Energy Efficiency Design Index Verification through Actual Power and Speed Correlation

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Abstract. The International Maritime Organization (IMO) mandatory requirement for Energy Efficiency Design Index (EEDI) has been in place since 01 January 2015 to address emission and global warming concerns. This regulation must be satisfied by newly-built ships with 400 gross tonnages and above. In addition, the MEPC-approved 2013 guidance, ISO 15016 and ISO 19019 on EEDI serves the purpose for calculation and verification of attained EEDI value. As such, verification should be carried-out through an acceptable method during sea trial and this demands extensive planning during propulsion power system design stage. Power and speed assessment plays the important factor in EEDI verification. The shaft power can be determined by telemeter system using strain gage while the ship speed can be verified and calibrated by differential ground positioning system (DGPS).

An actual measurement was carried-out on a newly-built ship during sea trial to assess the correlation between speed and power. In this paper, the Energy-efficiency Design Index or Operational Indicator Monitoring System (EDiMS) software developed by the Dynamics Laboratory-Mokpo National Maritime University (DL-MMU) and Green Marine Equipment RIS Center (GMERC) of Mokpo National Maritime University was utilized. Mainly, EDiMS software employs four channels – engine speed, ship speed, shaft power and fuel consumption - for the verification process. In addition, the software can continuously monitor air pollution and is a suitable tool for inventory and ship energy management plan. Ships greenhouse gas inventory can likewise be obtained from the base of emission result during the engine shop test trial and the actual monitoring of shaft power and ship speed. It is suggested that an integrated equipment and compact software be used in EEDI verification. It is also perceived that analog signals improve the measurement accuracy compared to digital signal. Other results are presented herein.

Keywords: shaft power, ship speed, exhaust gas emissions, energy efficiency design index (or operational indicator) (EEDI, EEOI), ship energy efficiency management plan (SEEMP).

1. Introduction

Shipping is the most efficient form of cargo transportation and with its increasing globalization have lead to the continued growth of the maritime transport. Along with this development, ships’ exhaust emissions into the environment have become a big concerning issue. In addition, potential harmful influence on human health, cause acid rain and contribute to global warming are seen to be some of the negative effects of these emissions. In 2009, the shipping sector was estimated to have emitted around 3.3% of global CO₂ emissions of which the international shipping contributed roughly 2.7% or 870 million tonnes. If unabated, shipping’s contribution to greenhouse gases (GHG) emissions could reach 18% by 2050 [1].

To address this concern, the IMO’s pollution prevention treaty (MARPOL) under Annex VI has adopted the mandatory energy-efficiency measures to reduce emissions of GHG from international shipping. In July 2011, the ‘Energy Efficiency Design Index’ (EEDI) was adopted setting the minimum energy efficiency requirements and must not be exceeded the given threshold by new ships built after 2013. It is based on a complex formula, taking the ship’s emissions, capacity and speed into account. The target requires most new ships with 400 gross tonnages and above to be 10%- , 20%- , and 30% more efficient.
by the year 2015, 2020 and 2025 respectively. The required EEDI value for newly-built tanker vessels with variation capacities is shown in Figure 1.

\[
E = \frac{C_2 \cdot e_1}{T} = \sum C \frac{f \cdot c}{S \cdot t} \cdot \frac{d}{0}
\]

(1)

**Figure 1** Required EEDI newly-built tanker vessels with variation capacities

Power and speed assessment plays the important factor in EEDI verification in accordance with the ISO regulations (Equation 1). The engine power can be measured by telemetric system using strain gage. The ship speed is obtained by differential ground positioning system (DGPS). An actual measurement was carried-out on a newly-built ship during sea trial to assess the correlation between speed and power. During sea trial, the output power, sailed route and ship speed were measured simultaneously. All signals were recorded and analyzed by **EVAMOS (Engine / Rotor Vibration Analysis Monitoring System)** software with **EDiMS** developed by the DL-MMU and the GMERC of Mokpo National Maritime University [2]. The software can continuously monitor air emission and is a suitable tool for inventory and ship energy management plan. Ships GHG inventory can likewise be obtained from the base of emission result during the engine shop test trial and the actual monitoring of shaft power and ship speed. It is suggested that an integrated equipment and compact software be used in EEDI verification. It is also perceived that analog signals improve the measurement accuracy compared to digital signal.

