Predrag Čudina

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ANALYSIS OF THE ENERGY EFFICIENCY DESIGN INDEX WITH A PROPOSAL FOR IMPROVEMENT

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Preliminary communication

Summary

This paper presents the actual method for the calculation of Energy Efficiency Deign Index and analyses the influence of particular variables on the resulted EEDI. Perceived inconsistencies of the actual method of calculation of the attained EEDI are presented with explanation of the influence that the actual calculation has on the design of new ships. Objections are clearly demonstrated on the example of conceptual design of Handy Bulk Carrier. Alternative proposals for improvement of calculation of attained EEDI are introduced. Suggested alterations eliminate observed deficiencies of the existing calculation.

Key words: *energy efficiency design index; ship design*

1. Introduction

In 2011 International Maritime Organization adopted amendments to MARPOL Annex VI, according to which Energy Efficiency Design Index (EEDI) became mandatory for all new ships contracted on or after 1 January 2013 [1]. Amendments set measures to reduce emissions of greenhouse gases - reference lines for the calculation of the required EEDI for various types of ships and formula for calculation of the attained EEDI. Also, required EEDI reduction factors (improvements of design efficiency) were set for the period up to 1 January 2025.

2. Calculation of Attained and Required Energy Efficiency Design Index

Attained EEDI must be less than or equal to the value required for the particular period [1].

$$\text{Attained EEDI} \leq \text{Required EEDI} = (1 - X/100) \times \text{Reference line value}$$

where:

X – reduction factor for the required EEDI compared to EEDI Reference line

The reference line for required EEDI can be calculated as:

$$\text{Reference line} = a \times b^{-c}$$

where:

b (t) – deadweight

a (-), c (-) – non-dimensional parameters for the different ship types

Formula for calculation of attained EEDI is as follows [2,3]:

$$\frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE} *\right) + \left(\left(\prod_{j=1}^{n} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME} **\right)}{f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref}}$$

In the most cases (bulk carriers, tankers, gas carriers, ro-ro cargo ships, general cargo ships, refrigerated cargo carriers and combination carriers with the standard configuration of the propulsion system and without ice class) formula can be simplified as follows:

$$EEDI_{attained} = \frac{P_{ME} \cdot C_{FME} \cdot SFC_{ME} + P_{AE} \cdot C_{FAE} \cdot SFC_{AE}}{f_i \cdot DWT \cdot V_{ref}}$$

where:

P_{ME} (kW) – 75% of the selected maximum continuous rating (SMCR)

C_{FME} (-) – non-dimensional conversion factor between main engine fuel consumption and CO_2 emission

SFC_{ME} (g/kWh) – main engine specific fuel oil consumption

P_{AE} (kW) – required auxiliary engine power to supply normal maximum sea loading, calculated as:

$$P_{AE} = 0.05 \times SMCR \text{ for SMCR} < 10{,}000 \text{ kW}$$

$$P_{AE} = 0.025 \times SMCR + 250 \text{ for SMCR} \geq 10{,}000 \text{ kW}$$

C_{FAE} (-) – non-dimensional conversion factor between auxiliary engine fuel consumption and CO_2 emission

SFC_{AE} (g/kWh) – auxiliary engine specific fuel oil consumption

$f_i = 1 + (0.08 \text{ x } LWT / DWT)$ – for ships built under Common Structural Rules

LWT – lightweight of the ship

DWT (t) – deadweight on summer load draught

V_{ref} (kn) – ship speed on deep water corresponding to DWT and P_{ME}, no sea margin

Basically, attained EEDI represents the quantity of emitted CO_2 per deadweight tonne and knot.

3. Influence of Particular Variables on the Attained EEDI

It can be demonstrated that the formula for calculation of attained EEDI favours designs with low P_{ME}, i.e. with low *SMCR*. If we consider deadweight and f_i as fixed, EEDI is a simple function linearly proportional to the main engine power P_{ME}, and inversely proportional to the ship’s speed V_{ref}. Knowing that power grows approximately with the cubic exponent of ship’s speed, it is easy to conclude that the numerator of expression grows much faster than the denominator. This method of EEDI calculation has forced designers to set continuous service rating (*CSR*) on the level of 90% *SMCR*, or very close to it. As a consequence, there appears to be a problem of 'shortage' of the main engine power which is evident especially when sailing in heavy seas.

