Content

• IMO maritime energy efficiency framework
• EEDI formula and how to reduce EEDI
• Energy efficient ship design and technologies
• Energy efficient ship operation and support tools
• Future ship concepts
IMO Maritime Energy Efficiency Framework

EEDI, SEEMP and DCS are currently mandatory.

Initial IMO GHG Strategy agreed in 2018 and will be finalised in 2023.

**IMO GHG Strategy:**

- Specifies **targets** for future shipping GHG emissions
- Identifies some specific **actions** (energy efficiency measures)
- **Targets:**
  - Energy efficiency of shipping to reduce by an average of at least **40% by 2030**, with main aim of reaching **70% by 2050**, as compared to 2008.
  - **Total emissions:** Reduce the total annual emissions by at least **50% by 2050** as compared to 2008.
Attained EEDI: Calculation formula

\[
\text{EEDI} = \left( \frac{\text{gCO}_2}{\text{tonne.nm}} \right)
\]

- **Main Engines**
- **Aux Power (elec.)**
- **Innovative Energy Eff. Prop. Technologies**
**Attained EEDI: How to reduce EEDI?**

\[
\text{EEDI} = \frac{f_c \cdot \text{Capacity} \cdot V_{ref} \cdot f_w}{\text{Attained Speed}}
\]

**Ship specific design factor**

**Shaft Motor**

**Waste Heat**

**Energy Saving**

**Main power:**
\[ P_{ME} = 0.75 \text{MCR} \]

**Auxiliary power:**
- \( P_{ME} \geq 10000\text{KW} \):
  \[ P_{AE} = 0.025Me + 250 \]
- \( P_{ME} < 10000\text{KW} \):
  \[ P_{AE} = 0.05Me \]

**Capacity:**
- **DWT:** Bulk carriers, Containers, Tankers, Gas carriers, cargo ships, etc.
- **GTR:** Passenger Ship

**Capacity factor**

**Wave factor**

**Carbon factor**

**Attained EEDI:**
\[ \text{Attained Speed} \]

**[gCO}_2/(\text{tonne.nm})]
Ship design – Naval architecture and hydrodynamics
Description of hull forms – Principal Characteristics

- Ship’s lengths LWL and LPP
- Draught D
- Breadth on waterline BWL
- Block coefficient CB
- Waterplane area coefficient CWL
- Midship section coefficient CM
- Longitudinal prismatic coefficient CP
- Longitudinal Centre of buoyancy LCB
- Length displacement ratio Lwl/vol.1/3

Volume of displacement : $V$
Waterline area : $A_{WL}$
Block coefficient, $L_{WL}$ based : $C_{B, WL} = V / (L_{WL} \times B_{WL} \times D)$
Midship section coefficient : $C_{M} = A_{M} / (B_{WL} \times D)$
Longitudinal prismatic coefficient : $C_{P} = V / (A_{M} \times L_{WL})$
Waterplane area coefficient : $C_{WL} = A_{WL} / (L_{WL} \times B_{WL})$
Ship design best practice
Important main parameters for propulsion power

**Block coefficient**

$$Cb = \frac{\text{Displacement volume}}{\text{Length} \cdot \text{Breadth} \cdot \text{Draught}}$$

Shall be as low as possible

**Slenderness ratio**

$$M = \frac{\text{Length on waterline}}{\sqrt[3]{\text{Displacement volume}}}$$

Shall be as high as possible

**Froude number**

$$Fn = \frac{\text{Ship speed in m/s}}{\sqrt{g \cdot \text{water line length}}}$$

Shall be as low as possible
Ship resistances

- Frictional
- Wave making
- Eddy
- Air
- Total towing resistance
  \[ R_T = R_F + R_R + R_A \]
- Power needed
  \[ P_E = V \times R_T \]

- Resistances are generally proportional to ship speed \( V^2 \)
- Propulsion power needed is proportional to \( V^3 \)
- Fuel consumption per nautical mile is proportional to \( V^2 \)
Hull form

- Hull design optimisation leads to reduced resistances.