### 2. Engine power and ship speed measurement with EDiMS software

#### 2.1 Power measurement

For power measurement, the MANNER telemetric system was used. One full bridge strain gage (Wheatstone bridge) was installed to measure the shear stress on the intermediate shaft when the engine is running. The basic diagram of the Wheatstone bridge is shown in Figure 2. It includes 4 gages having variable resistors changing proportionally with the changing of the surface length of the shaft. When stress exists, it results in shaft deformation and changes the gage resistance and consequently change the ratio between the output and input voltage \((V_{out}/V_{in})\) applied on the strain gage. This ratio varies as a linear function of the stress on shaft. As such, the torque generated on shaft by the diesel engine can be measured after calibration. Together with the shaft speed measured by tachometer, the shaft power can be obtained by the following equations:
\[ P = T = T \frac{2n}{6} \]  \hspace{1cm} (2)

with:
\[ T = 2\pi G Z_p \]  \hspace{1cm} (3)
\[ Z_p = \frac{\pi d^3}{4} \]  \hspace{1cm} (4)

Where: \( P \) is power (W); \( T \) is torque (N); \( \omega \) is angular velocity (rad/s); \( n \) is shaft speed (r/min); \( G \) is modulus of elasticity (N/m²); \( Z_p \) is section modulus (m³); \( d \) is shaft diameter (m).

The engine power also can be measured via angular velocity signal. Two systems are recommended to be installed to ensure continuous engine power measurement in the event one of them failed. The principal method for measuring angular velocity is using equidistant pulses over a single shaft revolution. Rotating motion sensors such as gap sensor, magnetic switch sensor, or an encoder can be used to get the signal of pulses train which has frequency proportional to the angular velocity of rotating body. The frequency can be measured and then converted to voltage by an F-V converter. From achieved angular velocity, the angular acceleration can be calculated where torque and engine power is obtained. The telemetric system and strain gage installation is shown in Figure 3 while the system used for measuring engine power and ship speed is illustrated by schematic diagram in Figure 4.

2.2 Ship speed measurement

In order to measure the ship speed, the speed system including one DGPS antenna and the ship speed meter (CVC-100GD) was installed. In this system, the antenna acquires the DGPS signal in purpose to determine the ship’s location (by longitude and latitude) in real time. By the location signal, the ship speed and the sailed route can be obtained.

Figure 5 shows the sailing route guidelines for speed trials and should be carried out using double runs, i.e. each run followed by a return run in the exact opposite direction performed with the same engine settings. The number of such double runs shall not be less than three and should be performed in head
and following winds preferably. Each run shall be preceded by an approach run, which shall be of sufficient length to attain steady running conditions [4].

2.3 EEDI monitoring by EDiMS

Full formula for EEDI calculation:

\[
EEDI = \frac{\sum_{i=1}^{n} (P_{ME(i)} C_{ME(i)} SFC_{ME(i)} f_{i}) - \sum_{i=1}^{n} (P_{AE(i)} C_{AE(i)} SFC_{AE(i)} f_{j}) - \sum_{i=1}^{n} (P_{PTI} C_{PTI}) - \sum_{i=1}^{n} (P_{AE} C_{AE} SFC_{AE} f_{i})}{f_{i} C_{capacity} N_{ref} f_{M}}
\]

Engine Power (P) at 75% load

- \( P_{eff} \) main engine power reduction due to individual technologies for mechanical energy efficiency
- \( P_{AEff} \) auxiliary engine power reduction due to individual technologies for electrical energy efficiency
- \( P_{PTI} \) power take in
- \( P_{AE} \) combined installed power of auxiliary engines
- \( P_{ME} \) main engine power

\( C_{ME} \) Main engine composite fuel factor
\( C_{FAE} \) Auxiliary engine fuel factor
\( C_{FME} \) Main engine individual fuel factors