4. Negative Consequences of the Existing Method of Calculation of the Attained EEDI

In the rough sea, a propeller curve in the power-speed diagram shifts to the left, where the main engine can deliver less power. In this situation safety of the ship is reduced and both crew and cargo are endangered. All of this has already been observed, and the major main engine manufacturers revised the recommendations for the propeller light running margin, so now they recommend to increase it [4]. Unfortunately, this recommendation leads to the increase of the attained EEDI. As a conclusion it can be said that the present method of calculation of EEDI has the following negative consequences:

1. Lower safety level of ship
2. Endangered crew and cargo in heavy seas

and, what is especially interesting

3. Lower EEDI does not necessarily mean lower fuel consumption

5. Case Study: Concept Design of Handy Bulk Carrier

To elaborate on the above statements, let us consider the following case. Conceptual design of two Handy Bulk Carriers has been developed following design procedure elaborated and published in [5,6,7,8]. Developed designs have basic characteristics [9]:

DW = 35,000 t
L_{pp} = 176.0 m
B = 31.5 m
d_s = 10.2 m
CSR = 4,860 kW at 85.9 rpm

5.1 Optional Main Engines

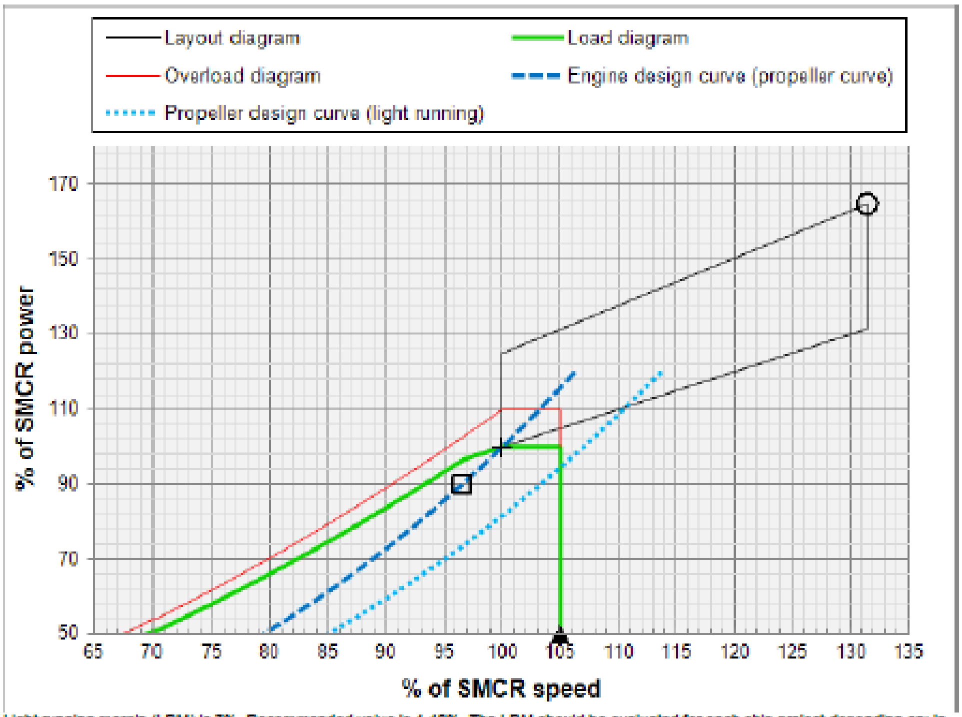
Main engine and *SMCR* are selected in two options:

A) MAN B&W 5S50ME-B9.5 TII
SMCR = 5,400 kW at 89 rpm (*CSR* = 90% *SMCR*), P_{ME} = 4,050 kW (75% *SMCR*)
B) MAN B&W 6S50ME-B9.5 TII
SMCR = 7,477 kW at 99.2 rpm (*CSR* = 65% SMCR), P_{ME} = 5,608 kW (75% *SMCR*)

Power-speed diagrams of the alternative main engines are shown in the following figures.