- Areas for improvement include:
  - Hull itself – Reduce skin friction.
  - After-body – Reduce wave making resistance.
  - Bulbous bow - Reduce wave making resistance.
  - Flow optimisation around hull appendices and openings.
Ship aerodynamics

- Reducing air resistance.
- More streamlined design of superstructures.
- Deck-board location of machinery systems.

Source: SVA Hydrodynamic Solutions
Hull air lubrication – New Technology

• Reduces hull skin friction by creating a partial air cushion.

• Up to 15% of fuel savings is claimed.

• This technology is still under trials and a number of pilot trials are underway.

• With Mitsubishi system, 6% savings has been reported in pilot cases.
Propulsion (propeller) technologies
Most of the technologies aim to recover part of the 40% losses
Improving Propeller Efficiency – Wake field improvement

- Improving the wake
  - Tanker/bulk carrier wakes: due to less streamlined body, large bilge vortexes and dead water zones are common
    - Will lead to propellers with larger expanded blade area ratio (EAR) – hence less efficient (more frictional losses)
    - Opportunities for wake improvement & propeller optimization
  - Containership wakes: more streamlined body produces better wake – e.g. only slight defect at 12 o’clock position
    - Good wake leads to propeller with smaller EAR, hence more efficient
    - Less opportunities for wake improvement; e.g. may use semi-duct
  - Efficiency improvements: ~3-5% (HSVA 2006)
Mewis Duct – Becker Marine System

- It channels the water flow more accurately over the propeller and so create better efficiency.

- Becker Mewis Duct device have indicated energy savings up to 8% with an average of 6.5%.
Mitsui OSK - Propeller Boss Cap Fin (PBCF)

- Boss fins rotate with propeller to eliminate propeller hub vortex and generate additional thrust
- Claimed 5% fuel saving or 2% speed increase
Contra-rotating propeller / podded contra-rotating propeller

- Eliminates exit rotational losses which are almost 8-10% for conventional propellers.
- Improves propulsive efficiency by 16-20%.
- Better cavitation performance.
- **Main issue:** Reliability, maintainability and availability of the system
Engine technology
Marine diesel engines – Most energy efficient

[Image of a marine diesel engine]
De-rated engines

- De-rating of the engine – Choice of a larger engine but with:
  - A reduced MCR;
  - Same normal maximum cylinder pressure for the design continuous service rating; and
  - Lower mean effective pressure.

- The above results in a lower fuel consumption (lower SFOC).

- SFOC reduction of up to 5%
Long stroke engines

- Long stroke engines: As the name implies, they have longer stroke than other engines.
- They produce higher thermal efficiency than normal stroke engines (due to more recovery of gas energy towards end of stroke).
Long stroke engines

Layout diagrams of new MAN G-ME engines with increased stroke

Potential fuel savings of 4-7%

Waste heat recovery system and hybrid propulsion

- Exhaust gas economizer: Aalborg Industries
- Steam / power turbine: Peter Brotherhood Ltd
- Shaft motor/generator / PMS: Siemens AG
- Main engine tuning: Wärtsilä SULZER
- Shore connection: Siemens AG
- Power Management System (PMS)

- Up to 12% more efficient, depending on engine size
Renewable energy technologies and alternative power system
Renewable energy – Wind and sail concepts

Wartsila’s concepts

**Wing shaped sails** of composite material installed on deck – possible efficiency gain of ~20%.

**Flettner rotors** installed on deck – provides thrusts perpendicular to wind direction.
- Pilot cases have been tried successfully

**Kites (Skysails)** are being developed as towing-kites.
- Suited more to larger vessels at speeds below 16 knots.
- A proper routing system is required.
Renewable energy - Solar

- NYK’s PCC Auriga Leader – 200m x 32m x 34m; 6200 cars; 18,700 dwt.

- 328 solar panels, USD 1.68m, 40 kW, ~0.3% of installed power.

- Combined sails with solar are also proposed.

No significant potential
Ship design with alternative fuels

• This was covered in previous lecture.

• Largest carbon reduction will only be possible with renewable energy/fuel.

• **LNG as marine fuel**: A transition fuel (clean and slightly lower carbon)

• **Biofuels** – Generation 2 and beyond

• **Synthetic fuel** from renewable energy / raw material.