Ship Design Parameters

\( V_{ref} \) Ship speed
Capacity Deadweight Tonnage (DWT)

EDiMS software is included in EVAMOS program developed by DL-MMU. Figure 6 shows the design concept display unit of EDiMS. For monitoring EEDI on the simple propulsion system, EDiMS software simply requires signals from engine speed, ship speed and shaft power. The fuel consumption and NO\(_x\), SO\(_x\), PM emission value measured from shop test can be used by the curve fitting method of the Equation 6. Likewise, the fuel consumption of prime mover can be applied alternatively by converting voltage signal of fuel flowmeter. SO\(_x\) emission is calculated from sulphur content and fuel consumption quantity.

![Figure 6 EDiMS system and display unit configuration](image-url)
\[ y = c_0 + c_1 x + c_2 x^2 + c_3 x^3 \]  \hspace{1cm} (6)

Where \( c_0, c_1, c_2, c_3 \) are coefficients for each of fuel consumption, NO\(_x\), SO\(_x\), PM emission - \( y \); \( x \) is the part load ratio for maximum continuous rating.

**Figure 7 EDiMS monitor display configuration**

**Figure 8 EDiMS raw signal and emission values display**
Figure 7 shows the setup configuration of EDiMS software. In the case of absence of ship speed signal from DGPS, ship speed can be estimated by using the shaft speed and propeller pitch data with assuming there is no slip. The full equation of EEDI (Equation 5) used for EDiMS includes several adjustment and tailoring factors to suit specific classes of vessels and alternate configurations and operating conditions, but in the case of simple propulsion system without driven generator installed on shaft and ignoring the negligible factors, the fundamental formula can be simplified to Equation 7:

\[
EEDI = \frac{(P_{ME} \times C_{FME} \times SFC_{ME}) + (P_{AE} \times C_{FAE} \times SFC_{AE})}{\text{Capacity} \times V_{ref}}
\]  

For ships with main engine power of 10,000 kW or above:

\[
P_{AE} = 0.025 \times MCR_{ME} + 250
\]  

For ships with main engine power below 10,000 kW:

\[
P_{AE} = 0.05 \times MCR_{ME}
\]  

with \( MCR_{ME} \) is main engine power at MCR (kW).

2.4 EEDI monitoring by EDiMS on actual ship test

The EVAMOS program including EDiMS software was used for EEDI monitoring on a new built ship. Table 1 lists the ship and main engine specifications. The measurement was carried out during the speed test of sea trial in order to settle the relation between ship’s speed and engine load as well as the EEDI calculation. The comparison of measured fuel consumption during sea trial and the builder shop test is given in Table 2.

**Table 1 Specification of experiment ship and main engine**

<table>
<thead>
<tr>
<th>Ship</th>
<th>Type</th>
<th>Capacity</th>
<th>Ship length</th>
<th>Breadth</th>
<th>Draft</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tanker</td>
<td>158,863 tonnes</td>
<td>247.17 m</td>
<td>48.00 m</td>
<td>17.15 m</td>
<td>2016</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Main engine</th>
<th>Type</th>
<th>Power at MCR</th>
<th>Max. continuous speed</th>
<th>Cylinder bore</th>
<th>Stroke</th>
<th>No. of cylinder</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6G70ME-C9.2</td>
<td>16,590 kW</td>
<td>77.1 r/min</td>
<td>700 mm</td>
<td>3,256 mm</td>
<td>6</td>
</tr>
</tbody>
</table>

