IMO Train the Trainer (TTT) Course

on

Energy Efficient Ship Operation

Module 4 – Ship Board Energy Management

I M O

ACKNOWLEDGEMENTS

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MODULE 4
Ship-Board Energy Management

Module Aims and Learning Objectives

This module is intended to provide the awareness, knowledge, skills and motivation required of ship-board and office-based staff on ship-board energy management techniques and activities. It aims to provide the trainees with relevant information on the main ship-board Energy Efficiency Measures (EEMs), technical aspects including engines, auxiliary machinery and steam system, fuel management and technology upgrades. A number of topics are covered including:

- Typical ship-board organisational charts and role of various individuals and departments;
- Overview of main ship-board EEMs, their significance and potential saving levels;
- Trim optimisation, its impact and best practice;
- Ballast water exchange and management and its relevant EEMs;
- Hull and propeller roughness, fouling and its monitoring;
- Engines and machinery performance and use management;
- Fuel management aspects including storage, treatment and purification;
- Ship maintenance aspects and their impact on energy efficiency;
- Steam system and boilers;
- Ship-board machinery technology upgrades for energy efficiency.

Upon completion of this module, you will:

- Be able to talk about main ship-board staff and their role and responsibilities;
- Be able to provide a list of the main ship-board energy efficiency measures (EEMs);
- Explain what is trim, trim optimisation, its energy saving impacts and best practice;
- Be familiar with general aspects of ballast water management and its relevant EEMs;
- Explain issues of hull and propeller roughness, fouling, level of impacts on energy efficiency and options for monitoring;
- Explain engines and machinery efficiency characteristics and method of their utilisation management;
- Describe a typical ship-board steam system, relevant EEMs, and best practice for fuel saving;
- Discuss the fuel management aspects for energy efficiency;
- Describe a number of technology upgrades for energy efficiency for existing ships.

> The material presented herein is current at the time of preparations of this document. Because of the evolving nature of regulations, technologies and future studies in area of MARPOL Annex VI and in particular energy efficiency of ships, some aspects may require updating over time.
>
> The views expressed in this document are purely those of the author(s) and may not in any circumstances be regarded as stating an official position of the organizations involved or named in this document.
>
> This document is subject to change by the IMO.
>
> **Dr Zabi Bazari, EnEmSol, January 2016**

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1 Introduction to Ship-Board Roles and Responsibilities

1.1 Introduction

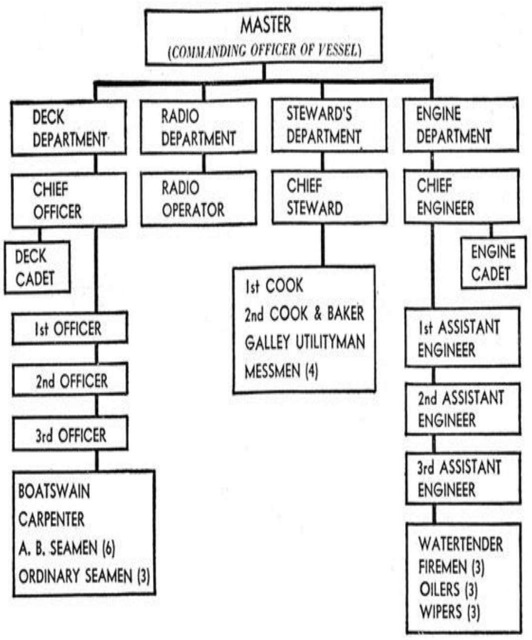
In this section, information is provided on ship-board management structure and organisational chart, main roles, main departments. It also highlights the main roles and responsibilities in particular for those that have significant impact with regard to ship-board energy management. Training of ship-board staff on energy management activities are highlighted in various IMO guidelines and thus the initial effort by companies will include awareness raising and change of ship-board culture with regard to energy efficiency.

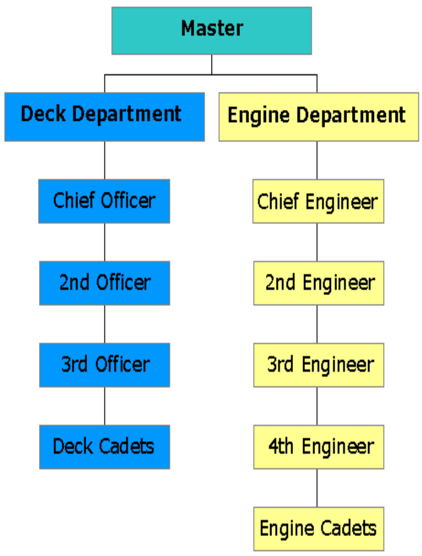
1.2 Ship-board organizational structure

The ship's crews are the personnel who sail on board a ship and are responsible for its operation, primarily when the ship is at sea (with some responsibility when at port). For the purpose of ship operation and traditionally, the crew of a commercial ship is divided into three departments [Wikipedia 2015]:

- Deck department
- Engine department
- Catering (steward's) department.

Figure 1.1 shows some typical ship-board management organizational charts. A brief description of the important roles is given below.





[Maritime Profession Promotion Foundation]

[Reference 2]

Figure 1.1 - Typical ship-board organizational chart

The Captain or Master is the ship's highest responsible officer, acting on behalf of the ship's owner / operator or manager. The Captain/Master is legally responsible for the day-to-day management of the ship. It is his/her responsibility to ensure that all the departments perform legally to the requirements of the ship's owner /operator or manager. The ship has a number of deck officers that assist the master. Master also usually has the advice of pilots while the ship is navigating in restricted waters, such as narrow or shallow channels. Also, each shipboard department has a designated head who reports to the master. The deck department is headed by a Chief Officer. The engine department is headed by a Chief Engineer. He has other licensed engineers to assist him with engine room watch and the performance of maintenance and repair activities in the engine room. The Chief Steward is the head of the catering department. He assists the captain in dealing with embarkation (entering a port) and disembarkation (leaving a port) formalities and other administrative tasks, if necessary. Additionally, in ports, he will take care of ordering and supervising the delivery of provisions and galley supply and distribution and is in charge of crew wages, etc. The above roles and their level of engagement will vary from one ship type to another.

1.3 Deck Department

Chief Officer[1]: The Chief Officer is the head of the deck department. He is second-in-command after the ship's master. The Chief Officer's primary responsibilities are the vessel's cargo operations, its stability and supervising the deck crew. The Chief Officer is responsible for the safety and security of the ship, as well as the welfare of the crew on board. The Chief Officer typically stands the 4-8 hours of navigation watch. Additional duties include ensuring good maintenance of the ship's hull, cargo gears, accommodations, the lifesaving and firefighting appliances. The Chief Officer also trains the crew and cadets on various aspects like safety, firefighting, search and rescue and various other contingencies.

Second Officer[2]: The Second Officer is usually in charge of ship navigation with a position below Chief Officer and above Third Officer. He/she is the third-in-command, after the Master and Chief Officer. The second officer typically stands watch from 1200 to 1600 at noon and again from 0000 to 0400 in the nights.

Third Officer[3]: The third officer primarily charged with the safety of the ship and crew. The Third officer generally serves as the ship's chief safety officer. The Third Officer is the next licensed position on board the vessel, as fourth-in-command.

1.4 Engine department4

The engineers on board ships are also called technical officers. They are responsible for keeping the machinery maintained and operational. Today, ships are complex systems that combine a lot of technology within a small space. This includes not only the engines and the propulsion system, but also for example, the electrical power supply, devices for loading and discharging, garbage incineration and fresh water generators. Additionally, more and more environmental protection technologies, fuel treatment systems and cargo conditioning devices are used on board ships. The upkeep of all these are in the hands of engine department staff.

Chief Engineer: The Chief Engineer on a commercial vessel is the official title of someone qualified to manage and oversee the engine department. The qualification for this position is colloquially called a "chief's ticket". The Chief Engineer is responsible for all operations and maintenance of all engineering equipment throughout the ship.

Second Engineer[5]: The Second Engineer is the officer responsible for supervising the daily maintenance and operation of the engineering systems. He or she reports directly to the Chief Engineer. The Second Engineer is second in command in the engine department after the ship's Chief Engineer. The person holding this position is typically the busiest engineer on-board the ship, due to the supervisory role this engineer plays and the operations duties performed. Operational

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[1] Also called Chief Mate or First Mate
[2] Also called Second Mate
[3] Also called Third Mate
[4] Also referred to as Engineering Department
[5] Also referred to as First Assistant Engineer

duties include responsibility for the refrigeration systems, main engines and any other equipment not assigned to the third or fourth engineers.

Third Engineer: The Third Engineer is junior to the second engineer in the engine department and is usually in charge of boilers, fuel, auxiliary engines, condensate, and feed systems. This engineer is typically in charge of bunkering, if the officer holds a valid certificate for fuel transfer operations.

Fourth Engineer: The Fourth Engineer is junior to the third engineer in the engine department. The most junior marine engineer of the ship, he or she is usually responsible for electrical, sewage treatment, lube oil, bilge, and oily water separation systems. Depending on usage, this person usually stands a watch. Moreover, the fourth engineer may assist the third officer in maintaining proper operation of the lifeboats.

1.5 Steward's department

Chief Steward: The Chief Steward directs and assigns personnel that do functions such as preparing meals, cleaning and maintaining officers' quarter, and managing the stores. The Chief Steward also does other activities such as overtime and cost control records, and may requisition or purchase stores and equipment. Other additional duties may include taking part in cooking activities. The Chief Steward is assisted by a chief cook and his/her assistant cooks, mess men and assistant stewards.

1.6 Shipboard activities for energy efficiency

Based on the above description, all ship staffs have roles to play on ship energy efficiency. However, the role they could play would be different and its effectiveness will vary. For example:

- The Master, being overall in command of the ship, has a significant impact on all aspects of ship operation including planning, execution, controls and evaluations. The Master in particular could influence significantly all ship operational issues. Without Master's full awareness and drive, ship energy management is unlikely to succeed on-board ships. Areas that Master could significantly impact are those related to ship operational aspects such as voyage management, weather routing, just in time arrival and so on (those covered in **Module 3**); all of which has significant implications for ship energy efficiency. So, a ship's Master could have the highest influence for an energy efficient ship operation than any other ship-board staff.

- The Chief Officer (2nd in command) plays significant roles on the cargo and loading/unloading operations, ballast management operations, trim optimisation and aspects of hull and propeller condition and maintenance, etc. In this regard, all detailed operational issues are handled by Chief Officer and in this way he/she exerts a lot of influence on various ship activities including energy and environmental management. Good communications between Chief Officer and Chief Engineer would provide a more optimised operation between deck department requirements and engine department efficiency and maintenance requirements. Based on this, the Chief Officer is the second most important person on board ship that could influence the overall ship energy efficiency or inefficiency.

- The Chief Engineer being in overall charge of technical aspects of ship engineering systems and machinery operations, could play a major role on technical issues including the condition and performance of engines and various machinery and the way they are utilised. The Chief Engineer normally carries out most of the machinery condition assessment activities, engine record logs and reporting and communications with Master and Chief

Officer. By virtue of having the full picture of all engineering system, Chief Engineer is the third most important person on-board in terms of energy efficiency after the Master and Chief Officer.

- The Second Engineer, by virtue of being the most engaged person in the engine department on day to day operation and maintenance of various systems, has the second most important role in engine department in ensuring that all machinery are in optimal working condition and performance as well as their usage are limited to requirements.

The above list does not negate the importance of all ship-board personnel in impacting the ship-board energy efficiency activities. It only highlights those that could have more influence. In fact, all personnel could play their role and without their buy-in the task of ship-board energy management will not be successful. Building up a culture of care for environment and fuel saving between staff is a prerequisite for any successful ship-board energy management.

1.7 Importance of communications between departments

One of the issues observed most of the time is the lack of optimal organisational communications between various departments that lead to waste of energy. For example, communication between deck and engine departments is essential for machinery use optimisation. In an effective ship-board energy efficiency programme, the collaboration and communications between all departments need to be enhanced. This may be achieved via consideration of energy efficiency at daily meetings and relevant ship-board work planning for reduction of electricity, compressed air, fresh water, etc. use.

1.8 Reference and further reading

The following list provides references for this section and additional publications that may be used for more in-depth study of topics covered in this section:

1. Wikipedia 2015, "Seafarer's professions and ranks", http://en.wikipedia.org/wiki/Seafarer's_professions_and_ranks accessed August 2015.
2. http://maritime.org/doc/merchant/prelim/part3.htm, accessded August 2015
3. Maritime Profession Promotion Foundation, **http://www.seagoinghk.org/eng/default.asp?deckofficer**, accessed August 2015.
4. "STCW: A guide for seafarers, taking into account the 2010 Manila amendments", International Transport Workers' Federation publication, available on www.
5. "IMO train the trainer course material", developed by WMU, 2013.

2 Ship-board Energy Efficiency Measures

2.1 Introduction

In **Module 3**, the energy efficiency measures relating to ship's operation/commercial management were covered. It was widely argued and shown that these kinds of measures are not fully under the control of ship staff, thus the issue of communication and coordination between ship, shore office, charterer, shipper, etc. were highlighted.

In this module, energy efficiency measures are covered that to a large extend and primarily are in the hand and under control of the ship-board staff (although not all of them by 100%). They could be the subject of ship's in-passage activities for energy efficiency. An overview of major aspects of ship-board activities that impacts the ship's fuel consumption coming under this category are briefly introduced first and then fully described in other sections of this module.

2.2 Optimized ship handling

Optimum trim: Most ships are designed to carry a designated amount of cargo at a certain speed for certain fuel consumption. The same applies to ballast operations. Whether loaded and unloaded, for such conditions, normally there exists a ship trim that minimises the propulsion power, thus main engines' fuel consumption. In fact, for any given draft there is one optimum trim that gives minimum ship resistances. In some ships, it is possible to assess optimum trim conditions for fuel efficiency continuously throughout the voyage. Setting the ship trim is to a large extent in the hand of ship-board staff although loading, operational and navigational constraints may limit the full extent of proper use of this energy efficiency measure. The trim optimisation aspects are covered in detail in **Section 3**.

Optimum ballast: Ships normally carry ballast water to ensure ship's stability and safety. Normally, ballast levels should be adjusted taking into account the requirements to meet ship stability, steering aspects of the ship and optimum trim. This does not necessarily mean carrying lots of ballast water all the time. This unnecessarily increases the ship displacement that directly increases fuel consumption. Thus there is an optimum ballast condition that needs to be achieved through good cargo planning as well as voyage planning. Therefore optimising the ballast levels for energy efficiency within the framework of ship stability, safety, steer-ability and optimum trim can be regarded as an energy efficiency measure. The energy efficiency aspects of ballast water management are covered in **Section 4**.

Optimum use of rudder and autopilot: There have been large improvements in automated heading and steering control systems technologies. Whilst originally developed to make the bridge team more effective, modern autopilots can achieve much more. An integrated navigation system can achieve significant fuel savings by simply reducing the distance sailed "off track". The principle is simple; better course control through less frequent and smaller corrections will minimize losses due to rudder resistance. In some cases, retrofitting of a more efficient autopilot to existing ships could be considered. This subject has already been covered under e-navigation in **Module 3** and will not be further discussed in this module.

2.3 Optimised propulsion condition

Hull maintenance: Hull fouling always happens in ships. The rate of hull fouling will depend on a number of factors such as quality of paint, ship service speed, periods of idle /waiting and ship geographical area of operation. Hull resistance can be optimized by new advanced coating systems, possibly in combination with hull cleaning at certain intervals. Regular in-water inspection of the condition of the hull is recommended. Consideration may be given to the possibility of timely full removal and replacement of underwater paint systems to avoid the increased hull roughness caused by repeated spot blasting and repairs over multiple dry dockings.

Propeller cleaning: Propeller cleaning and polishing or even appropriate coating may significantly increase fuel efficiency. The need for ships to maintain efficiency through in-water hull and propeller cleaning should be recognized and facilitated by port States. The topics of hull fouling and monitoring together with propeller cleaning and polishing are further described in **Section 5**.

