.6 and 11.0 m</td>
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</table>

Fig. 4 shows the influence of the propeller diameter when going from about 9.8 to 11.0 m. Assuming that the constant ship speed coefficient of 0.24 is valid, thus, N3 for the 8G80ME-C9.5 with an 11.0 m propeller diameter has a propulsion power demand that is about 4.9% lower compared with N1 valid for the 7S80ME-C9.2 and, with a propeller diameter of about 9.8 m.

Fig. 5 shows the influence on the main engine efficiency, indicated by the SFOC for the three cases. N2 for the 8G80ME-C9.5 has an SFOC of 157.2 g/kWh, whereas the N3, also for the 8G80ME-C9.5, has a higher SFOC of 157.8 g/kWh because of the higher mean effective pressure.

The 157.2 g/kWh SFOC of the N2 for the 8G80ME-C9.5 is 3.2% lower compared with N1 for the nominally rated 7S80ME-C9.2 with an SFOC of 164.5 g/kWh. Several differences lead to this result, such as the higher stroke/bore ratio of this G-engine type and the higher maximum MEP and, not least, because one extra cylinder offers the benefit of engine derating.

**Main Engine Operating Costs – 15.8 knots**

The main engine fuel consumption and operating costs at NCR (given as N1-N3 in Fig. 4, 5 and 6) have been calculated for the three main engine/propeller cases operating at the relatively high ship speed of 15.8 knots, see Table 2. Furthermore, the corresponding EEDI value has been calculated on the basis of the 75% SMCR-related figures (without sea margin).

**Fuel consumption and EEDI**

Table 2: Calculated main engine examples

<table>
<thead>
<tr>
<th>Engine ratings at 15.8 knots design speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 7S80ME-C9.2 M1 = 27,750 kW x 77.5 r/min</td>
</tr>
<tr>
<td>2. 8G80ME-C9.5 M2 = 26,800 kW x 67.3 r/min</td>
</tr>
<tr>
<td>3. 8G80ME-C9.5 M3 = 26,380 kW x 63.0 r/min</td>
</tr>
</tbody>
</table>

Fig. 6 shows the influence of the engine shaft power at NCR when going from 77.5 to 67.3 r/min. Assuming that the constant engine efficiency is valid, thus, M1 for the 7S80ME-C9.2 with an engine shaft power of about 25,875 kW has an expected propulsion power demand at NCR of 24,875 kW, whereas the N2 and N3, both for the 8G80ME-C9.5, have a lower propulsion power demand at NCR of 24,130 kW and 23,714 kW, respectively.

Table 2: Calculated main engine examples

<table>
<thead>
<tr>
<th>Engine power at NCR [kW]</th>
<th>Expected engine power at NCR (%)</th>
<th>Relative power reduction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>7S80ME-C9.2</td>
<td>M1 = 27,750</td>
<td>25,875</td>
</tr>
<tr>
<td>8G80ME-C9.5</td>
<td>M2 = 26,800</td>
<td>24,130</td>
</tr>
<tr>
<td>8G80ME-C9.5</td>
<td>M3 = 26,380</td>
<td>23,714</td>
</tr>
</tbody>
</table>
Installing one cylinder more than required to achieve the necessary engine power means a higher first cost and maintenance cost of the engine. But when evaluating the fuel consumption over a complete load profile, the yearly cost savings will, in most cases, quickly pay back the increased first cost and maintenance cost.

When multiplying the propulsion power demand at N1 (Fig. 4) with the SFOC (Fig. 5), the daily fuel consumption at NCR is found, as shown in Fig. 6. Compared with N1 for the 7S80ME-C9.2, the total reduction of fuel consumption of the 8G80ME-C9.5 at N3 is about 7.6%.

The reference and the actual EEDI figures have been estimated and are illustrated in Fig. 7. The reference case 1 has a resulting EEDI value that is higher than the requirement of phase 1 (2015) limit. Cases 2 and 3, with reduced engine power and lower SFOC values, are within the limit of phase 1, but not compliant with phase 2 (2020).

Considering the minimum propulsion power, Fig. 3 shows that cases 1 and 2 are rated higher than assessment level 1, which means that the propulsion power is found to be sufficient without further evaluation needed. However, case 3 SMCR rating is below assessment level 1 power level and needs to be evaluated after assessment level 2, before it can be concluded whether the vessel is sufficiently powered or not.

Operating costs

Whereas the previous comparisons of engine fuel performance are based on a constant engine load of 90% (NCR), the yearly operational costs of the engine greatly depends on the engine’s load profile.

Large crude oil carriers typically sail in a predictable pattern with long time contracts of long haul, trans-oceanic crude oil transportation, where the two major load points are defined by laden and ballast condition. Some manoeuvring time is to be excepted, as well as some time at full power to either catch up, or increased load due to rough weather.

An example of a load profile for a VLCC, see in Fig. 8, is applied to calculate the total main engine operating costs, including lubrication oil per year, assuming an operation profile of 250 days/year. For this purpose, a fuel price of 300 USD/t and lubrication oil price of 1,000 USD/t is assumed and the results are shown in Fig. 9.
The relative savings in operating costs in net present value (NPV) with the 7S80ME-C9.2 with a propeller diameter of about 9.8 m used as the basis, indicates an NPV saving for the 8G80ME-C9.5 engines after some years in service, as illustrated in Fig. 10. After 10 years in operation the saving is about 3.0 million USD for case 2, 8G80ME-C9.5 with the SMCR speed of 67.3 r/min and propeller diameter of about 10.6 m. For case 3, also with an 8G80ME-C9.5 but with an SMCR speed of 62.9 r/min and a propeller diameter of about 11.0 m, the saving is about 3.6 million USD.