• **Hydrogen** from renewable electricity

• **Fuel cell** technology + battery + hybrid solution
Fuel Cell Technology – Long term

Research is concentrated on pilot systems of up to about 500 kW
A longer term future
Hybrid-Electric Ships

- Mechanical propulsion
- Hybrid propulsion
- Electric propulsion
Hybrid-electric and energy storage (battery) technologies

A ship concept with fuel cell and battery

Typical hybrid system configuration. Source: Wartsila
Future concept ship - Super Eco Ship 2030(NYK)

- Potential reduction in CO2 emissions
Energy Efficient Ship Operation
Just-in-time operation

Speed reduction via better ship management
Just in Time

- **Just in Time (JIT) concept**: Where the idea is from?

- **JIT in shipping**: Operation management to avoid unnecessary waiting and idle periods of ship operations in all phases of a voyage or modes of operation:
  - at sea operation
  - at port operation
Why ship’s waiting / inactivity?

Commercial ships’ movement is influenced by many factors such as:

- **Requirements of “cargo owner”:** Where and when of cargo.
- **Slotting issue in ports:** Berth availability / cargo space availability.
- **Regulatory issues** that may lead to:
  - Prevention of entry to port.
  - Detention for some periods of time.
- **Technical failures** that leads to loss of ship availability.
- **Lack of business** (cargo).
Ship actual itinerary – Main players?

- Improvements to ship itinerary requires efforts by all parties involved:
  - **Charterer** (operation department): On time decision making on ship itinerary and overall steaming speed.
  - **Ship master**: On-time operation of the ship, within the terms of charter party.
  - **Port authorities**: On time berth availability / loading / unloading / etc.
  - Interaction between above parties that leads to actual (achieved) ship itinerary.
Virtual Arrival to help with JIT operation

- **Virtual arrival**: Is a specific tool for achieving Just In Time.

- **Agreements and communications** with port and charterer is essential

- **Virtual arrival aim**: Reduce waiting times / achieve longer passage time thus reduced ship’s voyage average speed.

- A significant level of **fuel saving** is expected with virtual arrival.

- A significant reduction in port-area emissions.
Just in Time and Virtual Arrival – VA Processes

Step 1 - Identification of change in itinerary: For example to identify a delay at the next port of destination.

Step 2 - Agreement to new itinerary: Parties involved agree to a change in ship’s itinerary.

Step 3 - Speed adjustment: As a result of the newly agreed itinerary, the ship’s speed or the engine RPM is reduced.
Just in Time and Virtual Arrival – Benefits

- **Ship benefits:** Fuel saving and CO2 reduction and cost reductions are the main benefits.
  - **Port benefits:** Reduced port congestion, less emissions, reduced noise and enhanced safety.

- Other benefits include:
  - Other emissions reductions
  - Releasing ship for other activities
  - The improved planning of in-port activities
Slow Steaming

Permanently reducing the operational speed of the ship
Slow steaming – What and Why?

• **Slow steaming**: This term refers to running a ship at a **significantly lower speed** than its **design speed**.

• **Main purpose**: To reduce a ship’s fuel consumption and avoid over-capacity in the market.

• **When practiced**: Mainly practiced when:
  - Fuel prices are high
  - The market is faced with ship over-capacity.
Ship fuel consumption versus speed

- Propulsive power $\alpha$ (Ship speed)$^3$
- Fuel consumption $\alpha$ (Ship speed)$^3$
- Fuel consumption per nautical mile is proportional to (Ship speed)$^2$

- Impact of speed on fuel consumption
- Different levels of slow steaming
- Impact of ship size on fuel consumption

Source: Geography of Transport System, adapted from Notteboom et al (2009)
### Slow steaming advantages and disadvantages