Main engine maintenance: Marine diesel engines have a very high thermal efficiency (~50%). This is the best efficiently currently available on the market and is the main reason why diesel engines are unrivalled in shipping. The high efficiency is due to the systematic minimization of heat and mechanical loss of such engines and improved performance parameters that has taken place over many decades. In particular, the new breed of electronic controlled engines can provide efficiency gains with wider flexibility for example for slow steaming. To keep these engines in optimal condition and performance, they need to continuously undergo on-board condition and performance monitoring. Maintenance in accordance with manufacturers' instructions in the company's planned maintenance schedule will also maintain efficiency. The use of engine's condition monitoring can be a useful tool to maintain high efficiency. The topic of engines and how to improve their condition and performance for optimal efficiency is covered in **Section 6**.

2.4 Optimised auxiliary machinery

There is a significant number of auxiliary machinery on board ships that use electrical power to function. Such machinery has a number of redundancies for safety and operational purposes so that if one fails, the redundant one could take over and ensure continuous safety and operation of the ship. There aspects to choice of such machinery as well as their operation that impact a ship's energy efficiency. For example, the way such machinery is used could lead to poor maintenance as well as high energy use. Such topics are further covered in **Section 6**.

2.5 Fuel management

Shipping normally uses Heavy Fuel Oil (HFO) that is of lowest quality amongst marine fuels and could be of poor quality, if care is not exercised during procurement and use. Control of quality and quantity of fuels purchased and also on-board fuel treatment can provide significant benefits for safeguarding the machinery from damage but also in terms of energy efficiency. This topic is covered in **Section 7**.

2.6 Maintenance and energy efficiency

Ship maintenance operations and management are fundamental for energy efficient operation of its machineries and systems. Deterioration of ship systems' condition takes place due to normal wear and tear, fouling, mis-adjustments, long periods of operation outside design envelopes, etc. As a consequence equipment downtime, quality problems, energy losses, safety hazards or environmental pollution may result. The end outcome is a negative impact on the operating cost, profitability, customer satisfaction and probable negative environmental impacts. Thus good maintenance is in line with good performance and energy efficiency. This topic is further discussed in **Section 8**.

2.7 Technical upgrades and retrofits

There are a whole host of technologies that may be used to improve the energy efficiency of an existing ship. Although a decision to choose and install such technology upgrades is outside the hand of ship-board staff, nevertheless this topic will be covered in this module. Typical technologies could include the following.

Optimum propeller and propeller inflow considerations: Selection of the propeller is normally determined at the design and construction stage of a ship but new developments in propeller design have made it possible for retrofitting of later designs to deliver greater fuel efficiency. It is important to know that such changes should be decided by looking at the ship as a whole from hydrodynamic points of view taking consideration for all elements of a ship's duty cycle. Additionally, improvements to the water inflow to the propeller using arrangements such as fins and/or nozzles could increase propulsive efficiency power and hence reduce fuel consumption.

Efficient auxiliary machinery and electrical motors: Technology could help in this area via a host of initiatives such as energy saving lamps, energy efficient electrical motors, energy efficiency pumps, etc.

Waste heat recovery: Waste heat recovery is now a commercially available technology for some ships. Waste heat recovery systems use thermal heat losses from the exhaust gas for either electricity generation or additional propulsion with a shaft motor. It may not be possible to retrofit such systems into existing ships. However, they may be a beneficial option for new ships. Waste heat recovery technologies to reduce the need for hot water or steam may be considered for existing ships where such requirement dictates longer operation of the auxiliary boilers.

All the above technology upgrades and retrofit options that are of immediate interest to existing ships are discussed in **Section 9**.

2.8 Boilers and steam system

In some ship types, boilers and steam are using significant amount of energy for either propulsion turbines or for other auxiliary services such as operation of cargo and ballast pumps, cargo heating, fuel oil treatment and conditions and so on. The associated energy efficiency measures related to all aspects of steam generation and use are covered in **Section 10**.

2.9 References and further reading

The following list provides references for this section and additional publications that may be used for more in-depth study of topics covered in this section:

1. ABS 2013 "Ship Energy Efficiency Measures, Status and Guidance", http://ww2.eagle.org/content/dam/eagle/publications/2013/Energy%20Efficiency.pdf, accessed August 2015.
2. "IMO train the trainer course material", developed by WMU, 2013
3. Resolution MEPC.213(63), "2012 Guidelines for the development of a ship energy efficiency management plan (SEEMP)" IMO MEPC, Adopted on 2 March 2012.

3 Trim Optimisation

3.1 Introduction

Most ships are designed to carry a certain amount of cargo at a designated speed, consuming a certain amount of fuel under a specified trim condition. Loaded or ballast, trim has a significant influence on the resistance of the ship through water. Therefore, optimizing the trim can deliver significant savings.

For any given draft and speed, there is a trim condition that gives minimum resistance. Therefore, the vessel optimum trim is a function of draft and speed. A ship's optimum trim may be established as part of routine operations or through tank testing or use of computational methods. Nowadays, Computational Fluid Dynamics (CFD)[6] methods are extensively used to estimate optimal trim settings for energy efficiency. However, these may require information from ship model tests and /or full-scale measurements.

Operationally, design or safety factors may preclude the full use of trim optimization. The possibility of trimming a ship should be seen in relation to stability, maneuverability and other safety and operational aspects. It is the master or chief officer of the vessel that will ultimately ensure all situations are considered. To ensure best practice, the concern of masters with regard to loading and ballasting aspects needs to be taken into account.

3.2 Economic benefits

Trim optimisation has significant economic benefits in terms of fuel savings. These economic benefits will vary from one ship size and type to others. It should be emphasised that even small trim changes can have a large impact on vessel performance. A 2% to 4% reduction potential in fuel consumption is generally referred to in most literatures. However, depending on ship type and operation draft, this number may be higher or lower. Therefore, for energy saving, all possible measures should be tried to help with ensuring that this potential is realised. Sailing just 5-10 centimetres off optimal trim might cause ships to operate at higher fuel consumption levels than normal [Tero Illus, 2012].

There is a bulk of evidences on significant fuel saving potentials due to trim. Ship resistance is altered due to the trim of a vessel through viscous resistance which is a function of the wetted hull surface area. When trim changes, wetted surface area and thereby hull resistance will be affected. By definition, if resistance increases, fuel consumption and emissions also increase.

Thus to reduce fuel consumption and emissions, trim needs to be optimised before and during a ship's voyage through a proper loading of the ship or use of ballast water in order to achieve a floating position that consumes the least propulsion power. Ships normally record their trim before the voyage by directly reading the draft marks. So, considering that the weight distributions on the ship allow trim adjustment, finding the appropriate and optimal floating position before voyage becomes possible (this is referred to as "static trim" when ship is not sailing). However, knowing the exact trim and draught during a ship's voyage is important. The trim under operational condition is normally referred to as "dynamic trim" and is different from "static trim" due to the impact of ship

[6] Computational Fluid Dynamics (CFD) is a branch of fluid mechanics that uses numerical methods and software systems to solve and analyse problems that involve fluid flows including liquids and gases. In shipping, it is widely used for estimating ship resistances and improves ship design via reduction of number of trial and errors experimentations such as ship's model tank testing. CFD methods involve significant level of numerical calculations; thus high computer powers that is readily available. On-going research and development has yielded much more accurate estimation of a ship's resistance and powering using this technique; including its use for establishing a ship's optimal trim.

motion. Its measurement requires real-time readings through sensors and relevant on-board data systems.

A vessel with high trim and draught fluctuations (more changes of dynamic trim) during its voyage might benefit more from trim adjustments than the one with small fluctuations. The following are two real examples of proven savings by trim optimisation:

- **Containership Example [**Tero Illus, 2012**]:** This case is for a 5,500 TEU container ship over 136 sea days crossing. It was found that the average percentage of propulsion power loss due to non-optimal trimming was 5%, whilst the vessel was on long, trans-oceanic legs, although lower on shorter and more coastal routes. The trim-related saving potential was calculated at 350 tons of HFO for the crossing. Even if operational constraints meant that the ship was only able to follow an optimum trim 80% of the time, 280 tonnes of fuel would still have been saved. Such a saving translates into more than US$ 100,000 reduction in bunker costs for the vessel operator in less than five months.
- **VLCC Example [**Melvin Mathew, 2012**]:** The results of a study on the impact of trimming on a VLCC showed that VLCCs can benefit significantly from trim optimisation due to their size and rate of daily consumption. The saving is dependent on the rate of use of the suggested optimum trim by the crew. This can be influenced by external conditions, such as extreme weather, as well as the crew's commitment to apply the trim guidance given to them. This study showed that proper use of trim adjustments, translates into propulsion energy savings of 1.8%, which equates to about 505 tonnes of fuel consumption reduction with saving levels of more than US$ 200,000 annually.

3.3 Definitions

Trim: Trim is normally defined as the difference between the aft draft and the forward draft:

Trim = T_A-T_F

Where:

T_A	Aft draft (m)
T_F	Forward draft (m)

When the trim is positive, it means that the stern of the vessel is more inside the water than forward. Accordingly, positive trim means trim to aft and negative values of trim means trim to forward. The concept of trim is shown in **Figure 3.1**.

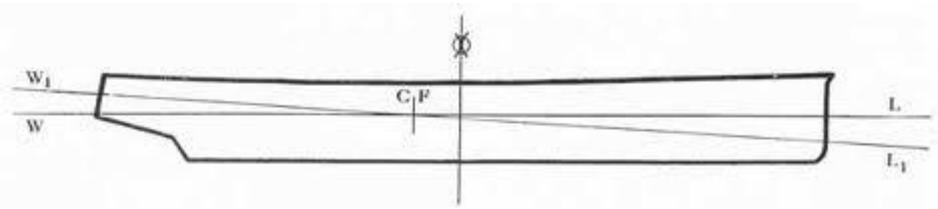

Figure 3.1: Concept and definition of trim

Optimum trim: Optimum trim refers to a ship's trim under which the required propulsive power is minimal for the specific operational speed and draft of the vessel.

Load planning: The ship loading plan specifies the loading levels and how the loads should be distributed in different cargo spaces. The load planning should be done by consideration of corresponding regulations (e.g. load line convention) but above all the ship stability. The process of loading of a ship is with port's staff and loading superintendents but the master or chief officer is ultimately responsible for all the loading and unloading operations.

Loading computer: A loading computer system is a computer-based system for the calculation and control of ship loading conditions for compliance with the applicable stability requirements and longitudinal and local strength requirements. The ship-board loading computer system consists of software (calculation program) and an appropriate computer (hardware).

Even keel: This refers to ship condition when the draft of a ship fore and aft is the same. In other words, even keel refers to zero trim.

Static trim: This refers to a ship's trim when the ship is in still water (not moving). In this case, it is the difference between aft and forward drafts; mainly dictated by the ship's cargo, ballast, fuel on board, etc. distributions.

Dynamic trim: This refers to a ship's trim when the ship is underway and moving. It is different from static trim due to the ship sinkage phenomena. The ship sinks down relative to the still water level when it is underway, due to its forward movement and environmental effects. The level of sinkage is characterized by a dynamic sinkage at the forward and a dynamic sinkage at the aft of the ship. Normally, the forward sinkage is more than the aft sinkage and is a function of ship speed as well. Dynamic trim thus is static trim plus trim changes due to ship sinkage while underway.

3.4 Physics of trim

A ship's resistances and its trim are closely related to each other. This is due to the fact that trim could change parameters that impact the hydrodynamic performance of a ship. The high impact of trim on ship performance is well known in particular for container ships and RoRo vessels. Large fuel savings are claimed due to changes to the ship trim.

The possible explanations for the relatively large dependencies of ship performance on the trim could be attributed to the following impacts of trim [Force Technology 2011]:

- Changes to wave resistance
- Changes to wetted surfaces and thereby the 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

On fast container ships and RoRo vessels, there is much to be gained by introducing the correct (optimum) trim. However, a reduction in fuel consumption due to changes to trim might be achieved even on tankers and bulk carriers [Force Technology 2011].

10.5.1 Impact of trim on powering requirement

There are different methods of determining a ship's optimum trim. The best results are obtained from self-propulsion tests using a scale model (model tank testing). In self-propulsion tests, not only the changes in hull resistance are investigated and the choice of propeller is examined but also the propulsion coefficients are normally measured. These tests, if performed over a sufficient range of speed and draft, could provide input in identifying optimum trim. **Figure 3.2** shows the parameters that are normally measured under self-propulsion tests.

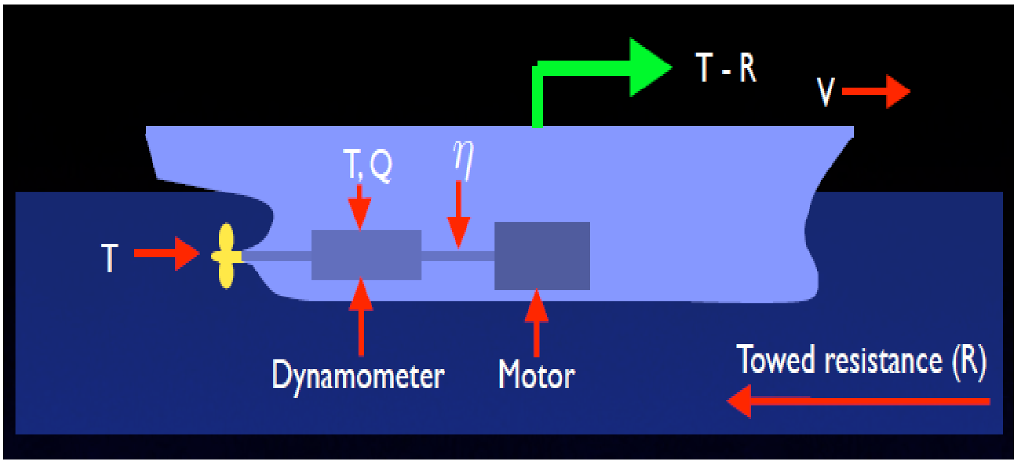

Figure 3.2: Schematic of parameters measured under model self-propulsion tests [Rod Sampson 2008]

Alternatively, with today's accuracy, trim tables based on use of CFD software tool calculations can be comparable to resistance model tests. However, both resistance tests and CFD methods tend to ignore the impact of the propeller; this may have a significant impact on evaluations of vessels with light drafts.

To determine the optimum trim, the vessel's loading conditions need to be investigated in order to find the extreme operational speeds and drafts. A test matrix is then set up; with drafts evenly divided in the test matrix. Typically, the ship is tested at both forward and aft trims depending on the feasibility of the vessel to undergo those trims. Normally, forward trim is often not possible for the lighter drafts due to restrictions in the propeller's submergence. Also, a simple resistance test under light drafts with aft trim, will not give the correct trim indication as the effects of the propeller inflow and submergence that makes a positive contribution to performance are not present.

Figure 3.3 by Lloyd's Register shows an example of such trim guidance table developed using CFD. As indicated, the ship is converted into a digital model with consideration of both ship hydrodynamics and aerodynamics. This digital model that resembles the full scale ship model is then trimmed at a variety of ship speeds and drafts and corresponding fuel consumption is estimated. The fuel consumption is then normalised relative to optimum values to show trims that would lead to high fuel consumption.

When you choose trim optimisation from Lloyd's Register we create a computer model of your ship, enabling us to perform a rapid and cost-effective analysis.

Speed		14 – 15.9 knots						16 – 17.9 knots					
Trim (metres)		-2 – -1.51	-1.5 – -1.01	-1 – -0.51	-0.5 – -0.01	0.01 – 0.5	0.51 – 1	-2 – -1.51	-1.5 – -1.01	-1 – -0.51	-0.5 – -0.01	0.01 – 0.5	0.51 – 1
Draught (metres)	7.9 – 8.5	Avoid 6.4%	Fair 2.5%	Good 1.6%	Optimal 0.0%	Fair 2.2%	Avoid 8.5%	Avoid 4.5%	Fair 2.1%	Good 6.4%	Optimal 0.0%	Fair 3.2%	Avoid 7.2%
	7.2 – 7.85	Fair 2.0%	Good 0.6%	Optimal 0.0%	Good 0.3%	Good 0.9%	Fair 2.8%	Good 1.2%	Good 0.6%	Good 0.0%	Optimal 0.0%	Good 0.4%	Avoid 3.3%
	6.5 – 7.15	Good 0.6%	Good 0.2%	Optimal 0.0%	Good 0.6%	Fair 2.0%	Avoid 3.0%	Good 0.1%	Optimal 0.0%	Good 0.1%	Good 0.5%	2.0% Fair	Fair 2.8%

An example section of the trim optimisation table you will receive for your ship. This contains a set of optimal trims according to draught and speed, and is specific to your vessel.