MAN Diesel & Turbo

Engine room and performance data for 5S50ME-B9.5-TII
with high load tuning.
Project name: BC 35000 DWT
Report made by: PC



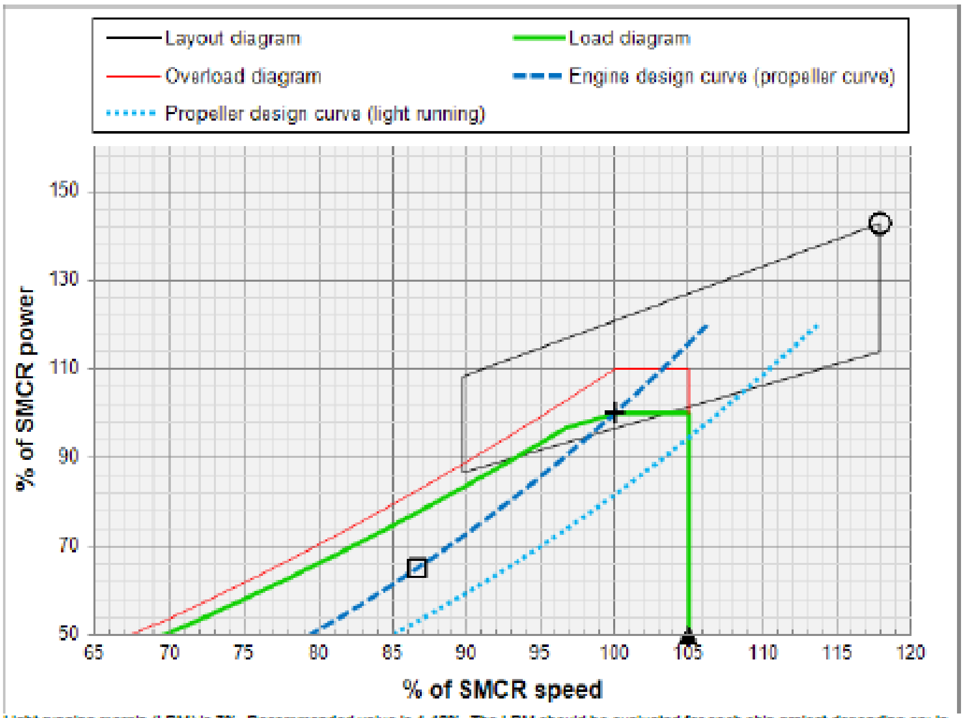
Light running margin (LRM) is 7%. Recommended value is 4-10%. The LRM should be evaluated for each ship project depending on: in-service increase of vessel resistance, ship manoeuvring requirements and requirements related to a possible barred speed range (short passing time).

Point		Power kW	Speed r/min	MEP Bar
+	SMCR: Specified Maximum Continuous Rating (60.7% of NMCR)	5,400	89.0	16.7
□	NCR: Normal Continuous Rating (90.0% of SMCR)	4,860	85.9	15.6
	Maximum over load (110% of SMCR)	5,940	-	-
▲	Maximum speed limit (105% of SMCR)	-	93.5	-
○	L1, NMCR: Nominal Maximum Continuous Rating	8,900	117.0	21.0

Fig. 1 Power-Speed Diagram of the 5S50ME-B9.5 TII Engine

MAN Diesel & Turbo

**Engine room and performance data for 6S50ME-B9.5-TII
with low load variable turbine area tuning.
Project name: BC 35000 DWT
Report made by: PC**



Light running margin (LRM) is 7%. Recommended value is 4-10%. The LRM should be evaluated for each ship project depending on: In-service increase of vessel resistance, ship manoeuvring requirements and requirements related to a possible barred speed range (short passing time).