**Table 2 Fuel consumption of 6G70ME-C9.2 engine at sea trial and builder shop test**

<table>
<thead>
<tr>
<th>Load</th>
<th>25%</th>
<th>50%</th>
<th>70%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>M/E r/min</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Round</td>
<td>R-1</td>
<td>R-2</td>
<td>R-1</td>
<td>R-2</td>
<td>R-3</td>
</tr>
<tr>
<td>Mean value at sea trial (g/kW-hr)</td>
<td>164.98</td>
<td>164.79</td>
<td>168.2</td>
<td>166.25</td>
<td>167.75</td>
</tr>
<tr>
<td>Shop test result (g/kW-hr)</td>
<td>175.66</td>
<td>165.34</td>
<td>163.46</td>
<td>165.86</td>
<td>170.18</td>
</tr>
</tbody>
</table>
Based on the fuel consumption of builder shop test, the coefficients for fuel consumption were obtained to be: $c_0 = 208.86; c_1 = -1.896, c_2 = 0.0253, c_3 = -0.0001$. By using these coefficients, EDiMS software can estimate the engine fuel consumption for each power load ratio at any certain engine speed. The fuel used for engine is heavy fuel oil (HFO), the CO$_2$ emission rate $C_{FME} = C_{FAE} = 3.144$ ton CO$_2$/ton fuel (Figure 9); $SFC_{AE} = 190$ g/kW-hr; $P_{AE} = 664.75$ kW. In addition, with the signals of shaft power from strain gage and ship speed from DGPS sensor, the EEDI was calculated and monitored online. Under the IMO guidance for speed - power measurement, the measuring time for each round is at least 10 minutes at constant condition. All data were saved on computer and can be analysed again in laboratory.

![Figure 10 Sailed route and ship speed measured by DGPS sensor at 75% load Round 1](image)

![Figure 11 Sailed route and ship speed measured by DGPS sensor at 75% load Round 2](image)

![Figure 12 Shaft power measured by strain gage at 75 % load Round 1](image)
Table 4 Measuring results and EEDI calculation

<table>
<thead>
<tr>
<th>Load</th>
<th>70%</th>
<th>75%</th>
<th>100%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Round</td>
<td>R-1</td>
<td>R-2</td>
<td>R-1</td>
</tr>
<tr>
<td></td>
<td>R-2</td>
<td>R-3</td>
<td>R-4</td>
</tr>
<tr>
<td></td>
<td>R-1</td>
<td>R-2</td>
<td></td>
</tr>
<tr>
<td>Engine power (kW)</td>
<td>11,314</td>
<td>11,076</td>
<td>12,058</td>
</tr>
<tr>
<td></td>
<td>11,866</td>
<td>11,862</td>
<td>11,970</td>
</tr>
<tr>
<td></td>
<td>15,673</td>
<td>15,648</td>
<td></td>
</tr>
<tr>
<td>Fuel consumption (g/kW-hr)</td>
<td>164.98</td>
<td>164.79</td>
<td>168.2</td>
</tr>
<tr>
<td></td>
<td>166.25</td>
<td>167.75</td>
<td>166.84</td>
</tr>
<tr>
<td></td>
<td>171.66</td>
<td>171.83</td>
<td></td>
</tr>
<tr>
<td>Ship speed (knots)</td>
<td>13.52</td>
<td>14.53</td>
<td>15.37</td>
</tr>
<tr>
<td></td>
<td>13.80</td>
<td>15.60</td>
<td>14.72</td>
</tr>
<tr>
<td></td>
<td>15.36</td>
<td>17.79</td>
<td></td>
</tr>
<tr>
<td>EEDI (g CO₂/t nm)</td>
<td>2.89</td>
<td>2.63</td>
<td>2.75</td>
</tr>
<tr>
<td></td>
<td>2.98</td>
<td>2.66</td>
<td>2.83</td>
</tr>
<tr>
<td></td>
<td>3.59</td>
<td>3.10</td>
<td></td>
</tr>
<tr>
<td>EEDI&lt;sub&gt;average&lt;/sub&gt;</td>
<td>2.76</td>
<td>2.80</td>
<td>3.35</td>
</tr>
</tbody>
</table>

The data measured during this sea trial using the EDiMS software confirms the correlation between engine fuel consumption, shaft power, ship speed and CO₂ emission. Based on these factors, EDDI value was calculated and shown in Table 4. Officially, the correction speed should be used for calculation with the concern of the wind, sea wave and the other sea conditions and is a complex calculation. The ship speed used in this study (non – official test) is actual speed without correction. The measurement results indicated that the EEDI value of subject vessel increases at higher load. The required EEDI is the limit for the attained EEDI of a ship and depends on its type and size and its calculation involves use of reference lines and reduction factors. Reference line represents the reference EEDI as a function of ship size. Reduction factor represents the percentage points for EEDI reduction relative to the reference line, as mandated by regulation for future years. This factor is used to tighten the EEDI regulations in phases over time by increasing its value. The reduction factor at different phase implementation is shown in Table 5.