Figure 3.3: Typical prediction of flow field and impact of trim using CFD method [Lloyd's Register 2011]

Nowadays, the use of CFD for generation of trim guidance matrices is common practice in the industry.

10.5.2 Impact of trim on ship powering

Figure 3.4 shows the impact of trim on powering for a number of drafts for a fixed speed. As can be seen, there are large differences in the impact of trim at different drafts. In this case, at the deeper drafts, forward trim is better and the opposite is the case for the light drafts. Optimum trim is often seen relative to the even keel condition. Here it is important to mention that masters often trim their ships aft for increased manoeuvrability.

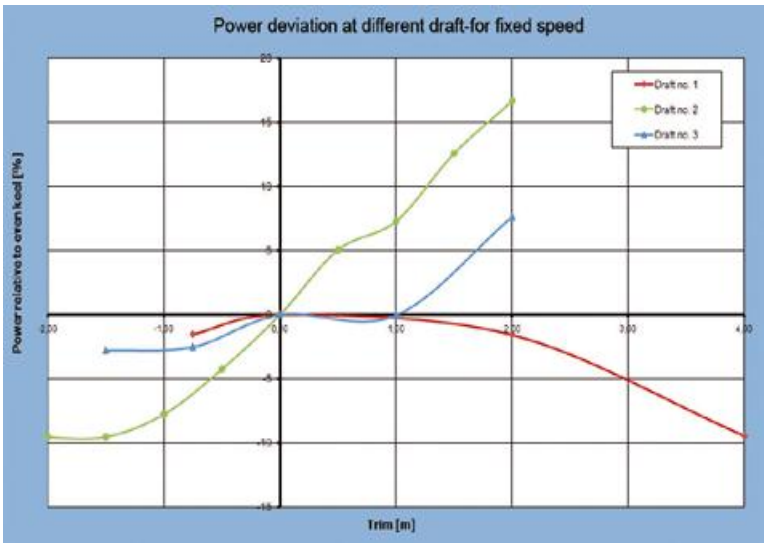

Figure 3.4: Trim guidance at different drafts [Force Technology 2011]

Referring back to **Figure 3.3** indicates similar trend. Normally, the ship trim is optimal when trimmed by the head.

10.5.3 Impact of sea conditions

A frequently asked question is how optimum trim changes with rough sea conditions as compared to calm water? In **Figure 3.5**, a vessel has been evaluated in both calm water and waves. Waves A and B are irregular sea states and the ship's heading is into a head sea. It can be seen that sea condition has no significant impact and the results for two waves is the same – i.e. optimum trim is at forward trim of -1.2 m. Ship real case experiences also show similar observations.

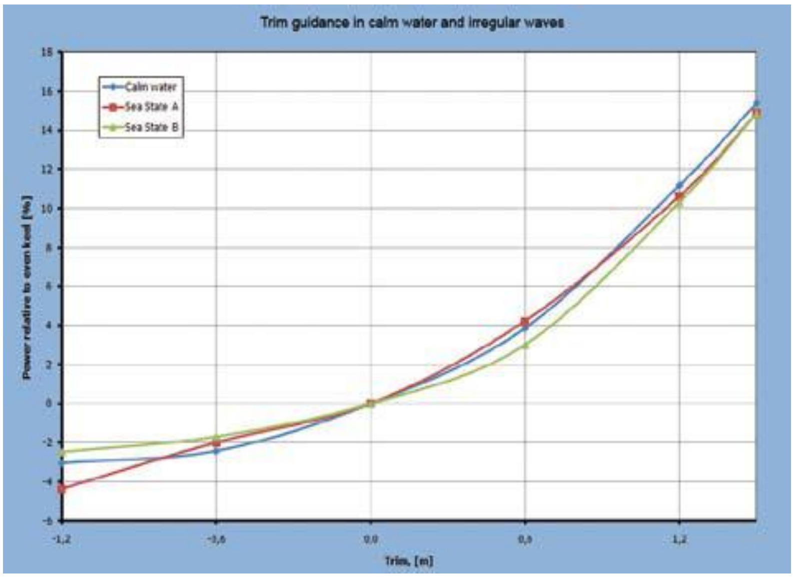

Figure 3.5: Impact of waves relative to calm waters [Force Technology 2011]

10.5.4 Impact of ship speed

Figure 3.6 shows the variation of propulsive power as a function of trim and vessel speed represented by Froude number. This has been developed for a large cargo vessel that represents most of large car-carriers, Ro-Ro vessels and container ships [Nikolaj Lemb Larsen 2012]. These ships normally have a pronounced bulbous bow, slender hull, centre skeg and one propeller.

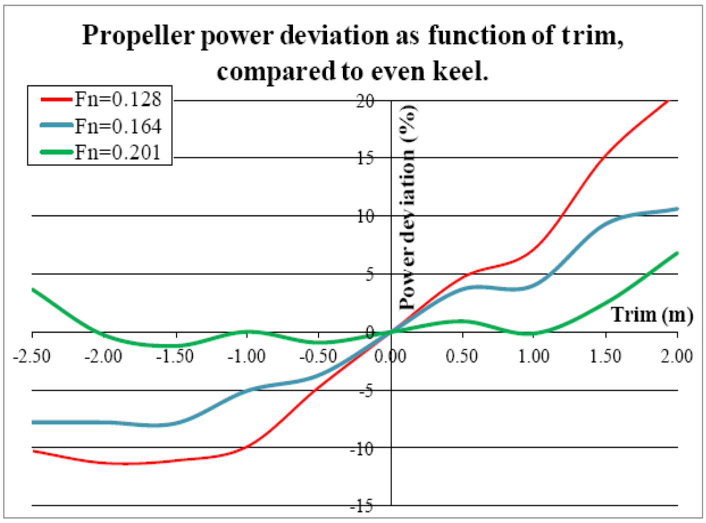

Figure 3.6 - Propulsion power as a function of trim [Nikolaj Lemb Larsen 2012]

In this case at lower speeds (Froude numbers), trim by forward gives the best results. As the speed increases, the optimal trim gradually moves closer to even keel (no trim).

3.5 Operation guidance

The current industry practice points to the fact that in the great majority of cases, even keel operation (zero trim) is the normal practice. This generally may represent the optimal trim for ships with high block coefficients and non-pronounced bulbous bow (e.g. bulkers and tankers). These ships are not normally operating at very high speeds; thus having a relatively lower wave making resistance.

In ships with a slimmer body and higher speed, the impact of trim on performance could be significant. In particular, the trim may have impact on performance of the bulbous bow, and thereby wave making resistance. This will signify that these types of ships are more sensitive to trim and therefore greater care should be exercised with trim optimization.

With the recent development in energy efficiency regulations, more companies have opted out to establish their ships' optimum trims; with the extensive use of CFD capabilities for this purpose. The issue, however, is that all the saving levels given are based on analytical forecasts and it is extremely difficult to do actual in-operation measurements to confirm the level of fuel savings.

Based on the above facts and for best practice, it is not sufficient to develop a trim matrix and then assume that the specified trim guidance is going to lead to energy efficiency. Practical tests and trials will be required to refine the trim tables. The best way is to use these trim guidance tables but also at the same time gather feedback from masters on their judgement of trim table and its impact on ship powering requirements. The feedback by masters on best trim for ship handling and powering requirements can help to refine the company best practice in this important area.

In using trim optimization, the following ship types would be given greater consideration:

- Container ships
- RoRo cargo and passenger ships
- RoRo car carriers

As indicated above, in addition to identifying and documenting the optimum trim as a function of ship speed and draft, it is proposed that the experience gained by ship staff on the impact of trim on a vessel's fuel consumption should be gathered in order to improve the ship's "trim matrix". Also, the effective use of the loading computer's capabilities is important to ensure safe trimming of the vessel with an optimal level of ballast water.

3.6 Tools for support

There are a number of tools that could be used for this purpose:

CFD methods for trim matrix: The effect of trim on fuel consumption can be measured at the model scale in a towing tank, or simulated at full scale using CFD. Many different speed and draft combinations can be simulated in a time efficient manner using fully viscous flow description analytical techniques. As a result, a trim matrix or map similar to that shown previously can be specified, where the optimum trim as a function of ship speed and draft are specified. The ship master or deck officer would normally follow this as a guide for setting the trim.

Dynamic trimming systems: These systems rely on a number of signals that are recorded whilst the ship is underway. The signals provide an indication of the ship's actual trim and some performance aspects of the vessel. Then the system uses analytical or artificial intelligence methods to forecast an optimum trim. Similar to “trim matrix” as explained above, this makes a good deal of theoretical sense but the actual effectiveness has yet to be established. Dynamic trim optimization includes collecting and monitoring real-time data of propeller thrust and manoeuvring rudder angles, weather conditions and sea-state. These data are then analysed constantly and the optimal trim value is calculated and displayed on a real time basis to give advice to the crew on-board.

Loading computers: The change in ship trim is achieved via cargo load planning and a ballasting plan when in port. When underway, the shift of ballast water and fuel between their relevant tanks may be used to adjust trim. During loading, occasionally there are limitations for achieving optimum trim due to the level of cargo and loading limitations that may not allow additional ballast for a proper trim. Nowadays, loading computers provide additional functionality for the representation of trim, optimal trim and also loading options to achieve the optimal trim. Trim linked to a loading computer helps the deck officers to achieve a better loading plan and optimal trim.

3.7 Barriers to trim optimisation

The good application of trim optimisation can be affected by the following constraints:

Ship loading: The weight distribution on board must be determined in order to allow trim optimization. Therefore, adequate communication between ship and port is paramount. As stated above, the loading computers may be effectively used for safe loading as well as for setting the optimal trim.

Operational risk challenges: This includes the oversight of bending moments and shear forces when practicing trim optimization. In this respect, it should be noted that not all vessels have real time stability assessors or calculators on-board. Additionally, danger to cargo in particular for those ships with deck cargos, is also another constraint.

Real-time bunker and water transfers on-board: The officers on the watch might have incomplete knowledge of the bunker and water (grey/fresh water) transfers on-board. Therefore, they may not be aware of the effects of such activities on the trim. Again this highlights the importance of ship-board communications between deck department and engine department.

Watch changeover: Sometimes the information regarding ballast operations is not passed on during the watch changeover between the crew.

Removing of the above barriers requires not only good understanding of the subject and training of ship-board crew and their dedication on best practice but also a continuous improvement approach to the problem for long-term sustainable culture of best practices.

3.8 Frequently asked questions

In this section, a number of frequently asked questions are raised and a summary of the discussion in this section is provided.

How much trim impacts fuel consumption?

There is no clear cut answer to this important question. Whilst the impact of trim is known to be significant under some conditions or for some ship types, there are no hard facts from ships' actual operations on the exact level of savings that may be made using perceived optimal trim. This is due to the fact that the measurement of savings under real operational conditions is quite difficult to assess. There is ample evidence from model tank tests and CFD analytical methods that show trim has a significant impact on ship fuel efficiency performance.

How does the optimal trim change with ship speed?

The change in optimal trim with ship speed and draft is through its impact on various types of ship resistances. It is quite reasonable to find that the optimal trim varies with ship speed and ship draft but this relationship will vary from ship type to ship type.

Is in-passage ship trim different from the trim set when in port?

It is well known that when the ship trim is set to zero during loading (even keel), the ship will give trim by bow due to the impact of ship speed (due to the ship sinkage phenomena). This means that the trim of the vessel while underway is different from its trim while at berth or waiting.

How in practice is trimming done while a ship is underway?

This is done via a shift of ballast water, and in some cases bunker fuel, between alternative tanks and possibly shift of water.

Is optimum trim different for loaded versus ballast conditions?

A ship's hydrodynamic performance under loaded and ballast conditions could be significantly different due to changes in draft and wetted surface area and performance of the bulbous bow. The same is true for trim under loaded and ballast conditions. Therefore, there is a need to have the optimal trim established for various draft levels. Also for ships operating in a variety of loading, and therefore variety of draft conditions, the optimal trim needs to be established for all the working drafts.

How is the trim set / changed?

The change in ship trim is achieved via the proper cargo load planning and ship ballasting plan. The combination is used to achieve the desirable trim. After the loading is complete, ballast water shifting and to some extent bunker fuel shifting between tanks can be used to aid trimming. In any case, it is better that load planning is done by considering the optimal trim as otherwise it may not be possible to trim the ship properly with the use of ballast water only.

Based on what has been described in this section, the following may be stated:

- Trim could influence ship fuel consumption significantly, with the evidence showing up to 4% of savings.
- Trim impact is the result of changes to ship hydrodynamics and thereby ship resistances.
- For every ship, there is an optimal trim that will give minimal ship resistances and maximise fuel efficiency.
- The optimum trim is a function of ship speed and draft.
- For certain ship types, in particular those with higher design speed, slimmer body, pronounced bulbous bow and flat stern design, trim will provide more impact.
- Optimal trims are established either through extensive model testing or CFD analytical methods.
- To achieve optimal trim, due consideration should be given to ship loading and its load planning.
- Ballast water, and to some extent bunker fuel, may be used to trim the vessel.
- Most loading computers on-board provide functionalities and trim tables to achieve the desirable ship trim.
- It is difficult to measure the actual saving levels due to trim while the ship is underway due to impact of other operational conditions (speed, draft, weather and sea impacts).

3.9 References and further reading

The following list provides references for this section and additional publications that may be used for more in-depth study of topics covered in this section:

1. Tero Illus, 2012 "Taking the guesswork out of trim", BIMCO bulletin, V107, August 2012. http://www.eniram.fi/wp-content/uploads/2013/10/2012-08-BIMCO-Taking-guesswork-out-of-trim.pdf accessed August 2015.
2. Melvin Mathew, 2012 "Trim Optimisation", MarinLink 2012, http://www.eniram.fi/wp-content/uploads/2013/06/News-2013-03-Marine-Link.pdf accessed August 2015.
3. Force Technology 2011, "Understanding of the physics of trim", Ship and Offshore Green Tech, 2011.
4. Rod Sampson 2008, "Self propulsion tests", lecture presentation, Newcastle University, April 2008. http://research.ncl.ac.uk/cavitation/archive/Lecture%2014%20-%20Self%20propulsion%20test.pdf accessed August 2015.
5. Lloyd's Register 2011, Company factsheet May 2011, www.lr.org accessed August 2015.
6. Nikolaj Lemb Larsen 2012, "Understanding the physics of trim", presentation to Green Ship Technology Conference, March 2012.
7. "IMO train the trainer course material", developed by WMU, 2013.
8. ABS 2013 "Ship Energy Efficiency Measures, Status and Guidance", http://ww2.eagle.org/content/dam/eagle/publications/2013/Energy%20Efficiency.pdf, accessed August 2015.

4 Ballast Water Management (BWM) and Energy Efficiency

4.1 Introduction

Ballast water (BW) is essential to control trim, list, draught, stability and stresses of a ship. Ballast water activities are largely regulated not only because of the above ship's safety implications but also since they have been recognized to be a pathway for the movement of undesirable and alien bio-species from their natural habitat to other ecosystems (**Figure 4.1**).

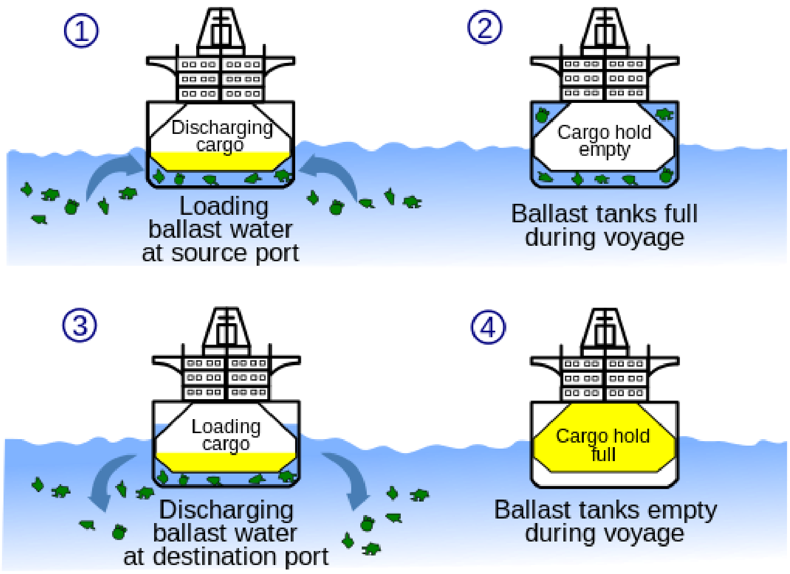

Figure 4.1: Transfer of bio-species due to ballast operations [Wikipedia]

Today, a full IMO Convention is devoted to ballast water management[7]. In this Convention, two main methods are highlighted: ballast water exchange (Regulation D-1) and achievement of ballast water standards (Regulation D-2).