Point		Power kW	Speed r/min	MEP Bar
+	SMCR: Specified Maximum Continuous Rating (70.0% of NMCR)	7,477	99.2	17.3
□	NCR: Normal Continuous Rating (65.0% of SMCR)	4,860	85.9	13.0
	Maximum over load (110% of SMCR)	8,225	-	-
▲	Maximum speed limit (105% of SMCR)	-	104.2	-
○	L1, NMCR: Nominal Maximum Continuous Rating	10,680	117.0	21.0

Fig. 2 Power-Speed Diagram of the 6S50ME-B9.5 TII Engine

As it can be seen, in both cases CSR is set at the same power and speed.

5.2 Calculation of the Attained EEDI

The calculation of the specific fuel oil consumption has shown the best results for the following cases:

A) For 5S50ME-B9.5, high load tuning, ISO conditions:

at SMCR 162.0 g/kWh

at CSR 160.0 g/kWh

for EEDI calculation 169.0 g/kWh

B) For 6S50ME-B9.5, low load, variable turbine area tuning, ISO conditions:

at SMCR 163.3 g/kWh

at CSR 156.3 g/kWh

for EEDI calculation 169.3 g/kWh

Speed-power estimation is shown in the following figure.

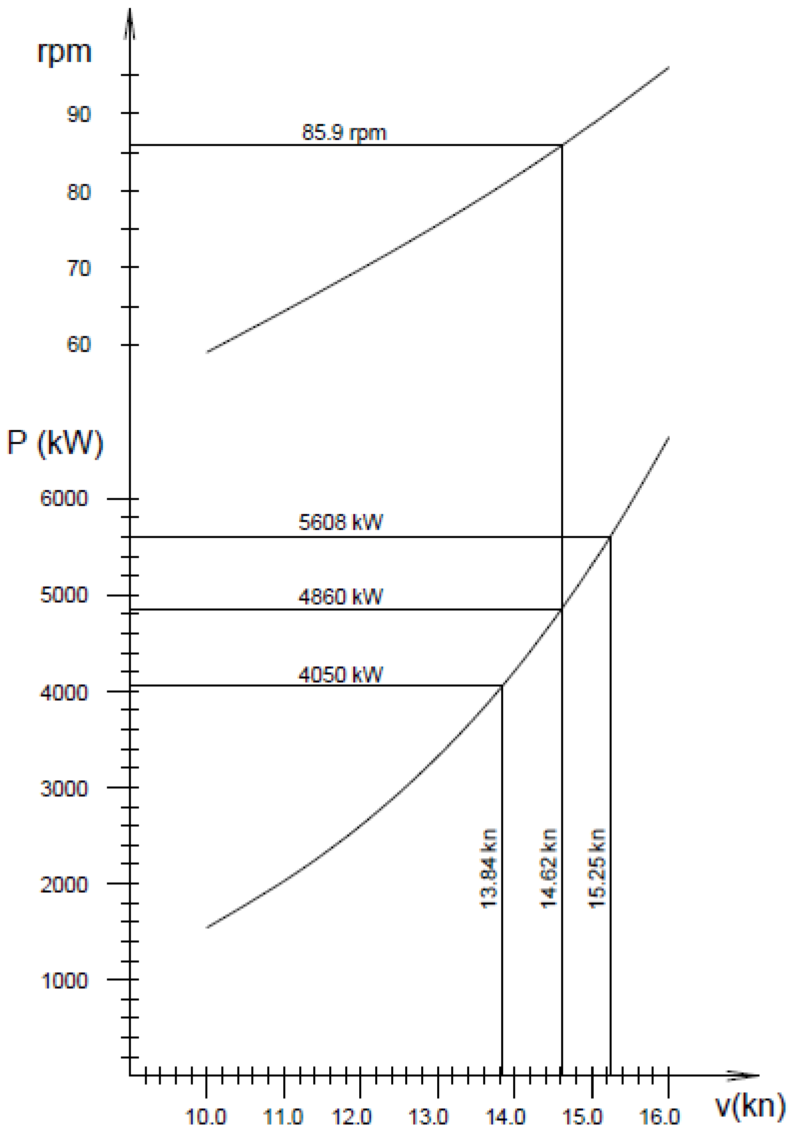


Fig. 3 Speed-Power Estimation

It can be observed that the speed in the case with 5S50ME-B9.5 (75% SMCR = 4,050 kW) is abt. 13.84 kn and in the case with 6S50ME-B9.5 (75% SMCR = 5,608 kW) is abt. 15.25 kn.