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Lower fuel consumption and cost</td>
<td>• <strong>Economics</strong></td>
</tr>
<tr>
<td>• Lower CO$_2$ per voyage</td>
<td>• Higher charter fees per voyage.</td>
</tr>
<tr>
<td>• Lower NO$_x$ per voyage</td>
<td>• Need for additional ships.</td>
</tr>
<tr>
<td>• Lower SO$_x$ per voyage</td>
<td>• <strong>Technical</strong></td>
</tr>
<tr>
<td></td>
<td>• Low load engine operation and maintenance issues.</td>
</tr>
<tr>
<td></td>
<td>• Increased hull fouling rates</td>
</tr>
<tr>
<td></td>
<td>• <strong>Ship’s crew</strong></td>
</tr>
<tr>
<td></td>
<td>• More maintenance work.</td>
</tr>
<tr>
<td></td>
<td>• Longer periods away from ports.</td>
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</tbody>
</table>
Slow steaming: Technical issues

• Main engine operational limits (minimum load for safe engine operation).

• Economiser performance and reliability (economiser fouling, not enough steam production)

• Turbocharger operation, performance and maintenance (fouling, lack of energy for turbo operation, possible need for operation of auxiliary air blowers, …)

• Propeller performance (not optimal condition).

• Hull paint type and fouling rate (increase in fouling, impact on performance of hull coating, …).

The above technical issues can be resolved via investment in technology and new operational practices.
Slow Steaming: When is it practiced?

• When there is over-capacity in the market or a slow down in global trade

• When the fuel prices are high.

• When the charter rates are low.

Recently, there are debates on “ship speed limits” and whether it is a good idea to regulate it or not?
Weather routing
Weather Routing – Why?

• Ship safety by avoiding extreme adverse sea conditions

• Save fuel and possibly reduce the voyage duration:
  • Avoid head winds and currents, if possible
  • Adjust speed according to water depth

• Mainly effective for long ocean passages where alternative routes exist.

• Mainly effective for short sea shipping with variable water depth operation.
Weather Routing – Impact of water depth and wind on fuel consumption

Fuel consumption increase (%) for different water depths and ship speeds

<table>
<thead>
<tr>
<th>Ship Speed</th>
<th>Water Depth</th>
<th>Increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>15</td>
<td>3</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>17</td>
<td>100</td>
<td>0</td>
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<tr>
<td>20</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>20</td>
<td>100</td>
<td>0</td>
</tr>
</tbody>
</table>

Approximate relation between wind direction and increased fuel consumption for each unit of Beaufort.

<table>
<thead>
<tr>
<th>( w_d )</th>
<th>Type</th>
<th>Increase (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>315-360, 0-45</td>
<td>Head wind</td>
<td>4</td>
</tr>
<tr>
<td>45-135, 225-315</td>
<td>Side wind</td>
<td>2</td>
</tr>
<tr>
<td>135-225</td>
<td>Tail wind</td>
<td>1</td>
</tr>
</tbody>
</table>

Specialised weather routing services are provided by dedicated companies.
Trim optimization
Trim Optimisation – Physics of trim

- There are large dependencies of ship performance to ship trim.

- Changes to ship resistance:
  - Changes to wave resistance
  - Changes to wetted surfaces (thus frictional resistance).
  - Changes to form resistance due to transom submergence

- Changes to various propulsion coefficients including:
  - Resistance coefficients
  - Thrust deduction
  - Wake fraction

- Changes to propulsive efficiencies including:
  - Relative rotative efficiency.
  - Propeller efficiency
Trim Optimisation – Impact of trim

- Trim impact depends on ship speed and draft.
- The impact of trim either is measured by model test or calculated using CFD.
- Guidance table for trim is normally prepared for shipboard use.
- As indicated impact of trim could be significant.

Source: Lloyd’s Register
Trim Optimisation – Operation best practice

• Current practice: *Even keel operation* (zero trim).

• This generally represents the optimal trim for ships with high block coefficients (e.g. tankers, bulk carriers (not containers)).

• In ships with slimmer body and higher speed, the impact of trim on performance could be significant:
  • Container ships
  • RoRo cargo and passenger ships
  • RoRo car carriers

• Effective use of the loading computers capabilities is important for safe trimming of the vessel.
Ballast water optimization
Ballast Water Optimization

Why ballast water?

• Ballast water is essential to control trim, list, draught, stability and stresses of the ship.

Ballast water regulations?