The impact of Ballast Water Management (BWM) on a ship's fuel consumptions is not normally considered despite the evidence that, regardless of the management method established, the overall energy efficiency of a ship is affected by ballast water because:

- The ballast exchange requires the additional use of the ballast water handling equipment and in particular pumps.
- Treatment systems developed to reach D-2 standards require the installation of additional energy consuming equipment on board ships.

In addition to the increased use of ship-board power due to additional ballast treatment equipment, ballast water impacts the ship's energy efficiency in two additional ways:

- The change in ship displacement; thus wetted surfaces and ship resistance. Generally, the more ballast water or ballast sediments are carried around, the bigger the ship displacement will be and the higher ship's energy consumption is expected.

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[7] Refer to IMO website (www.imo.org) for regulatory details

- The change in ship trim: Trim optimisation via the effective use of ballast water could lead to gains in energy efficiency as has been discussed in the previous section.

In ballast water operations and management, one should use considerable foresight in choice of regulatory compliance methods due to the fact that many variables such as type and size of ship, ballast tank configurations and associated pumping systems, trading routes and associated weather conditions, Port State requirements and manning would impact the choice of the system.

4.2 Port and voyage planning aspects

The amount of ballast water discharge/uptake in a port depends on type of vessel, amount cargo loaded/un-loaded and ship loading planning. The need to counterbalance the detrimental effects of weight distribution during and after loading/unloading must be addressed in ports. The cargo distribution should be considered as having an impact on the quantity of ballast as well as on the ability to optimize the trim without jeopardizing the ship's strength and stability.

Therefore, the port and ship responsible persons must develop plans and procedures to optimize the ballast water intake through the establishment of the cargo loading/unloading process and the final cargo plan.

In addition to the anticipated ballast plan, the dynamics of the voyage should be taken into account especially when ballast water exchange has to be carried out. Ballast water and trim optimisation and adjustments while in passage should be pre-planned relative to the port operations that normally give and even-keel no trim. Sediment uptake and removal should be controlled as part of voyage planning to ensure the minimal level of sediments. As part of voyage and daily activity planning, the case for these two should be included and discussed. The voyage should be planned taking into account when ballast water exchange or adjustments are to be carried out. Also, trim optimisation and adjustments, while in passage, should be pre-planned relative to the port even-keel operation.

4.3 Typical ballast water systems without treatment

Figure 4.2 shows a typical ship's ballast water engineering system. It is comprised of ballast pumps, relevant piping system and flow control methods. This system is normally installed according to IMO guidelines and is operated in accordance with the system design criteria and the manufacture's operational and maintenance instructions.

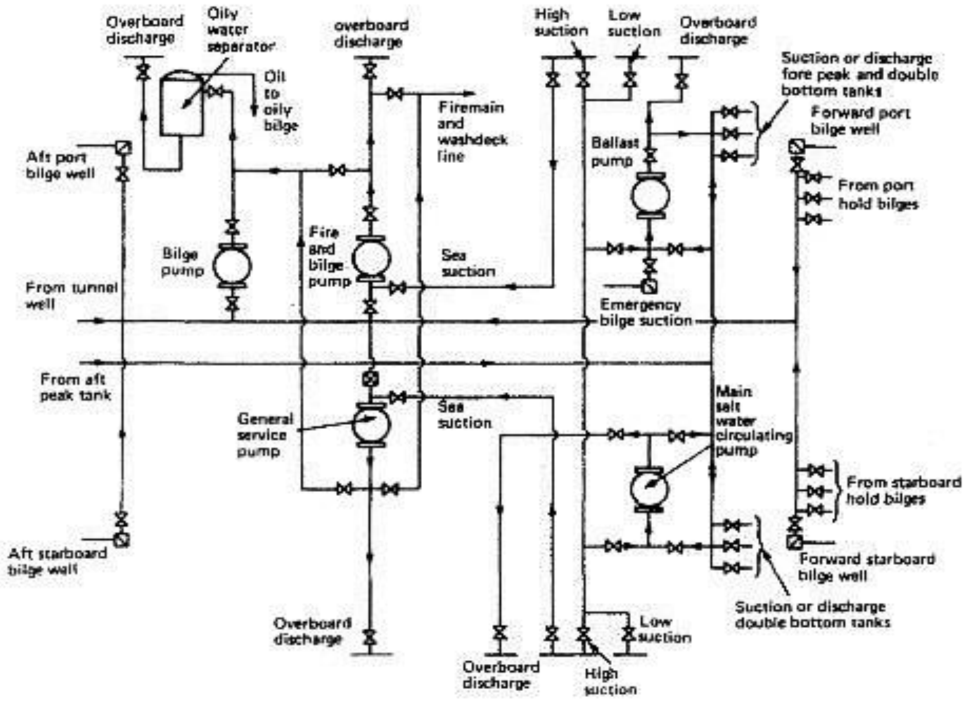


Figure 4.2: Typical ballast and bilge pump arrangement [Machinery Spaces.com]

The ship-board use and operation of such a system is normally described in the ship's Ballast Water Management Plan (BWMP). All failures and malfunctions of the system are recorded in the Ballast Water Record Book (BWRB) according to IMO requirements.

4.4 Ballast Water Management Plan (BWMP)

As soon as the Ballast Water Management Convention enters into force, it will be a requirement for each applicable ship to have a BWMP that specifies requirements for this purpose (most ships currently have such a BWMP in different formats). The following are normally included in the BWMP:

- Acceptable methods for ballast exchange and relevant procedures.
- Details of the procedures for the disposal of sediments at sea and to shore. Method of the use of port reception facilities for sediments.
- Designation of the on-board officer-in-charge of the implementation of BWMP. The identification of a responsible person should enhance the planning of BWM operations. In this respect, adequate training of such crew members should encompass awareness on the energy efficient operation of the BWM equipment and optimization for deadweight management and trim optimization.
- Method of the sediment removal or reduction at sea, and when cleaning of the ballast tanks takes place.

Principle of sediment management: To reduce the sediment levels, the following general advice is provided by the IMO:

- All practical steps should be taken during ballast uptake to avoid sediment accumulation.
- When sediment has accumulated, consideration should be given to flushing tank bottoms and other surfaces when in suitable areas.

- The volume of sediment in each ballast tank should be monitored on a regular basis.
- The frequency and timing of removal will depend on factors such as sediment build up, ship's trading pattern, availability of reception facilities, work load of the ship's personnel and safety considerations.
- Removal of sediment from ballast tanks should preferably be undertaken under controlled conditions in port, at a repair facility or in dry dock.
- The removed sediment should preferably be disposed of in a sediment reception facility if available, reasonable and practicable. Disposal should take place in areas outside 200 nm from land and in water depths of over 200 m.

Officer-in-charge: Basic tasks and responsibilities held by the officer-in-charge according to IMO guidelines include:

- An officer should be made responsible to ensure the maintenance of appropriate records and to ensure that ballast water management procedures are followed and recorded.
- When carrying out any ballast water operation, the details need to be recorded in the Ballast Water Record Book.

The officer-in-charge of ballast water management should perform the following duties:

- Ensuring that the ballast water operations follow the procedures in the BWMP.
- Ensuring that the Ballast Water Record Book and any other necessary documentation are maintained.
- Being available to assist the inspection officers authorized by a Party[8] for any sampling that may need to be undertaken.

Since the Ballast Water Management Convention has not yet entered into force, the management of BW is not a worldwide obligation. However, an increasing number of countries require proper BWM before arriving in their waters. Currently, a small amount of the world's fleet carries BW treatment systems. Thus, the present dominant technique to manage BW is through the "ballast water exchange".

4.5 Methods of ballast exchange

There are three methods of ballast water exchange which have been evaluated and accepted by the IMO. The three methods are the sequential method, the flow-through method and the dilution method.

- **Sequential method** – A process by which a ballast tank is first emptied and then refilled with replacement ballast water to achieve at least a 95 per cent volumetric exchange.
- **Flow-through method** – A process by which replacement ballast water is pumped into a ballast tank, allowing existing ballast water to overflow from the tank (see **Figure 4.3**). For effective ballast exchange, the volume of flow through water should be at least 3 times the volume of the water in the tanks.

[8] A Party, in IMO terminology, refers to a state that has ratified a Convention (in this case the Ballast Water Management Convention).

- **Dilution method** – A process by which replacement ballast water is supplied through the top of the ballast tank with simultaneous discharge from the bottom at the same flow rate and maintaining a constant level in the tank throughout the ballast exchange operation.

Figure 4.3: Ballast water exchange using flow-through method [Wikipedia]

For ballast water exchange, particular care should be taken of the following:

- Stability, which is to be maintained at all times as regulated by the IMO or flag or port authorities.
- Longitudinal stress and torsional stress values, not to exceed permitted values with regard to prevailing sea conditions, where applicable.
- Sloshing[9] impact reduction due to water movement should be considered in order to minimise the risk of structural damage, in particular at non-favourable sea and swell conditions.
- Wave-induced hull vibrations when carrying out ballast water exchange.
- Limitations of the available methods of ballast water exchange in respect of sea and weather conditions.
- Forward and aft draughts and trim adjustment, with particular reference to bridge visibility, slamming, propeller immersion and minimum forward draft; and energy efficiency (optimum draft).
- Additional workloads on the master and crew.

As explained, the ballast water exchange process has implications for both safety and energy use. Also, it is shown that trim optimisation has a significant impact on ship energy efficiency.

4.6 Energy efficiency aspects

In general, observing the following will lead to energy efficiency:

- **Carrying less ballast water:** The displacement of a vessel is a function of lightweight, fuel, cargo and ballast weights. As such, less ballast water means lower displacement and lower resistances (or more cargo). Therefore, it is generally desirable to have less ballast from an

[9] Sloshing in ships refers to the movement of liquid inside a tank due to ship motion. Strictly speaking, the liquid must have a free surface (tank partial fill) to create a slosh dynamics problem

energy efficiency point of view. Of course this should not contravene any of the regulations nor compromise ship safety.

- **Optimizing use of the equipment:** This item relates to the use of ballast water equipment via management of the amount of ballast water to uptake, discharge, correct method of uptake/discharge and so on. The aim would be to reduce or optimise the usage of relevant ship-board equipment.

- **Efficient ballast management operations:** This means performing ballast exchange or ballasting and de-ballasting in a way that is more energy efficient. For example:
  - **Gravity assisted ballast exchange** is preferred to simple pumping in/out processes. When the gravity-assisted method is used, there is less need to run the ballast pumps.
  - **Sequential ballast exchange** method, where tanks are first de-ballasted and then ballasted again is more energy efficient than the “flow-through ballast exchange” method, where the thanks are allowed to overflow. Again, this is for reasons of the amount of water that needs to be displaced; thus the number of hours for ballast pumps to operate.
  - **Trim optimisation:** Ballast water is used to adjust the ship trim as discussed before. Trim optimisation using ballast water leads to significant energy savings on some ships.
  - **Steam driven ballast pumps:** In some ships, ballast pumps are steam driven. The use of a boiler for this purpose is extremely inefficient. Therefore, minimisation of the use of steam-driven ballast pumps by better planning of the ballast water operations can lead to energy savings.
  - **Sediment removal:** It is usual to take in sediments as part of ballast water operations. These sediments could be heavy and thus causes higher ship fuel consumptions when they are carried around. Thus, sediment removal leads to better cargo capacity and better energy efficiency.

4.7 References and further reading

The following list provides references for this section and additional publications that may be used for more in-depth study of topics covered in this section:

1. Wikipedia “Ballast water discharge and the environment”, https://en.wikipedia.org/wiki/Ballast_water_discharge_and_the_environment accessed August 2015.

2. Machinery Spaces.com “Bilge and ballast systems for general cargo ships”, http://www.machineryspaces.com/bilge-and-ballast-system.html accessed August 2015.

3. For more information on ballast water management equipment and development, see “Guide to ballast water treatment systems 2013” by IHS http://www.rwo.de/rwo/ressources/documents/1/25412,Ballast-Water-Guide-2013.pdf

4. For information on regulatory framework, convention, guidelines, etc., refer to IMO website at: http://www.imo.org/OurWork/Environment/BallastWaterManagement/Pages/Default.aspx

5. For more information on ballast water regulatory aspects and best practice, see: American Bureau of Shipping “Guide for Ballast Water Exchange”, July 2010 (Updated October 2010”,

https://www.eagle.org/eagleExternalPortalWEB/ShowProperty/BEA%20Repository/Rules&Guides/Current/171_BallastWaterExch/Guide.

6. “IMO train the trainer course material”, developed by WMU, 2013.

5 Hull and propeller condition

5.1 Ship resistance and hull roughness

As discussed earlier, the ship resistances due to wetted surface areas are composed of frictional and wave making resistance. Frictional resistance, in particular for slower speed ships, is the primary component of total resistance. A tanker at its design speed will use the majority of its fuel overcoming frictional resistance when sailing in calm water. When the hull moves through the water, water will be dragged along, creating a body of water following the ship and forming what is referred to as a "boundary layer". In the forward part of the ship this boundary layer will be comparatively thin, but it grows in thickness along the sides of the hull. A boundary layer will form even on completely smooth hull surfaces. Increasing the roughness of the hull surface tends to increase the boundary layer, consequently increasing the frictional drag of the hull.

In ship resistance, another major player is the ship speed relative to water close to hull surface. The effect of surface roughness on the resistance depends on the effective speed of the water relative to the hull, and this varies over the hull surface. For example increased surface roughness in the bow area will cause greater resistance than in the aft areas or under the hull bottom because the effective speed of the water will be less. So in reducing the roughness, different part of the ship will have different level of impacts even if their original roughness is the same.

The smother the hull, the less resistance the ship will have and thus the faster it will go for the same power output, saving fuel and reducing GHG emissions. Fouling will reduce the smoothness (increase roughness) of the hull and even may add weight to the vessel reducing the cargo carrying capacity. These impacts make the hull roughness and fouling a major issue of control for energy efficiency.

Figure 5.1 shows this relationship between increase in required propulsion power or fuel consumption and hull roughness. It has been suggested that each 10 µm to 30 µm of additional roughness can increase total hull resistance by about 1 percent for full form ships (of course the increase in resistance will be influenced by ship speed as well).

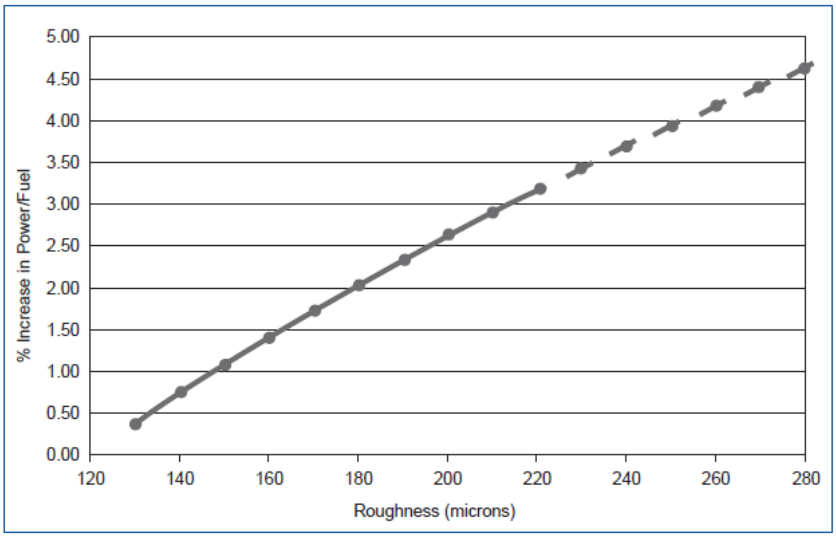


Figure 5.1 – Typical increase in power/fuel required to maintain vessel speed of a fast fine ship vs increasing hull roughness [International Paint 2004]

It is not uncommon for a new ship to be delivered with surface roughness as low as 75 µm and later in life enter dry-dock with a roughness of 250 µm. Historical records have shown that even with good maintenance practices average hull roughness can increase by 10 to 25 µm per year, depending on the hull coating system, even when fouling is not included [ABS 2013]. **Figure 5.2** shows typical ship increased resistance as a function of time and impact of hull surface improvements due to maintenance efforts.