EEDI calculations are shown in the following figures.

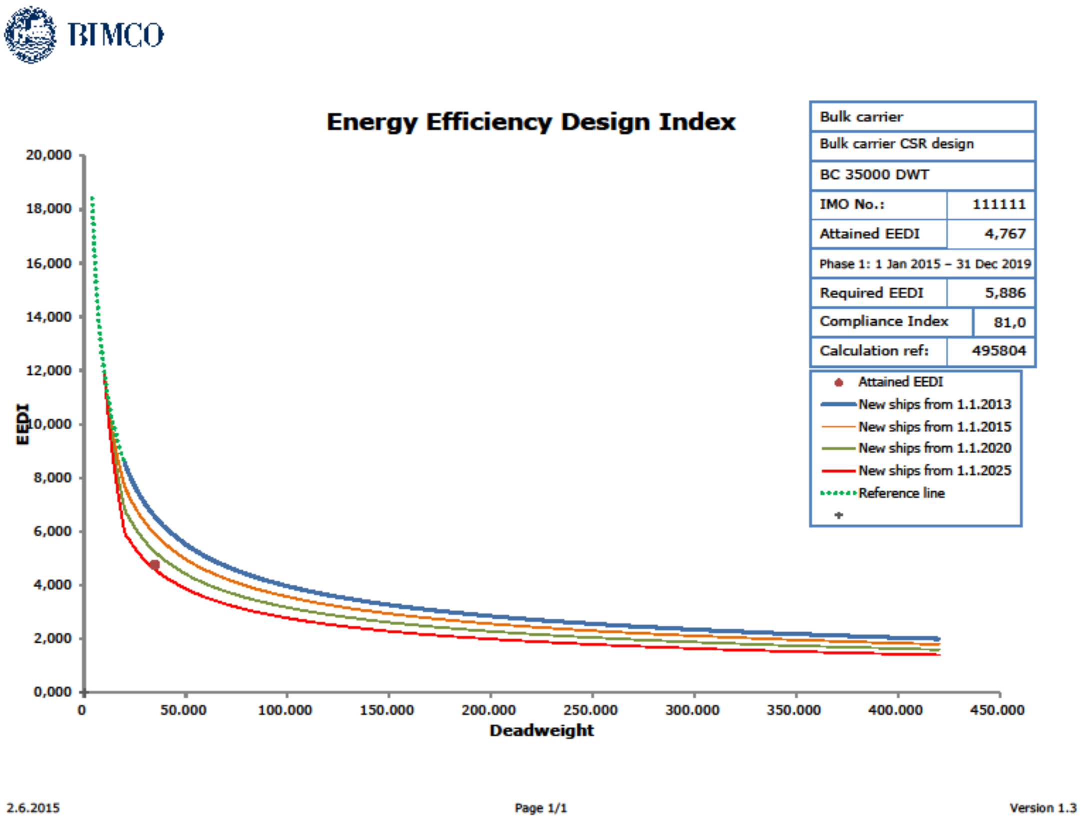


Fig. 4 EEDI for 5S50ME-B9.5 TII Engine

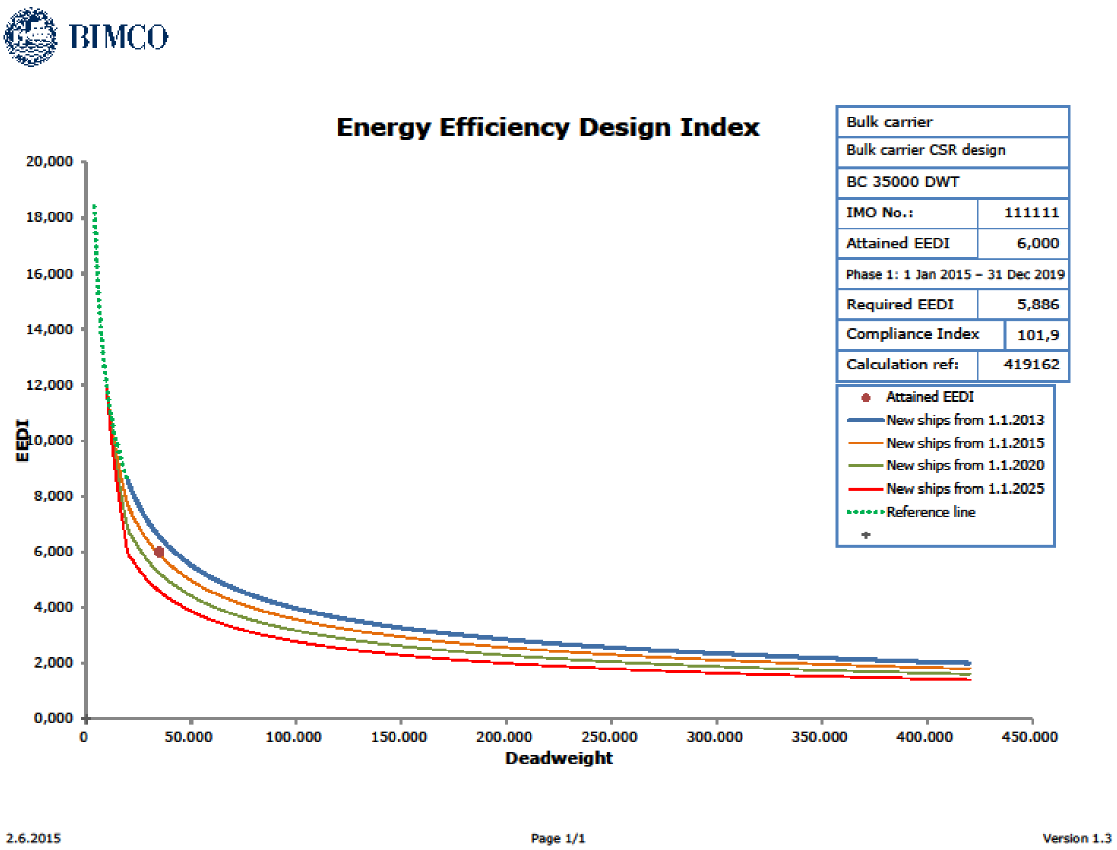


Fig. 5 EEDI for 6S50ME-B9.5 TII Engine

Required EEDI for the phase 1 is 5.886. In the case of 5S50ME-B9.5 attained EEDI is 4.767 and it is much better than required one, even close to the limit set for the end of the monitoring period, i.e. for the phase 3. In the case of 6S50ME-B9.5 attained EEDI is 6.000 (worse for abt. 26% than for 5-cylider engine), even not satisfying the phase 1 requirement.

5.3 Fuel Oil Consumption

Calculation of the main engine daily fuel oil consumption for the standard conditions (CSR, d_s, no sea margin) is as follows:

A) For 5S50ME-B9.5:

dfoc = 4,860 kW x 160.0 g/kWh x 24 hours x 10^{-6} = 18.66 t/day

B) For 6S50ME-B9.5:

dfoc = 4,860 kW x 156.3 g/kWh x 24 hours x 10^{-6} = 18.23 t/day

It can be seen that version with 5-cylinder main engine has daily fuel oil consumption higher for abt. 0.43 t (abt. 2.4%) than the version with 6-cylinder engine. This situation indicates that the actual calculation of the attained EEDI is imperfect and that it would be advisable to improve it.

5.4 Safety Level of Ship

Analysis of safety level for both optional designs is shown in the following figures.