• Ballast water activities on board ship is heavily regulated.
• The regulations mainly relate to prevention of transfer of AIS (Aquatic Invasive Species).

Ballast water operations?

• Ballast water exchange
• Loading ballast water
• Discharging ballast water
Ballast Water Optimization – Energy efficiency methods

• **Carrying less ballast water:**
  • For energy efficiency, it is generally desirable to **carry less ballast**.
  • Of course this should **not contravene any of the regulations and compromise ship safety**.
  • Also, this should not cause **non-optimal trim**.

• **Efficient ballast management operations:** This means performing ballast exchange / ballasting / de-ballasting in a way that is more energy efficient, e.g.:
  • **Gravity assisted ballast exchange** is preferred to simple pumping in/out processes.
  • **Sequential ballast exchange** is more energy efficient than the **flow-through method** as less water needs to be displaced.

• **Trim optimisation:** Ballast should be used effectively to adjust the ship optimum trim

• **Sediment removal:** Sediment removal leads to better cargo capacity and more energy efficiency.
Hull coating and maintenance
From flow theories:

- Resistance
- Power:

\[ R = c \times V^2 \]
\[ P = R \times V = c \times V^3 \]

Actual values differ:

- For large high speed ships (containerships)

\[ P = c \times V^{4.5} \]

- For medium speed ships (RoRo, feeders, etc.)

\[ P = c \times V^{4.0} \]

- For slow speed ships (tankers, etc.)

\[ P = c \times V^{3.5} \]
Hull Coating

- For lower speed ships skin friction resistance dominates;
- For a VLCC at full load condition 90% of resistance is from hull friction;
- Strategy: Reducing hull frictional resistance.
- There are advanced hull coating that may be used for this purpose.
- Application of advanced coatings will be more expensive but return in terms of saving could be high.
Hull monitoring and cleaning

- Hull fouling takes place over time.
- Rate of fouling depends on a number of factors:
  - Ship operation regions
  - Speed and operation profile
  - Hull coating and hull surfaces quality
- Net result: significant increase in fuel consumption.
- Use of proper hull monitoring analysis system and cleaning could support the reduced fuel consumption.
- A lot of service providers perform hull performance monitoring.
Ship-board operational planning
Ship-board operations planning – Areas to cover

• Ship operation involves a variety of activities and tasks including:
  • Loading
  • Unloading
  • Ballasting and de-ballasting
  • Inner gas generation and top ups for crude oil and product tankers
  • Bunkering
  • Manoeuvring
  • Stand-by
  • Normal passage operation
  • Waiting and anchorage
  • Fresh water generation
  • Potable water generation

• Planning of the above require good coordination between deck and engine departments.
Ship-board operations planning – For electrical load reduction

- Avoid unnecessary energy use via switching off the machinery when not needed.
- Stop all non-essential machinery and equipment use via planning:
  - Step 1 – Identify these items.
  - Step 2 – Define procedures for the execution of tasks
  - Step 3 – Implement the procedure.
  - Step 4 – Monitor and control.
- Avoid use of excessive parallel operation of machinery.
- Optimize HVAC operation on board.
- Coordinate and enhance deck and engine departments communications on issue of efficient use of machinery.
Ship-board operations planning – For auxiliary boiler use reduction

• Effective use of exhaust gas economiser.

• Avoid additional use of auxiliary boilers:
  • The requirement for steam need to be examined and planned.
  • The steam system maintenance/boilers should be done properly.

• Cargo heating plan
  • For ships with cargo heating requirements.
  • The cargo heating plan is best to be made soon after loading cargo.
  • The plan will include how and when and what temperatures?
  • It is also part of best practice for vessels to complete the heating log abstract (daily basis).
  • A review of the heating log abstract will help with better future planning.
Cargo Heating Plan

- Two typical cargo heating pattern graphs (good practice / poor practice).
Conclusions

• There are a large number of measures for improving ship design and operation for energy efficiency.

• To meet the future targets of Initial IMO GHG Strategy, all these measures need to be encouraged (market-wise and/or regulatory-wise).

• Future ship designs and uptake of technologies are driven by EEDI regulations.

• IMO is currently investigating if any of the operational measures could be the subject of future regulations.