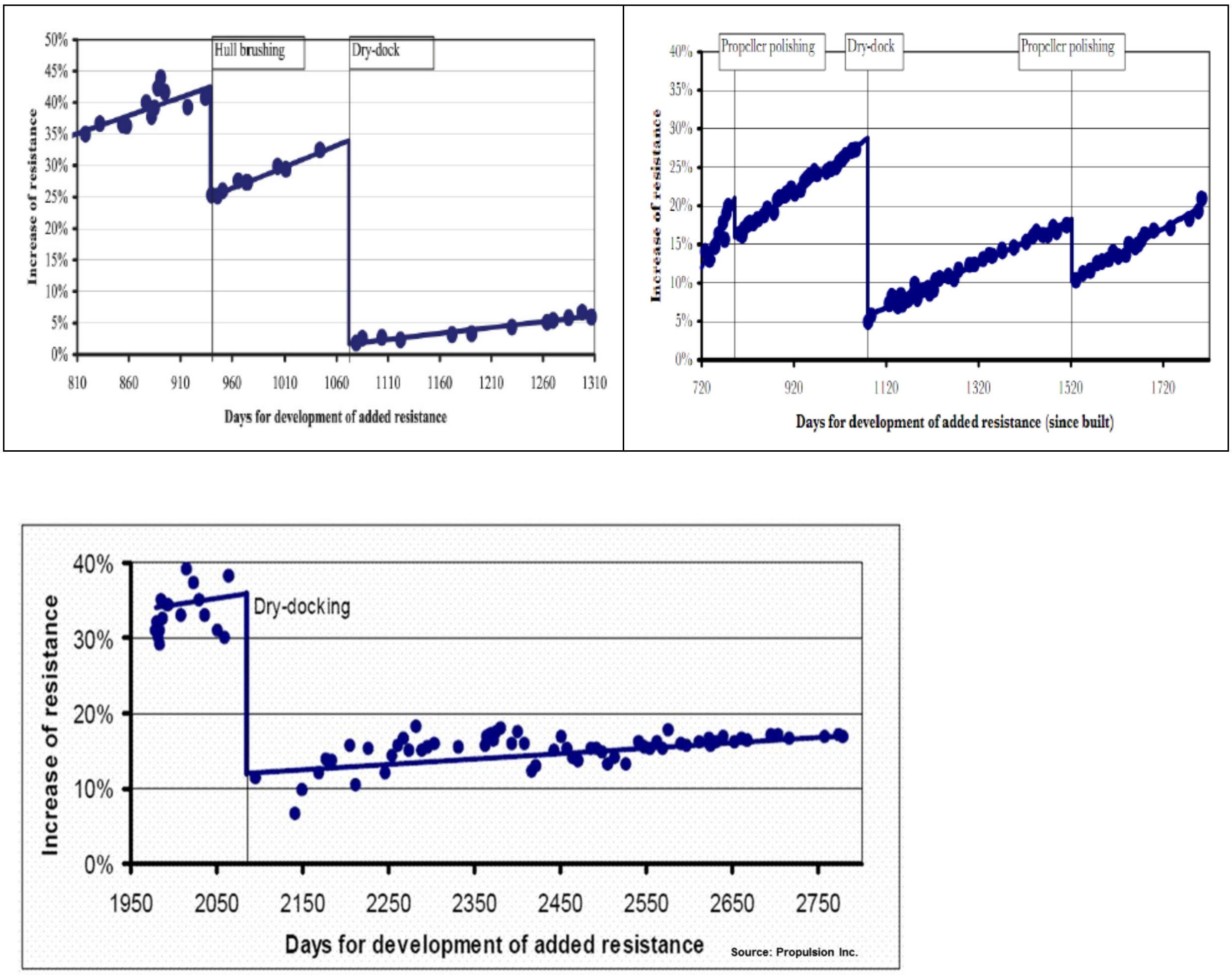


Figure 5.2 – Changes in ship resistance with time **[Monk and Kane]**

5.2 Causes of surface roughness

Hull surface roughness comes in many forms and from many sources which can be broadly categorized as physical or biological. These sources are further grouped based on size as either micro roughness (less than 1 mm) or macro-roughness (greater than 1 mm). The physical micro-roughness can be increased in service by mechanical damage, failure of the applied coating and even improper preparation of the surface and/or improper application of a new coating. Biological roughness (fouling) also has a significant impact on resistance, even at the micro level (slime, algae, etc.). See **Figure 5.3** for some types of fouling. Predictions based on model tests of a light displacement fine-form ship indicate that a light slime covering the entire wetted surface can increase total resistance by 7 to 9 percent. A heavy slime results in a total increase on the order of 15 to 18 percent. Small barnacles and weeds push this up to a 20 to 30 percent increase in total resistance [ABS 2013].

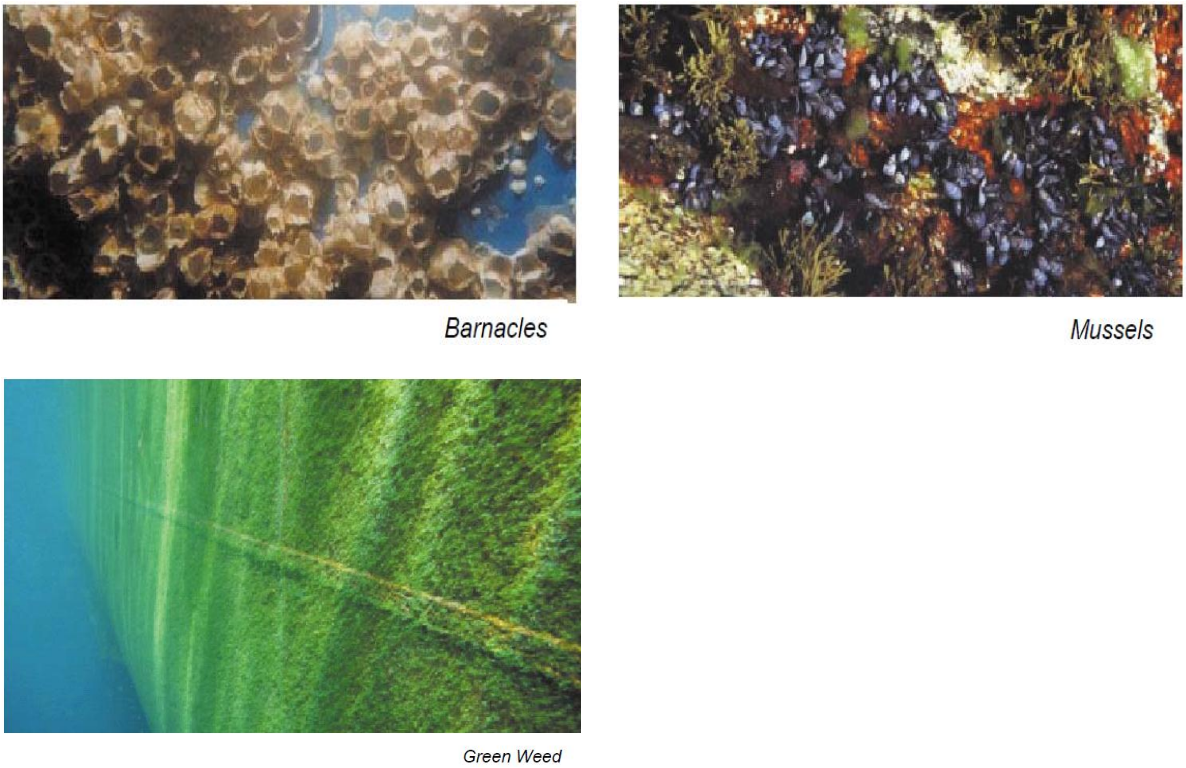


Figure 5.3 - Example of fouling [International Paint]

Biological fouling is a very complex process that depends on factors such as the ship's loading condition, its operating zones, the effectiveness of anti-fouling paint and environmental conditions. If a ship is constantly moving it will not gather as much marine growth as one that spends long periods in port or at anchor. If a vessel is left static for extended periods it will allow the marine growth, that cause fouling, to attach itself to the hull and propeller which will reduce the speed of the ship and increase the fuel consumption. Hull cathodic protection also tends to work better when the ship is moving.

The main factors that influence hull fouling rates are:

- Initial roughness of the hull
- Quality of hull coating
- Robustness of the coating with respect to mechanical damage
- The areas of the hull where there is sunlight, along the sides of the hull and near the waterline.
- Temperature of water (colder water generally means less fouling)
- The salinity of the water (performance coating will be a function of salinity of water)
- Amount of algae in the water
- Ship speed and its operation profile (hull moving, speed, at berth, at anchor, layby, etc.). or static)
- Hull maintenance

During the operation of the ship, surface roughness can increase due to cracking and damage to the coating as well as due to corrosion which can also attract marine growth. The growth of organic species will include slime, weed fouling, and barnacles as examples shown in **Figure 5.3**. Current antifouling paints tend to last for a maximum period of 3–5 years when the self-polishing coating must be renewed however its performance is reduced gradually over time as explained later. The hull will also require cleaning / brushing that can either be performed by divers or automatically with either the whole hull or just critical parts being targeted. Having a shorter interval between the applications of coatings may therefore reduce energy consumption but there are some problems as the ship will require an additional dry-docking that is very costly.

5.3 Hull roughness reduction

Taking care of the underwater portions of the hull is all about minimizing roughness. This can be achieved via smooth surface finish, more appropriate paint, more appropriate operation and more appropriate hull and propeller maintenance. In order to minimize a ship's frictional resistance, the owner must address both physical and biological roughness. There should be a smooth surface to start with and it should be maintained at proper intervals. Mechanical damage and coating failures have to be addressed and fouling has to be controlled. Regardless of what system is selected to manage roughness, care should be taken to make sure the cleaning methodology is compatible with and compliments the coating system. Regardless of the type of coating, it is also worth noting that the amount of fouling can vary greatly with trading pattern and operational profile.

5.4 Hull coatings

There are currently three different coating types in wide usage and they offer different resistance to fouling, have a different impact on hull roughness and have different requirements for cleaning frequency. These are [ABS 2013]

- **Controlled Depletion Polymer (CDP)** – A traditional antifouling type based on water soluble natural or synthetic pine rosin mixed with a biocide. An insoluble reinforcing polymer resin is added to create a skeleton to give the rosin better mechanical properties. The controlled dissolution of the rosin matrix releases the biocides. Over time a build-up of insoluble materials at the surface in a leached layer slows the release of biocide and makes recoating difficult. Moving water (or cleaning) is required to wear off this resin skeleton and release the next layer of coating and biocide. Typical life before recoating is 3 years, but because of the build-up of this leached layer and reduced biocide release micro fouling (green slime or weeds) can become a problem in less than two years. The average hull roughness increase is estimated at about 40 µm per year in surface profile, but this can vary greatly.
- **Self-Polishing Copolymer (SPC)** – An insoluble metallic or organic synthetic polymer (e.g. copper-acrylate or silyl-acrylate) that contains a biocide. Through a chemical reaction – hydrolysis – the polymer becomes soluble. Its subsequent dissolution releases the biocide. The chemical reaction provides good control of the rate of dissolution and results in a much thinner leached layer and smoother surface profile than possible with CDPs. No ship movement is required as there is no residual 'skeleton' and the surface is actually self-smoothing. Five years of service for high quality systems can be achieved. Average hull roughness increase is estimated at about 20 µm per year.
- **Foul-release Coating** – A biocide-free coating that uses non-stick properties to control fouling. It is usually silicone or fluoro-silicone based and designed to shed any micro or macro growth when the vessel is underway. For slower vessels (less than 15 knots) this is a challenge for even the best coatings so some 'soft' cleaning is usually required to remove the micro fouling. If the vessel is stationary for some time, barnacles and other macro-size biota can become attached. Achieving a full release of all fouling through ship speed impact has proven to be a challenge in some cases. The coating gains some of its effectiveness from its extremely smooth surface and this must be maintained for best performance. Roughness

in a foul-release coating will reduce its ability to discourage adhesion and slime/ micro fouling can take hold. Mechanical damage from example from tugs is especially critical for these types of coatings requiring special care in operations as the damaged parts has no fouling protection. Average hull roughness increase is estimated at 5 µm per year, but this is based on a very limited service experience.

The factors that govern the type of underwater hull coating that may be applied to a ship are;

1. Cost: The more effective anti-fouling coatings tend to be more expensive.
2. Speed of vessel: Fast vessels such as HSC tend to have harder coatings.
3. Fresh-water or salt-water: The coating quality should be chosen accordingly.
4. Compatibility: Some coatings cannot be used on top of others due to adverse physical and chemical interactions
5. National regulations: Some types of anti-fouling paints are banned in certain countries.
6. Area of operation: Severity of fouling in area vessel is trading, some sea areas are much worse than others.

When searching for the best hull coating, it is important to consider a coating that provides a smooth surface that can be reasonably maintained in its smooth state, and that prevents adhesion of fouling organisms. Also, the coating must be applied properly, monitored and managed to maintain its best qualities.

If done correctly, the right coating upgrade can offer significant fuel saving improvement. In general, application of a good high-quality coating can yield an average reduction of up to 4% in propulsion fuel consumption. Reducing an already rough hull to smoother one (via getting rid of fouling, surface blasting, etc.) and applying advanced coating even can provide 10-12% decrease in fuel cost. A full blast to remove surface roughness and application of prime, anti-corrosive and high quality anti-fouling coating can cost about US $10/m2. This converts for a VLCC to about US $300,000 [ABS 2013]

Since the banning of TBT (Tributyltin) based on "The International Convention on the Control of Harmful Anti-fouling Substances on Ships, 2001", most anti-fouling coatings are self-polishing copper and tin based paints but it should be borne in mind that some countries are either banning or considering banning the use of copper based paints in certain areas particularly in inland waters.

Biocide-free silicon-based coatings are also available but their market share is very small due to their high cost. These coatings are commonly referred to as "foul-release coatings" as they have a soft surface onto which it is difficult for most organic growth to hold. Research has shown that these new coatings are equally as effective as TBT-based systems but there is still some debate and not everyone is totally convinced.

In general the more advanced products do yield better results, however if a particular ship operating in a particular area, is getting fouled up faster with one product, it is worth considering changing to a different one. It is also worth talking to other ship operators in the same area and asking which produce works best for them, as they can give unbiased advice which one may not get from an original vendor.

5.5 Hull Cleaning

Regular in-service cleaning to remove fouling organisms is clearly beneficial unless it is carried out in a way that results in a damaged coating or a 'roughed' up surface. From a fuel efficiency point of view, the emphasis should be on hull and propeller "roughness" management and not just on the control of "fouling".

In the case when only partial cleaning is possible due to operational circumstances, the hull areas should be cleaned in the following order to provide the best performance enhancement:

• Forward third of hull

• Remainder of hull working from forward to aft with emphasis on areas which have more exposure to light

A proactive approach that pre-empts any type of widespread macro fouling is always recommended simply because the cost of having such fouling present outweighs the cost of cleaning by a very large margin. Regular cleaning of micro-fouling is also often cost effective if the proper cleaning technique is used so that the surface roughness is not degraded and coating material is not removed.

For best results, the scheduling of cleaning should be based either on monitoring of performance indicators (like power versus speed) or on regular pre-cleaning inspections. In both cases a threshold is established that identifies when cleaning is economically justified. For visual inspections the threshold includes the percentage of the hull surface that is fouled and the type of fouling. Regular inspection, photographs and roughness measurements would be a prudent way to monitor the impact of cleaning and the condition of the coating.