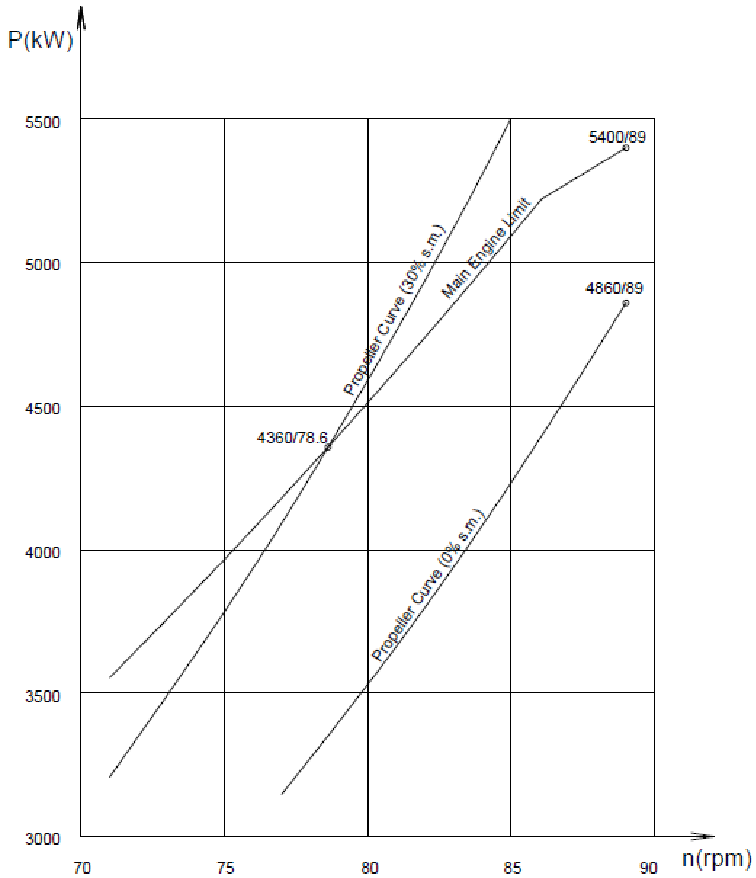


Fig. 6 Available Main Engine Power in Heavy Seas (for 5S50ME-B9.5 TII)

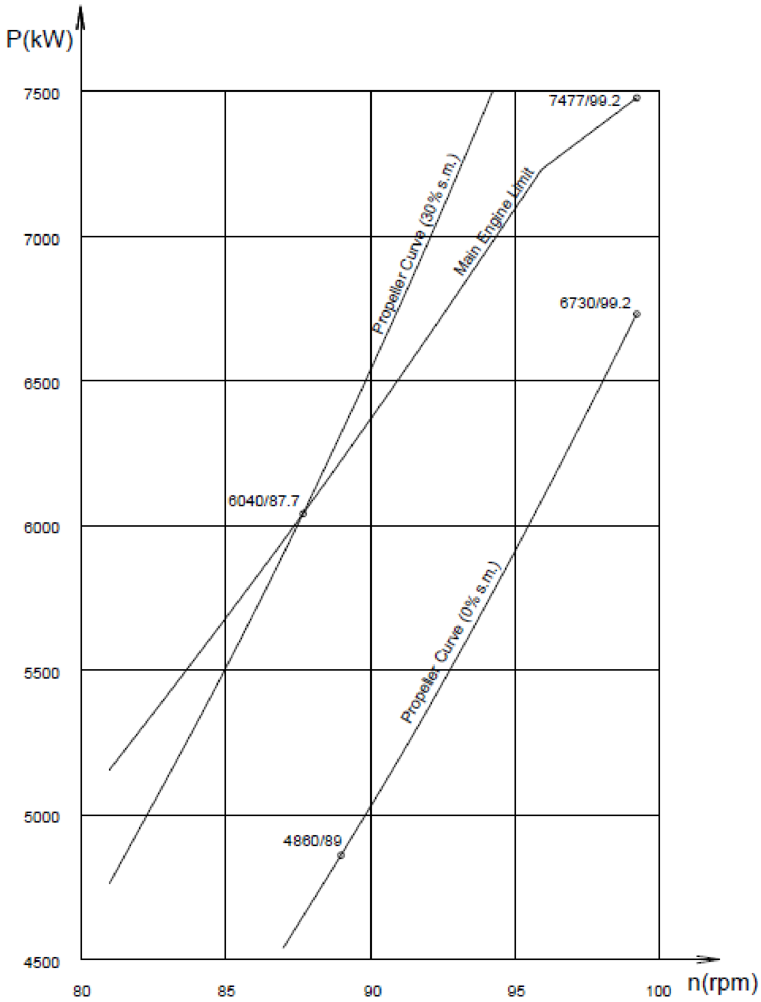


Fig. 7 Available Main Engine Power in Heavy Seas (for 6S50ME-B9.5 TII)