Main Engine Operating Costs – 15.0 knots
The main engine fuel consumption and operating costs at NCR (given as N'1-N'3 in Fig. 11, 12 and 13) have been calculated for the three main engine/propeller cases, see Table 3, operating at the relatively lower ship speed of 15.0 knots, which may be a more normal choice in the future. Furthermore, the EEDI value has been calculated on the basis of the 75% SMCR related figures (without sea margin).

Fig. 11 shows the influence of the propeller diameter when going from about 9.8 to 11.0 m. Assuming that the constant ship speed coefficient of 0.24 is valid, thus, N3’ for the 7G80ME-C9.5 with an 11.0 m propeller diameter has a propulsion power demand that is about 4.8% lower compared with the N1’ valid for the 6S80ME-C9.2 with propeller diameter of about 9.8 m.

Fig. 12 shows the influence on the main engine efficiency, indicated by the SFOC for the three cases. N3’ with the 7G80ME-C9.5 has a relatively low SFOC of 152 g/kWh compared with the 163.5 g/kWh for N1’ for the 6S80ME-C9.2, i.e. an SFOC reduction of about 3.1%, caused by the derating potential used for the one cylinder larger 7G80ME-C9.5 engine, and applying the more efficient G engine.
The daily fuel consumption at NCR is found by multiplying the propulsion power demand at N’ (Fig. 11) with the SFOC (Fig. 12), see Fig. 13. The total reduction of daily fuel consumption at NCR of the 7G80ME-C9.5 is about 7.7% compared with the 6S80ME-C9.2.

The reference and the actual EEDI values have been estimated and are shown in Fig. 14. As can be seen for all three cases, the actual EEDI values are now lower than the reference figure because of the relatively low ship speed of 15.0 knots. Particularly, case 3’ with 7G80ME-C9.5 has a low EEDI – as the only example compliant with IMO Tier II.

The relative savings in operating costs in net present value (NPV) for the 6S80ME-C9.2 with a propeller diameter of 9.6 m as the basis, indicate a saving in NPV for the 7G80ME-C9.5 engine after some years in service, see Fig. 16. After 10 years in operation, the saving is about 2.7 million USD for the 7G80ME-C9.5 with an SMCR speed of 63.7 r/min and a propeller diameter of 10.6 m, and about 3.1 million USD for the derated 7G80ME-C9.5 with the low SMCR speed of 59.6 r/min and a propeller diameter of 11.0 m.

Operating costs
Same as for the case with a vessel speed of 15.0 knots, an example of a load profile for a VLCC is given in Fig. 8, which is applied to calculate the total main engine operating costs including lubricating oil per year, 250 days/year. For this purpose, a fuel price of 300 USD/t and a lubricating oil price of 1,500 USD/t has been assumed, and the results are shown in Fig. 15.

The relative savings in operating costs for 15.0 knots are rated lower than assessment level 1 and needs to be evaluated after assessment level 2, before concluding if the vessel is sufficiently powered or not.

The daily fuel consumption at NCR is found by multiplying the propulsion power demand at N’ (Fig. 11) with the SFOC (Fig. 12), see Fig. 13. The total reduction of daily fuel consumption at NCR of the 7G80ME-C9.5 is about 7.7% compared with the 6S80ME-C9.2.

The reference and the actual EEDI values have been estimated and are shown in Fig. 14. As can be seen for all three cases, the actual EEDI values are now lower than the reference figure because of the relatively low ship speed of 15.0 knots. Particularly, case 3’ with 7G80ME-C9.5 has a low EEDI – as the only example compliant with the phase 2 requirement. Considering the minimum propulsion power, it is shown in figure 3 that the three cases are rated lower than assessment level 1 and needs to be evaluated after assessment level 2, before concluding if the vessel is sufficiently powered or not.
Summary

Traditionally, super-long-stroke S-type engines, with relatively low engine speeds, have been applied as the prime movers in tankers.

Following the efficiency optimisation trends in the market, the possibility of using even larger propellers has been thoroughly evaluated with a view to using engines with even lower speeds, in particular for the propulsion of VLCCs.

VLCCs may be compatible with larger propeller diameters than the current designs. Together with optimisation of the hull and propeller design, higher fuel efficiencies can be achieved.

The ultra-long-stroke G80ME-C9.5 engine type meets this trend in the VLCC market. This paper indicates, depending on the propeller diameter used and engine derating, an overall efficiency increase of 4-8% when using a G80ME-C9.5 instead of the existing main engines applied so far.

The energy efficiency design index (EEDI) is also improved when using a G80ME-C9.5. In order to meet the EEDI values coming into play in 2020 and 2025, the design of the ship itself and the design ship speed applied (reduced speed) has to be evaluated by the shipyards, possibly together with the application of efficiency increasing devices such as WHR or, alternatively, the use of alternative fuels, to further reduce the EEDI, also taking into consideration the IMO minimum propulsion power requirements.