Use of underwater cleaning techniques and equipment should be done with care and with due consideration to original coating as well as amount of fouling. For example, removal of macro size fouling is difficult to be done without removing a significant amount of paint. If the antifouling is applied in different colour layers then these colours can be used to monitor paint removal during cleaning. In general, SPCs have a thinner leached layer than CDPs so the cleaning should use a less aggressive technique. Cleaning of foul-release coatings should only be done with a light touch and soft pads. In all cases, the advice of paint manufacturer should be followed, cleaning aspects should be reviewed with the cleaning company and condition before and after documented with good underwater photography of the cleaned surface.

Cleaning a light slime can yield up to 7-9% reduction in propulsion fuel consumption. Cleaning a heavy slime could give 15-18% and cleaning of a macro heavy fouling up to 20-30%. Hull cleaning by divers can cost about US $1.5 to 2.5 in the Far East. This could convert to US $50,000 for a full hull cleaning for a VLCC based on ABS's guide written in 2013. Of course, there is always no need to do a full hull cleaning, thus reduce the time and cost of hull cleaning but everything must be carried out with due care for the preservation of the coat system; otherwise things may give negative results.

Other aspects

Regulations: When planning for hull cleaning, it is also important to be aware of other regulatory instruments that govern the coating system. The IMO at its MEPC meeting in July 2011 adopted, as a voluntary instrument, the MEPC.207(62) resolution on "Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species". This asks for a Bio-fouling Management Plan and a Bio-fouling Record Book to be on-board. It is clear that while the proposed regulations undoubtedly will lead to added cost for ship maintenance and operation, it can also reduce the hull drag and fuel consumption if it is well managed with consideration for selection and maintenance of best coatings, and as such result in reduced total cost. Also, as indicated, there are local regulations that ban certain type of anti-fouling coatings that also need to be taken into account.

Area of operation: Anti-foul hull coatings used on seagoing vessels are generally designed for saltwater and ships that spend extended periods in fresh water or brackish water will tend to foul quicker. If a vessel is going to operate in fresh water on a particular charter for some time it will be worth considering reducing the hull cleaning period or changing the type of anti-foul paint used. In winter when the temperature of the water drops below a certain level, fouling of the hull is reduced but will increases in the summer months when the temperature of the water rises. In temperate zones the maximum fouling occurs in late spring though to early autumn. An in-water inspection of the hull in the summer month may be beneficial for ships operating in such conditions such as short sea passenger ships.

In water inspections: Regular in water inspections of the hull or dry-docking is the only certain way of assessing what the condition of the hull coating is. The speed and power output of the vessel should be continually monitored to establish if fouling is reducing the vessels performance. This can help the ship operator decide what the in- water cleaning or dry docking interval should be. The condition on the hull should be assessed regularly in line with the period detailed by the company and this period my need may need to be reduced if substantial fouling is evident. If a ship is laid up for any period of time an in-water survey of the hull is advisable and if the fouling is significant the ships hull should be cleaned and the anti-foul reapplied.

Hull cathodic protection system: The installation of a hull cathodic protection system should also be considered and as it can reduce the corrosion of the hull. Corrosion will increase the hulls friction and resistance to the water flow past the hull and thereby increase fuel consumption. It has the added benefit of reducing pitting of the hull plating which reduces the strength of the hull.

Lay-up: If a ship has been in lay up in a high fouling area for a long time it may need to be taken to dry dock to be cleaned before it can be put into service. When laying up a ship for any period of time it is worth considering where the ship is going to be moored and if possible avoid an area that is subject to high fouling.

5.6 Propeller roughness and energy efficiency

Similar to the hull surface, propellers suffer degradation in performance due to surface roughness. The absolute magnitude of the reduction in ship efficiency due to propeller roughness is less than those experienced with a rough hull surface, but it still has been estimated that it could cause an increase of as much as 6 percent of total fuel consumption. Further, the efficiency loss per unit of affected area is greater, making the economics of cleaning and polishing the propeller very compelling.

The effect will be greatest for propellers with large area aspect ratios and for propellers running at high rates of rotation. Polishing will mainly reduce the frictional loss of the propeller but will in many cases also reduce the rotational loss.

On a propeller, physical surface roughness is created by corrosion (on both sides of the blades and heavier in the outer half region); cavitation erosion (concentrated near the tips and back of blade); and impingement attack (on the leading edge and closer to the tips). Improper maintenance can also increase roughness; this could be overspray from hull coatings, grinding/polishing that is too aggressive or nicked edges.

Propeller coatings and polishing / cleaning

There have been important advances in foul-release coatings for propeller blades made in the last 15 years. These new coatings can have better surface properties than the polished propeller surface. Even though they have evolved with very good adhesion properties, the coatings are subject to damage by cavitation erosion and leading edge impingement. The cause of the damage to the coating also prevents any fouling and so the localized coating damage does not affect performance to any significant degree. The propeller coatings also offer protection against corrosion-induced roughness and fouling.

In service, regular underwater cleaning and reconditioning of the surface of a propeller is done with a small rotating disk that can easily conform to the complex shapes of the blades without gouging the surface. This tool removes all fouling and produces a fine surface scratch pattern in the range of 1 to 2 µm. This is similar to what would be expected of a newly manufactured blade surface. Any large deformation or damage, especially to the leading edges or tips, should also be repaired and smoothed out [ABS 2013].

The importance of the propeller being clean with a polished smooth surface cannot be over emphasised as the efficiency of any propeller can fall off rapidly if it becomes pitted and covered in marine growth. If the propeller is constantly rotating, there should not be a problem with marine growth but if there is not sufficient cathodic protection or the propeller is allowed to operate close to the surface, then cavitation pitting can be caused as a major problem. Marine growth will tend to accumulate much more when the propeller is not moving such as when the vessel is in port or at anchor. Running the engine every day for a short period can reduce this build-up if this is possible with not so much excessive fuel use. Preventive maintenance can be taken by polishing and applying coating to the propeller to reduce the build-up of marine growth and regular in-water surveys to inspect the propeller for damaged, pitting and marine growth.

It has been estimated that polishing a roughened propeller surface may result in a decrease in fuel consumption of up to 3%. Cleaning and polishing of the propeller can generally lead up to 6% improvement in fuel consumption. Divers can clean a 5 bladed and 10 m diameter propeller in about 3-4 hours for a cost of about US $3,000 in the Far East. In Europe the cost could be double as high. These numbers are quoted from ABS guidelines that are written in 2013, thus subject to inflation and market forces.

5.7 Condition-based hull and propeller maintenance

Maintaining a clean hull and propeller as advised above lead to significant fuel consumption reduction. The major questions are:

1. What are the optimal timing for hull and propeller cleaning?
2. What the best routine for cleaning to safeguard the integrity of existing paint system.
3. What is the time to apply a new coating and which one?

Condition-based hull and propeller maintenance tries to give an answer for item 1. Knowing when to clean the hull and the propeller is the goal of condition-based surface maintenance. This can be done in two ways:

- Measure/observe actual hull and propeller roughness/fouling and compare with baseline values that indicate when cleaning should be done.
- Use performance analysis packages that track changes in fuel consumption, shaft power and main engine power to identify degrading surface conditions.

The first method is based on a direct assessment of the actual surface condition which must be done by divers in port. By correlating the roughness and degree of fouling to losses in efficiency and increases in fuel consumption, the owner can make an economic decision on when hull cleaning and/or propeller polishing should be done.

For second method and a proper ship performance assessment, it is necessary to evaluate the speed power curve and for this purpose, the ship's speed though the water without the effects of weather, tides or currents should be established. This is very difficult to calculate accurately, particularly on an actual voyage, as these environmental factors may vary significantly a bit over the duration of the voyage. In such a condition, the best option would be to conduct performance monitoring in the form of periodic speed trials over a set distance, in both direction and in calm water. However, this is not always possible and thus limits the use of analytical methods.

The use of performance monitoring systems is attractive because it measures fuel consumption directly and while underway without the need for special arrangements in port. As stated, the impact of environmental condition on fuel consumption can be significant, thus it is necessary to isolate the effects of these parameters on fuel consumption. This is most reasonably done by collecting records of fuel consumption in controlled or at least repeatable voyage conditions. The data then has to be either normalized to remove effects of draft, trim, wind and waves, or compared with similar conditions in earlier tests. These approaches to performance monitoring have been in use for many years and there are quite a few vendors and products that endeavour to perform this function (see **Module 5**).

Nevertheless, it remains difficult to use these methods to reliably discern the small gains or losses in efficiency due to light fouling that are now often the threshold for cleaning decisions. With these methods it is also not possible to separate the propeller condition from the hull condition. In summary, the use of performance monitoring tools is generally recommended along with accurate fuel consumption measurement techniques, but these should not be relied on exclusively to indicate when hull cleaning and propeller polishing are necessary.

Thus, on a more practical aspect of condition monitoring, regular visual inspections that is supplemented by long-term records of coating types that has been applied, records of past roughness and fouling patterns. These added to performance data can be used to choose the best way to confidently maintain the condition of these critical surfaces. This is an all-inclusive approach to hull and propeller condition monitoring, as none of the above techniques on its own can provide the full answer to this important question.

5.8 References and further reading

The following list provides references for this section and additional publications that may be used for more in-depth study of topics covered in this section:

1. "IMO train the trainer course material", developed by WMU, 2013.
2. ABS 2013 "Ship Energy Efficiency Measures, Status and Guidance", http://ww2.eagle.org/content/dam/eagle/publications/2013/Energy%20Efficiency.pdf, accessed August 2015.
3. International Paint 2004, "Hull Roughness Penalty Calculator", publication 2004, http://www.international-marine.com/literature/hrpc_folder_paper.pdf
4. Munk, T and Kane D, "Technical Fuel Conservation Policy and Hull And Propeller Performance", Royal Institute of Naval Architects Design and Operation of Tankers Conference, June 2011.
5. International Paint "Coatings Technology: What Is Fouling?", http://www.international-marine.com/PaintGuides/WhatIsFouling.pdf accessed August 2015.
6. MEPC.207(62) resolution on "Guidelines for the Control and Management of Ships' Biofouling to Minimize the Transfer of Invasive Aquatic Species", 2011.

6 Engines and Machinery Load and Utilisation Management

6.1 Introduction

Ship operation involves a variety of activities and tasks. Some aspects are listed below:

- 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
- Etc.

The nature of the above operations will vary from one ship type to the other. Also, they may vary with area of operations and ports of calls. To improve fuel consumption, the requirements of various operations need to be carefully examined and ship machinery/resources are then used accordingly. Planning of the above require good coordination between deck and engine departments.

In this section, examples of ship-board planning activities are examined with main reference to engine load management, electrical load reduction and minimisation of use of auxiliary boilers. These activities are advocated under "system planning" as improvements require significant level of ship-board systems-use planning, good communication between staff and in particular between deck and engine departments as stated above.

6.2 Engine load management

6.2.1 Rational

It is well know that the efficiency of a diesel engine is a function of its load level or its load factor[10]. **Figure 6.1** shows the engine Specific Fuel Consumption (SFC) as a function of the load factor.

[10] **Load factor:** The engine load factor is defined as the actual power output of the engine relative to its Maximum Continuous Rating (MCR). The Load factor is normally specified in percent. *An engine working at 50% of its maximum load has a load factor equal to 50%.*

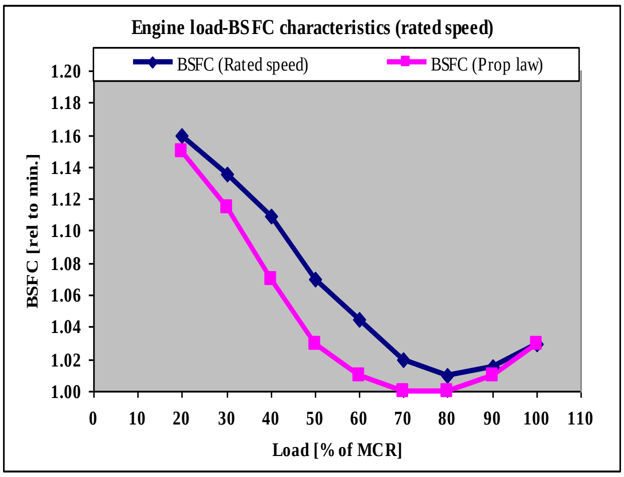


Figure 6.1 - Engine SFC as a function of load factor

In **Figure 5.1**, the curve for constant engine speed operation (rated speed) represents operation of electric generation engines (such as auxiliary engines, e.g. diesel generators) and the curve for propeller law shows the main engine operation characteristics. As can be seen there is no significant difference and for both types of application, the engine's SFC varies with the engine load. SFC is a minimum (i.e. efficiency is a maximum) for a certain load level; typically for engines it is in the range of 70 to 90% of an engine's Maximum Continuous Rating (MCR).

The above diagram also shows that under low load conditions, the SFC of the engine will increase (engine efficiency will reduce). Although the load on the main engine is primarily dictated by ship speed, the load on the auxiliary engines depends on the ship-board electrical loads that are a function of the number of machines, machinery and equipment being used at each point in time plus the number of engines used to satisfy the requirements.

In this Section, it is argued that engine loads should be managed, where possible, so that the engine fuel consumption is minimised. This will effectively mean operating the engines at 70 to 90% load range as discusses above with reference to **Figure 6.1**.

6.2.2 Load management for main engine

For the main engines in a direct-drive or gear-drive configurations (mechanically linked to propeller), there is not much that can be done as far as load management is concerned as normally ships have one main engine and load management normally applies to cases with more than one engine.

It should be noted that it is easy to show that the slow steaming leads to the main engine's operation at low loads at a less efficient load factor (see **Module 3, Section 2** on slow steaming). Overall, this low-efficiency operation of main engine has been accepted by industry since the impact of reductions in ship resistances on a ship's fuel consumption is much more effective than increases in the main engine's SFC for slow steaming cases. Therefore in main engines, non-optimal operation may be allowed due to slow steaming because of slow steaming greater benefits. However, in such conditions and if slow steaming is going to continue for long term, changes to engines performance characteristics are recommended via changes to turbochargers, injection system and other engine settings (engine adjustments for slow steaming optimised operation).

No matter what load the main engine is operating under, it is mostly recommended that the main engine load should be kept at a reasonably steady level under normal operation. This is achieved by keeping the engine speed (RPM) constant. Frequent changes to the shaft rpm, thus engine load, are not efficient and must be avoided

6.2.3 Load management for auxiliary engines

There is ample evidence that shows that load management for auxiliary engines is an effective way of reducing the engines' fuel consumption as well as their maintenance costs. Each ship normally has three or more auxiliary engines; each connected to one electric generator. The engine and generator as a combined system are normally referred to as diesel-generator (DG).

On-board ships, and often in order to assure against black out, two DGs are operated for long periods at less than 50% load factor. The periods for which these conditions are sustained can include all discharge ports, standby periods, tank cleaning periods, movement in restricted waters and ballast exchange periods.

This often leads to unnecessary simultaneous usage of multiple engines; at low load factors and beyond requirements. As a result, low load factor leads to poor energy efficiency performance. Additionally, the operation of diesel engines at low loads causes poor piston ring seal, sub-optimum turbocharger performance, low specific fuel consumption, elevated thermal stresses and increased specific lube oil consumption. In short, it leads to more maintenance and higher fuel consumption.

6.2.4 Method of analysis

In order to evaluate the prevailing practices on use of auxiliary engines, the following areas need to be investigated:

- The load factor of various ship's DGs needs to be established via collection and analysis of data. As the DGs' power output is normally measured and presented in the Engine Control Room, this measurement is quite straightforward.
- Alternatively, the engines utilisation factors[11] can be estimated. This can easily be estimated from the records of engine run hours that are available on a monthly basis. From utilisation factors for all the engines, it can then be established the time periods that one DG (1-DG), two DGs (2-DGs) or more DGs have been simultaneously operated.
- The next step is to evaluate if the utilisation of engines are excessive. This will require the evaluation of ship operation profile versus number of DGs that is actually required for operational or safety purposes. Benchmarks will need to be developed for this purpose.
- Final phase is to identify methods by which the run hours of the engines could be reduced; thus save fuel.

As an example of such analysis, **Figure 6.2** shows the periods for running 1-DG and 2-DG for a tanker. For this specific tanker, an analysis of the operational profile indicated that the period for 2-DG operation is excessive and it may be reduced from 48% of the total time to a lower number. This will result in improved energy efficiency and maintenance (see case study for an estimation of the benefits at the end of this section).