As it can be seen, when sea margin is 30%, 5S50ME-B9.5 can deliver only abt. 4,360 kW, while 6S50ME-B9.5 can deliver abt. 6,040 kW. When sea margin is 50%, 5S50ME-B9.5 can deliver only abt. 3,270 kW, while 6S50ME-B9.5 can deliver abt. 4,540 kW.

6. Proposal for Improvement of Calculation of the Attained EEDI

Hereinafter are presented two proposals for correction of the calculation of the attained EEDI. Both proposals are made in a way to minimize changes of the existing calculation and to achieve the desired effect to balance calculated EEDI with the main engine fuel consumption. Also, intention of the proposed corrections is to encourage the development of designs of a higher level of safety of the ship, crew and cargo.

Proposal 1: to define P_{ME} as 83.33% of *CSR*, instead of 75% of *SMCR*, i.e.:

$$P_{ME} = \frac{0.75}{0.9} CSR = 0.8333 \cdot CSR$$

Why 83.33% of CSR? As previously explained, actual EEDI calculation favours selection of MCR as low as possible. In the extreme case when CSR/SMCR = 0.9, 75% of SMCR corresponds to 83.33% of CSR.

In the shown optional designs, this proposal will result with the same result for the alternative A and significantly better result for the alternative B (main engine specific fuel oil consumption at 4,050 kW + 6% margin is abt. 167.5 g/kWh, P_{AE} = 0.05 x $SMCR$ = 373.85 kW, remained the same)

$P_{MEA} = P_{MEB}$ = 83.33% x CSR = 0.8333 x 4,860 = 4,050 kW

attained $EEDI_A$ = 4.767

$$\text{attained}\, EEDI_B = \frac{4050 \cdot 3.206 \cdot 167.5 + 373.85 \cdot 3.206 \cdot 185}{1.0196 \cdot 35000 \cdot 13.84} = 4.852$$

It can be seen that proposed calculation of EEDI gives very close results for both options – attained EEDI for option B is slightly worse mainly because of higher auxiliary engine power.

Proposal 2: to define P_{ME} as needed power to reach referent speed V_{ref}. Conditions for the definition of the power-speed characteristic remain unchanged: summer load line d_s, deep water, no sea margin. Referent speed V_{ref} must be defined in relation to the type and size of the vessel.

Just for illustration purposes, let us set V_{ref} for bulk carriers of 10,000 dwt and above as follows:

$$V_{ref} = 6.75 + 1.5625 \cdot \log DWT$$

The proposed formula is created in such a way that small bulk carriers of 10,000 dwt have referent speed of 13 knots, handy size bulkers of about 14 knots, and the largest VLOC of about 15.5 knots, which can be considered as appropriate speed for corresponding bulk carrier's sizes. In the following table referent speeds for typical deadweight are shown.

Table 1 Proposed referent speeds V_{ref}

DWT (t)	V_{ref} (kn)
10,000	13.00
30,000	13.75
50,000	14.09
200,000	15.03
400,000	15.50

For the optional designs referent speed can be calculated as follows:

V_{ref} = 6.75 + 1.5625 log (35000) = 13.85 (kn)

which is very close to the speed estimated for the main engine power of 4,050 kW (13.84 kn), with marginal influence on the EEDI calculation.

7. Conclusion

The presented improvement of calculation of the attained EEDI eliminates detected inconsistencies of the actual method. Higher safety level of ship, cargo and crew can be achieved without significant deterioration of the attained EEDI. Also, proposed calculation enables realization of ship designs with lower fuel oil consumption keeping the attained EEDI on the same level as the actual one. Of course, presented corrections should be considered only as a starting point for the development of a new calculation of attained EEDI for all types of ships covered by the regulations.

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Predrag Čudina, predrag.cudina@yahoo.com
Jadroplov Ltd, Development Division, Split, Croatia