Table 5 Reduction factor (%) for the EEDI relative to the EEDI reference line [5]

<table>
<thead>
<tr>
<th>Ship type</th>
<th>Capacity (DWT)</th>
<th>Phase 0 from Jan 2013</th>
<th>Phase 1 from Jan 2015</th>
<th>Phase 2 from Jan 2020</th>
<th>Phase 3 from Jan 2025</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tanker</td>
<td>&gt;15,000</td>
<td>0</td>
<td>10</td>
<td>20</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>3000-15,000</td>
<td>n/a</td>
<td>0-10*</td>
<td>0-20*</td>
<td>0-30*</td>
</tr>
<tr>
<td>General cargo ship</td>
<td>&gt;20,000</td>
<td>0</td>
<td>10</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td></td>
<td>4,000-20,000</td>
<td>n/a</td>
<td>0-10*</td>
<td>0-15*</td>
<td>0-30*</td>
</tr>
</tbody>
</table>

* Reduction factor to be linearly interpolated between the two values dependent upon vessel capacity. The lower value of the reduction factor is to be applied to the small ship size. n/a means that no required EEDI applies.

The reference line values can be calculated as (see Figure 1):

\[ R = a \times E^{-c} \]  \hspace{0.5cm} (10)

\[ R = (1 - r) \times f /100 \times R_t E \]  \hspace{0.5cm} (11)

For tanker: \( a = 1218.80, c = 0.488 \) [5]. Attained EEDI must always be less than or equal to required EEDI.
The subject vessel was built in 2016 and thereby must adhere to Phase 1 of the EEDI reduction factor equivalent to 10%. The shaft power ratio required by the IMO regulation is at 75% load only, however at all the other load conditions, the EEDI value (Table 4) is lower than the required limit (about 3.53 g CO₂/t nm). As such, the subject vessel satisfies the IMO regulation for Energy Efficiency Design Index. In addition, monitoring the SOₓ, NOₓ, PM emission are available in EDiMS software. All of these signals can be measured, analysed and displayed online. File management of all data can be saved on hard drive of PC storage or either be transmitted to onshore shipping company office through internet connection.

3. Conclusion

Owing to rapid development in the shipping industry and maritime transportation, air pollution emissions from ocean-going ships are continuously increasing. Exhaust gases from ships contain CO₂ and many other harmful pollutants. The increased volume of air pollutant results in serious negative effects to environment, to human health and contributes to global warming. In order to control CO₂ emission from shipping, the Energy Efficiency Design Index requirement was adopted by IMO for newly-built ships. The EEDI expresses the amount of CO₂ emission on transport ability, assesses the energy consumption of a ship under normal seagoing conditions. The passage of EEDI regulation came with one important compromise that could affect the magnitude of benefits in developing more efficient ships to serve the demand.

The Energy-efficiency Design Index or Operational Indicator Monitoring System (EDiMS) was developed by DL-MMU in order to analyse and monitor EEDI on the base of results during the engine shop test trial and the actual monitoring of shaft power and ship speed. It is recommended for EEDI verification to use a compact software capable of measuring the shaft power and ship speed simultaneously. This software is a suitable tool for inventory and ship energy management plan. Not only EEDI, EDiMS can estimate and help to control air pollution source in exhaust gases such as SOₓ, NOₓ and PM. All of the energy-efficiency indexes can be displayed online continuously and transmitted to other server via internet connection. The software capability should be continually improved according to the expectations and participations from the ship owners and shipping companies with accurate advices from specialists.

References

[3] MAN Diesel & Turbo, EEDI - Energy Efficiency Design Index, Copyright ©MAN Diesel & Turbo, D2366498EN-N2, printed in Germany GGKM-04152.