[11] Utilisation factor refers to % of time that a machinery is operated (relative to total time).

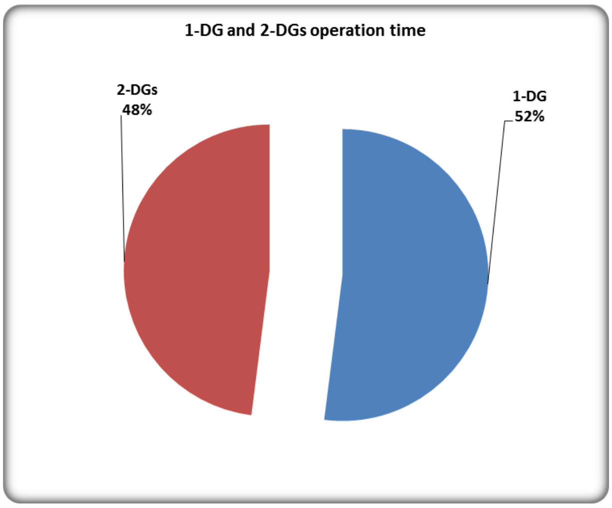


Figure 6.2 - Periods for 1-DG and 2-DG operation

6.2.5 Method of improvements

There are two ways of improving engine load factors and reducing the engine utilisation factors:

- Avoid use of multi-engine parallel operation when not needed. To achieve this, careful planning of ship-board activities that require electric power and its implementation is need. Also, there is a need to keep number of operating engine to a minimum as per requirements and avoid deliberate operation of multi engines when not need.

- As discussed in the following section, it is important that the demand side is also managed via better system planning for load reduction. Reduction of loads in this way helps to provide a better load management on DGs and avoids the running of two engines at low loads. As part of this, proper management of a ship's electrical demand including load reduction and load scheduling, could be used for reducing the number of DGs in use and also for optimising the DGs' performance via a better load level.

6.3 Electrical load reduction

It is often possible to reduce energy consumption on board by working towards more conscious and optimal operation of ship machinery and systems. These could be achieved more effectively if planned for each mode of operation. Examples of measures that can be considered include:

- Avoidance of unnecessary energy use via switching off the machinery when not needed. All non-essential and not-required machinery and equipment that do not affecting the ship and personnel safety should be stopped whilst in port and at sea to reduce the load on diesel generators. Such items should be identified first and then procedures for the execution of tasks to be developed and implemented.
- Avoidance of parallel operation of electrical generators; when one is sufficient for the purpose. This aspect is covered and fully discussed under "engine load management".
- Optimized HVAC (Heating, Ventilation and Air Conditioning) operation on board. The HVAC system operation should be aligned to outside weather conditions either via automatic settings or manual operations (more important for cruise ships).
- A proper coordination should be maintained on board between deck and engine departments especially for use of machinery/equipment items such as steering gear motors,

bilge and fire pumps, winches and mooring equipment, deck cranes and service and deck compressed air usage, etc. so that to reduce loads on generators.

The above activities will lead to reduced electrical power demand. Moreover jobs could be co-ordinated and bundled together so that two generators could be run more effectively and for a shorter period of time. This could be achieved via system planning and more coordinated actions.

6.4 Auxiliary machinery use reduction via system planning

There is a significant number of redundant machinery on board ships; this allows ship operation when one fails as well as for safety-critical situations where two machinery needs to simultaneously operate. In practice, redundant machinery is normally used more than necessary. This could include any type of machinery in particular fans and pumps. Any reduction in use of such machinery can lead to energy efficiency.

Proper planning of the use of number of machinery versus operation mode is an effective way of achieving this objective. Use of simultaneous use of multi machinery in parallel could be reduced via advanced planning and decision making on the number of machines to be used; taking into account the actual operational requirements. For example, when ship is in port, the plan should include switching off one or two engine room ventilation fans as main engine is not operating any more. Another example is the mooring equipment. When mooring equipment is not needed, the related pumps and machinery could be switched off.

To ensure safe operation, all these need to be proactively planned and executed. Without daily planning and establishment of relevant processes, the task of reduction in energy use cannot be accomplished. As emphasized before, coordination between deck and engine departments are of paramount importance for an effective and at the same time safe action to avoid mis-understanding or unexpected consequences.

6.5 Auxiliary fluid machinery

This refers to pumps, fans, compressors, etc that are extensively used on-board ships. There are a number of opportunities to save energy with these machineries that are briefly discussed. The main areas of evaluation include:

Sizing: The sizing of machinery against the actual operation requirements needs to be checked in order to identify cases of over sizing. This can be carried out by monitoring of the machinery operational performance against manufacturer's specification. In addition, the following may be indicative of oversized machinery:

- Continuous throttling of flow in order to match supply with demand (e.g. permanently fixed valve or damper positions).
- Short periods of operation when the machinery is used in on-off mode. For example, in a compressed air system, an oversize compressor will supply air to tank in a shorter period of time than a rightly sized compressor.

For each machinery, a "capacity factor" can be defined that is indicative of over-sizing or under-sizing. Capacity factor may be defined as the "operational capacity" divided by "design nominal capacity". A capacity factor significantly below or above unity is indicative of poor sizing or system's operational anomalies.

Operation profile: The operation profile of machinery represents the machinery's load versus time. Continuously operated machinery at a certain load will represent a steady operation profile.

Machinery with highly variable load will represent a non-steady load profile. Load and operation profiles are normally presented in histogram format, an example of which is shown in **Figure 6.3**.

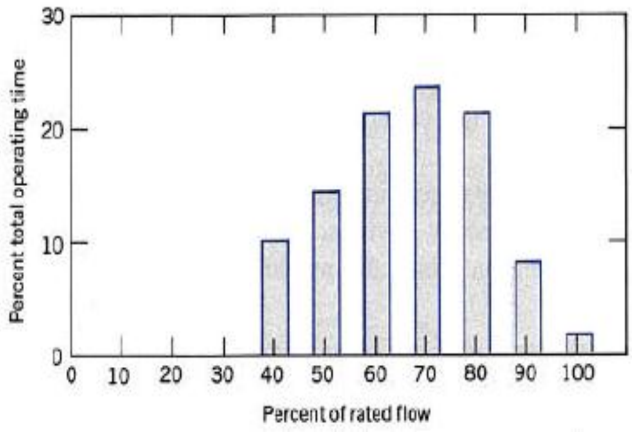


Figure 6.3 – Load profile for a typical pump

From operation profile, operation management strategy of the machinery could be decided. In particular, method of control and choice of on-off or Variable Speed Drive (VSD) modes can be established. For variation of flow, two methods of flow control could be used (see **Figure 6.4**):

- Valve system modulation (changes to valve open area) is the traditional way of flow control. This method of control is energy inefficient.
- Variable Speed Drive (VSD) is used to control flow without throttling. This is the most efficient way of flow control for fluid rotating machinery (see **Figure 6.5**).

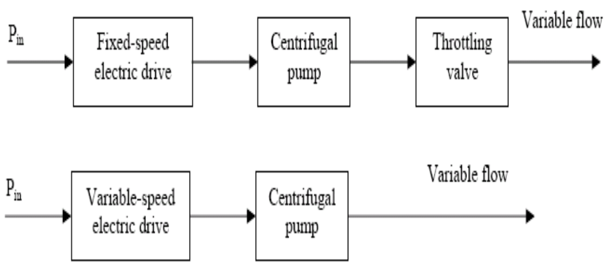


Figure 6.4 – Main types of flow control

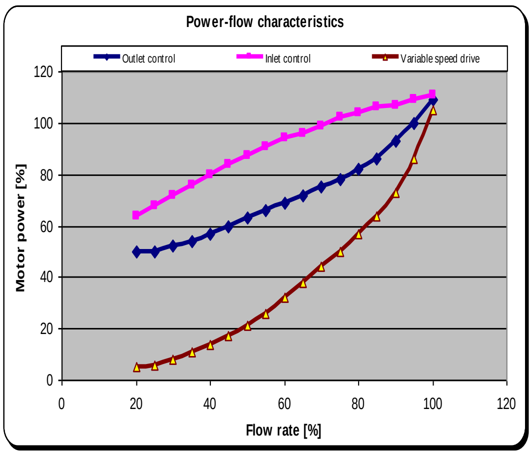


Figure 6.5 – Impact of Variable Speed Drive method of flow control on power demand

The load profile for a multi-machinery setup could provide valuable information on method of load sharing strategy and management between machinery.

Operational aspects

Based on the above evaluation and basic characteristics of fluid machinery, the main opportunities for energy saving are:

Fouling reduction: Fouling in fluid machinery is a common cause of performance deterioration. Fouling can be controlled via best-practice maintenance activities. For examples, fans are very sensitive to inlet fouling.

Mulit-machinery management: In general in a multi-machinery configuration (e.g. chiller plant compressors), the minimum number of machinery running for a particular duty represents the best machinery management strategy and ensures minimum overall machinery energy consumption.

Reducing idling mode of operation: In addition to operation of the machinery at optimal efficiency, it is prudent to reduce the none-productive operating hours of all machinery especially during port stays and also change over from on to off modes and vice a versa. In general the following policies should be implemented:

- Each machinery should be operated at its optimum efficiency.
- The none-productive hours of operation must be minimised by on-off controls. In particular, late turn-off and early turn-on of machinery should be avoided.

Flow control and management: As discussed earlier, control of flow is an area where significant savings may be made:

- <u>Throttle flow control:</u> A pump with variable flow requirements that is controlled by throttling could save energy by:
  - Replace the constant speed drive to variable speed drive (level of saving depends on the pump duty cycle).
  - Replace throttle control with on-off control, if feasible (switch on and off according to demand), especially if some storage capacity can be added to the system.
- <u>Excessive flow:</u> For example, pump flow rates in excess of system requirements, lead to increased energy losses. To avoid:
  - Ensure that pump flow is controlled according to process requirements.
  - Review and adjust control settings.
- <u>Demand control and demand reduction:</u> The need for flow should be investigated at the demand side. Every effort should be made to reduce demand by:
  - Preventing all leakages.
  - Conservation policies in compressed air, water, conditioned air, etc. lead to reduced energy consumption by corresponding systems.

6.6 Electric Motors

Electric motors provide the drive system for the majority of ship auxiliary and hotel systems. In electric propulsion, electric motors are used for driving the propellers. There are a number of ship auxiliary systems that support the operation of main power plant or required hotel services. Some of these are:

- Engine cooling system.
- Engine fuel system.
- Engines lub oil system.
- Compressed air system.
- Chiller plant for hotel HVAC system.
- Chiller plant for provision area.
- Steam system for hotel services and fresh water generation.
- Fresh water generation systems.

The main components of all the above systems are a number of rotating machinery, all driven by electric motors. Electric motors, excluding propulsion motors, consume the majority of the ship auxiliary electrical loads. Their efficient operation, therefore, is an important element of the overall ship energy management.

Basic characteristic

Electric motors used in ships are invariably of AC (alternative current) type. The typical characteristics of the electric motors are shown in **Figure 6.6**.

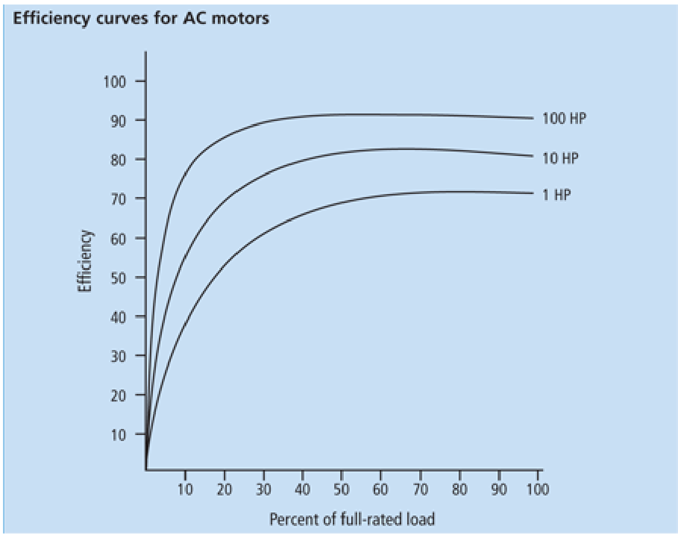


Figure 6.6 – Typical characteristic of electric motors [6]

According to **Figure 6.6** and other relevant information on electric motors, the followings are applicable:

- Electric motor efficiency is highest at its rated power. However, the efficiency does not reduce significantly up to about 40%. Below 40% of rated power, efficiency reduces significantly. This threshold of 40% is lower for larger motors.
- Electric motor efficiencies are usually below 80-90% depending on its size, denoting that there are losses associated with such motors. The loss is dissipated in the form of heat.

Main energy efficiency aspects associated with electric motors are as follows:

Sizing: The sizing of electric motors against actual performance needs to be checked in order to identify cases of over sizing. This can be identified via monitoring the performance data against the manufacturer's specification.

Operation profile: The operation profile of machinery is indicative of its load versus time. Continuously operated machinery at nominal load will represent a steady operation profile. Machinery with highly variable load will demonstrate a non-steady load profile.

Power factor: In electric motors, power factor is defined as the ratio of the actual power in kW divided by power directly derived using current and voltage of machinery in kVAR. A low power factor means added electric network losses.

In dealing with ship-board electric motors, the above needs to be analysed to find out about their relative efficiency and if there is a need for changing any motors during technical upgrades in order to improve efficiencies. Technical upgrades should be normally considered within the ships' machinery maintenance programmes.

6.7 References and further reading

The following list provides references for this section and additional publications that may be used for more in-depth study of topics covered in this section:

1. "IMO train the trainer course material", developed by WMU, 2013
2. OCIMF "Example of a Ship Energy Efficiency Management Plan", Submission to IMO, MEPC 62/INF.10, 8 April 2011.
3. ABS 2013 "Ship Energy Efficiency Measures, Status and Guidance", http://ww2.eagle.org/content/dam/eagle/publications/2013/Energy%20Efficiency.pdf, accessed August 2015.
4. MARSIG SEEMP Example, "Ship Energy Efficiency Plan, MARSIG mbH, Revision 0, 2012, http://www.marsig.com/downloads/MARSIG%20-%20SEEMP%20Template.pdf Accessed August 2015.
5. Bazari Z, 2012, "Ship Energy Efficiency – Developments and Lessons Learnt", Lloyd's Register, LRTA publication, November 2012.
6. "How to determine the efficiency of an electric motor using prony brakes", http://electricalengineering-access.blogspot.co.uk/2015/03/how-to-determine-efficiency-of-electric.html, accessed August 2015.

7 Fuel management

7.1 Introduction

Fuel quality has significant impact on engines' and boilers reliability and performance. When ordering a fuel, qualities in terms of grade of fuel, its specification, calorific value and suitability for engines and boilers need to be considered. It is well known that higher density fuels and higher water and sulphur contents all reduced calorific value that represents the energy content of fuel. Also, high sulphur contributes to undesirable air emissions of SOx and high metallic impurities put the engines and boilers at risk.

The limits for fuel quality parameter as set out in International marine fuel standard, ISO 8217, are based on the understanding that the fuel will be treated on-board the vessel to meet specific requirements for particulars of engines and boilers fitted on-board the vessel. On-board treatment systems are therefore vital in ensuring that fuel is purified effectively in order to ensure it complies with the necessary specifications of the relevant combustion system.

This section covers aspects of fuel management which includes bunkering, fuel quality analysis, storage and treatment. It starts at bunkering point and ends at the point where fuel is supplied to various combustion systems including engines, boilers, etc.

7.2 Fuel oil procurement and bunkering

The first major step in fuel management is to ensure that the right quality of fuel is ordered for the vessel. While requesting bunkers for a specific vessel, any limitations of ship's machinery capabilities, limitations on storage, operation profile, trading area for environmental compliance and giving enough time to get analysis before the fuel is put into use, should be considered.

The on-board fuel management starts first with the bunkering operation. During the bunker operation, safe handling and pollution prevention controls measures, correct measurements before, during and after bunker operations, loading in empty tanks (to avoid mixing of incompatible fuels) and collection of representative samples are the most critical issues. Quantity (by weight) of fuel bunkered should be established and recorded along with the on-board storage locations, and tracked to ensure selection of good subsequent heating or purification characteristics.

Quantity calculations aside, taking representative sample(s) of the fuel delivered to the vessel is a regulatory requirements as well as of paramount technical and commercial importance for safety of engines and boilers. Without adherence to correct sampling procedures, which give real insight into the quality of fuel loaded by the vessel, the analysis results provided may be flawed. Analysis of fully representative samples of each bunker batch serves as first line of defence against poor quality fuels. Such an analysis should be performed in order to assure the quality of fuel supplied and to identify potential problems at the earliest opportunity which helps to identify mitigating actions/claims that may arise due to the supply of poor quality fuels.

7.3 Fuel quality and quantity assurance

Bunkers come in a wide variety of quality levels and to meet the international quality standards (ISO 8217) and statutory requirements (mainly sulphur), the marine residual fuels are generally blended by manufacturers or suppliers with different components. Using better quality fuel and /or a higher grade of fuel can lead to an improvement in engine efficiency, safety of combustion systems and / or prevent degradation. On the other hand, to meet the regulatory requirement to reduce the sulphur level in bunker fuel, more and more refinery processes and also blend components are being used which could results in an increase in the levels of highly abrasive particles of Aluminium and Silicon (also called catalytic fines) or fuel's chemical stability over the long term. This has also raised concerns about the ignition and combustion quality of fuels along with the issues related to the stability and compatibility of the fuels.

Thus analysis of the representative sample(s) of the bunkered fuels should be carried out to ensure:

- Appropriate storage, handling and treatment actions are taken beyond bunkering up to consumption.
- The use of fuel in a most safe and efficient way.
- Compliance to environmental legislation.
- Maximise combustion performance.
- Appropriate actions are taken to avoid any adverse effects and mitigating disputes.
- Reduce commercial, technical and operational risks associated with using varying quality fuels.

The same applies to quantity measurement as discussed in **Section 7.5**.

7.4 Fuel storage and transfer

It is important that all precautions to be made to try to avoid co-mingling (i.e. loading on top of each other) of different batches of fuels. Incompatible fuels are the most common problem with the bunker fuel mixing that leads to clogged filters and in the worst case scenarios, complete paralysis of the fuel system lines as shown in **Figure 7.1**. This also helps in case the fuel supplied is of undesired quality then co-mingling makes it difficult to de-bunker the fuel if such situation arises.

Figure 7.1 - Clogged fuel pipes due to very poor quality fuels

If due to bunker planning and/or operational reasons mixing of the fuels is unavoidable then this should be done after performing the compatibility test between the fuels to be mixed that would indicate their stability after mixing. Ideally such a test should be carried out under lab conditions however this test can be carried out on-board the vessel as illustrated in **Figure 7.2**.

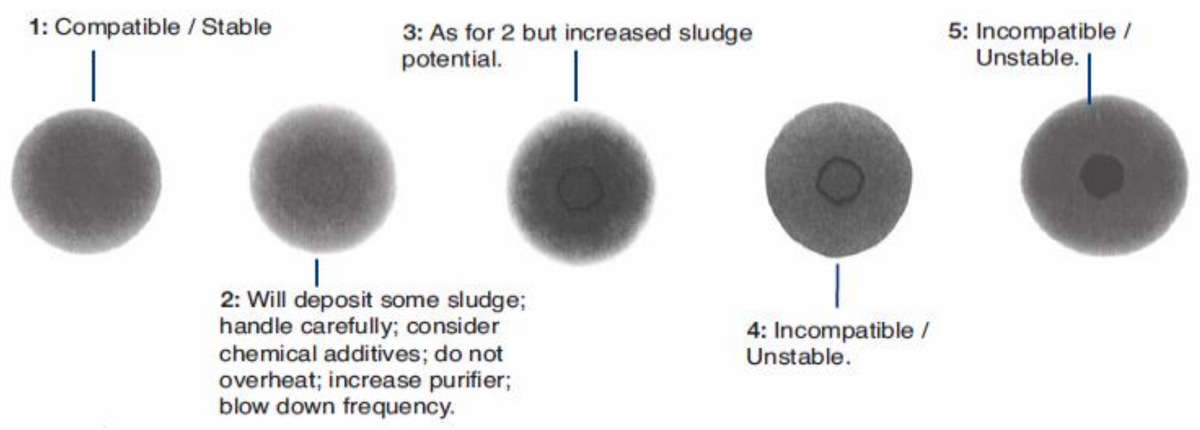


Figure 7.2 – Compatibility test procedure [ExxonMobil]

Fuel should be consumed in a first in, first out fashion. Avoid carrying or use fuels that are over a few months old. The longer a fuel is kept on-board, the chances of sediments in the fuel to drop out and stratification of the fuels increase. This then leads to more potential for filter clogging and other fuel issues and problems. Fuel that cannot be used for any reasons should be de-bunkered off the ship as soon as possible in consultation with vessel's technical superintendent.

7.5 Bunker measurements

Bunker measurement is normally carried out before and after bunkering by the chief engineer or his/her representative to ensure that the actual quantity of lifted bunkers is accurate. The method of measurements includes:

- Manual gauging of all the fuel tanks before and after bunkers: This together with making corrections for the trim/heel of the vessel gives the volume of the fuel in the tanks which is then subtracted from the pre-bunker readings. Using the fuel volume, temperature and the density of the fuel as provided by the fuel supplier and by applying correction factor for the observed temperature, the weight of the fuel is calculated. This calculation is based on the understanding that the density of the fuel given by the supplier is correct and that there is no excess water in the fuel. This weight is adjusted accordingly upon receipt of the analysis of the bunker drip sample if density of the fuel varies considerably from the reported values or the amount of water in the fuel is excessive.
- Use of the mass flow meters: Based on the performance of the available technologies, Coriolis mass flow meters are advocated to be a good choice for mass flow metering of the fuel during bunkering because of the direct mass measurement by this device. Manufacturers claim that such measurements are not affected by fuel temperature, pressure, and composition. Meter size and location of the meter plays an important role therefore proper installation and operation practices are critical for these meters.

Of the above methods, the use of Coriolis flow meters are still being investigated and tested in the field to ensure optimal performance and benefit these types of flow meters. Currently, option 1 above that involves fuel inventory check is the common practice in industry.

7.6 Fuel consumption measurement and reporting

Fuel consumption of main engines, auxiliary engines and boilers is normally measured and recorded on a daily basis. These are recorded in the engine logbook and reported to the company through noon reports and voyage reports. Method of daily fuel consumption measurement is done as follows:

- By the use of mass flow meters fitted for main engines, auxiliary engines and for the boilers.
- By manual gauging of the tanks and measuring the amount of fuels transferred to the specific machinery type.

Accuracy of fuel flow meters is of great importance. For energy efficiency monitoring, the vessel should be able to accurately measure the amount of fuel consumed on-board by the main consumers. This includes a thorough understanding of the fuel system and the placement of accurate fuel flow meters on the system, which must have a reasonable accuracy. Furthermore, the fuel oil temperature at the flow meters should be measured and related correction made from normally measured volumetric flow rate to mass flow rate. It is best if the accuracy of the fuel flow meters is regularly verified.

7.7 Fuel oil treatment – Settling and purification

7.7.1 Settling tank(s)

The role of settling tank is to separate heavy residues and water from the fuel through the natural settling process. In this way, these items are expected to settle gradually at the bottom of the settling tank. To provide best performance:

- Settling tank temperature should normally be maintained between 60-70C for HFO to reduce the density and viscosity of the fuel to facilitate gravitational separation.
- Transfer of fuel to the settling tank to be controlled automatically to top up in small quantities at frequent intervals. This is to help minimise the temperature drop and quantity of dirty/unsettled fuel in the tank immediately after the transfer.
- It is important to drain off water and sludge at the settling tank bottom drains at regular intervals. Frequent / low volume – "flash blowing" is the most effective way of removing settled contaminants.
- Some settling tanks are fitted with high and low outlets. In normal service conditions, it is always preferable to use the lower outlet to minimise the space available for sludge accumulation and give early warning of contamination issues. The high outlet should only be used when there are major issues such as when the tank is subject to a significant water contamination.

7.7.2 Fuel purification

Purifiers are almost invariably used in ships. The main task of purifiers is to separate water and other impurities from fuel. The purification process is based on centrifugal motion principle and the fact that materials with different densities will be subject to different centrifugal forces and thereby will separate from each other. **Figure 7.3** shows the typical arrangement of fuel oil purifiers on board ships.

Figure 7.3 – Typical purifier systems on-board

The efficiency of a centrifugal separator is affected by several factors such as composition of the fuel (nature, quantity and size of undesired components), unstable process fluid dynamics (homogenisation of the fuel before the separators, turbulence within the fuel, poor temperature stability of the process fluid), cleanliness of the separator (the gap between individual discs in the disc stack, fouling of the clean fuel centripetal pump, fouling of the control water system or sliding bowl parts) and general operation (separator throughput, incorrect discharge interval).

For good purifier performance, the following operating controls should be observed:

- Operate purifiers / clarifiers in an optimum manner with purification level dependent on contaminant levels.
- Where applicable, ensure correct gravity disc fitted to purifiers. Manual de-sludge cycle time should be set with regard to fuel contaminant levels.
- In order to optimise the volume available within the bowl the interface line should be as close to the edge of the separating disc as possible.

Sludge (oil residue) is considered to be the residual waste oil products generated during the normal operation of a ship, such as those resulting from the purification of fuel or lubricating oil for main or auxiliary machinery, separated waste from oil filtering equipment, waste oil collected in drip trays and waste hydraulic and lubricating oils.

Excessive sludge from the fuel oil system such as purifiers is a parameter that reduces the fuel efficiency of the ship via increased fuel waste. As a result, the monitoring of the fleet's sludge production in relation to the fuel consumption, with the aim of promptly identifying cases where corrective actions are needed is quite important. Some ships will benefit from use of fuel homogenisers to reduce sludge (see **Section 8**)

7.8 Fuel viscosity control

For use of fuels in engines it is very important to ensure that the fuel is heated to the correct temperature to maintain the required injection viscosity at the engine inlet. Incorrect injection viscosity results in poor atomisation which affects the efficiency by which the fuel is burnt.

Figure 7.4 shows the fuel oil steam heater for control of fuel oil temperature. The arrangement of viscosity controller and fuel filters are shown in **Figure 7.5**.

Figure 7.4 – Typical fuel oil heaters

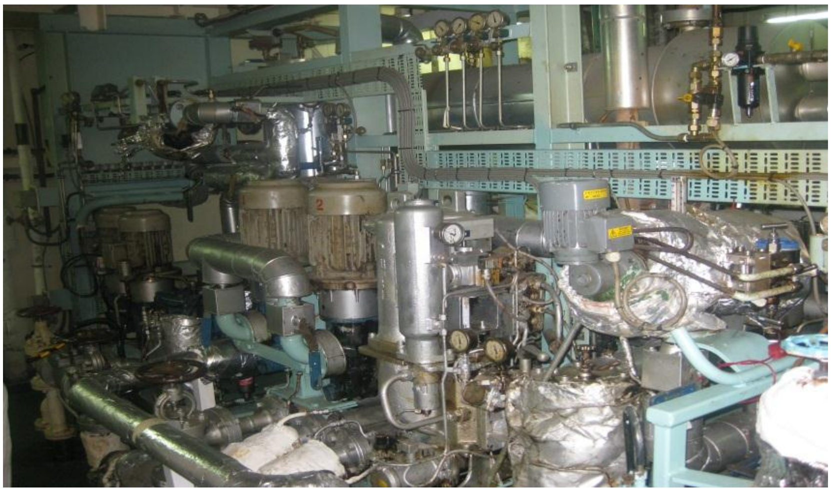


Figure 7.5 – Viscosity controller and fine filter units

It is best to put the viscosity controller on auto viscosity control mode than on the fixed temperature control mode. The correct function of the viscosity controller should be ascertained specifically when changing over from high viscosity fuels to low viscosity fuels and vice versa.

Due to the complex nature of marine residual fuels, it is difficult to predict the ignition and combustion performance of two fuels even if their standard quality parameters are the same. Poor quality fuels may lead to significant damages to the engine (see **Figure 7.6**). In view of this, it is good practice to monitor the engine's cylinder combustion performance through available diagnostic tools on-board, particularly at the start of the use of a new bunker. In case of any issues with the ignition / combustion of the fuels, appropriate actions should be taken to keep the engine parameters within the specified limits. Engines fitted with VIT (Variable Injection Timing) or similar arrangements can be adjusted accordingly to enhance the ignition / combustion efficiency.

View of damaged cylinder liner with piston fitted.

Figure 7.6 – Damage to engine piston and cylinder liner [Gard 2014]

7.9 Fuel oil additives

Fuel additives are chemical compounds formulated to enhance the quality and efficiency of the fuels used. Environmental legislation to reduce emissions and improve fuel economy is having a significant impact on fuel formulations and engine system design. As a result of low sulphur regulations, the composition, long term stability, lubricity, combustion quality, etc. of fuels are evolving due to either de-sulphurisation of heavy fuel oil or blending. Fuel contaminations with bio-related products mixed with fuels adds a new dimension to fuel's long term stability.

Typical types of additives are metal deactivators, corrosion inhibitors, oxygenates and antioxidants. Fuel additive suppliers advocate them as delivering flexible and advanced solutions to the ever-changing fuel market environment and fuel quality issues. Over many years, additive products have demonstrated benefits in some specific areas of marine applications.

The fuel additive technology could provide benefits for marine fuels mainly in areas of enhancing the fuel combustion and preventing the formation of particulates (combustion enhancing additives). Same additives also help prevent fouling of exhaust systems and economisers as well as provide a cleaner combustion system altogether. Therefore, it may be stated that additives have proven records with regard to:

- Improvement of fuel combustion and reduction of particulate matter and visible smoke.
- Overcoming soot build-up in the exhaust system, thus ensuring the efficiency of exhaust system including economiser via keeping them clean, foul free with a reduction in risk of fire.
- Reduction and inhibition of deposit build-up on piston rings, injector nozzles and valves.
- Reduction and prevention of cylinder liner lacquering build-up.
- Protection against fuel pump and injector needle seizures commonly associated with ultra-low sulphur fuels.
- Extension of engine maintenance intervals and less engine downtime; saving both time and money.

The impact of fuel additives on engine fuel efficiency has not been proven despite some significant claims made by some suppliers. However and in view of the better combustion efficiency and cleaner engine and exhaust system, some improvement in engine thermal efficiency is expected; but not significant.

Various fuel oil additives are available on the market. Use of additives, being chemicals, should take place with care and after full testing and consultation with engine manufacturers. Also, right dosage at well-defined periods should be observed. Also, treatment of fuel oil should be carried out in accordance with manufacturer's advice so as to ensure optimum performance from the combustion of fuel.

7.10 Energy efficiency measures

There is a number of energy efficiency measures directly related to fuel management aspect. These measures include:

- Vessels should carry the most economical amount of bunker in inventory. Carrying too much bunker fuel is not energy efficient as they have weight and any transport of extra weight will cause extra fuel consumption.
- Energy is also used for temperature control of fuel and its transfer. To ensure energy efficient storage and transfer, fuel temperature in storage tanks needs to be controlled to lowest temperature feasible in order to retain it in a fluid condition and also suitable for transfer. In the latter case it is only the fuel to be transferred which is to be heated. Steam heating and trace heating should only be applied as required and not be left running unnecessarily.
- Ensure tank fittings (manhole covers, vent pipes, etc.) do not allow water, cargo or other material to get into the fuel. Ensure heating coils are tight.
- Ensure that tank wall condition is in good order thus avoiding corrosion or other material being entrained with the fuel which then has to be removed.
- Maintain settling tanks at a temperature which will enable the purifier heaters to achieve the required treatment temperature.
- When a service tank is not in use it is not necessary to maintain usual high temperatures.
- Heater controls should be checked to ensure correct operation. Accumulations on heater elements should be minimised.
- Periodically verify that the viscosity controller is working correctly.
- Monitor fuel oil sludge levels and ensure that sludge levels are not high due to poor maintenance of the purifiers. As advocated, homogenisers can be used to reduce the sludge levels.
- Fuel measurement and metering is the first step for subsequent performance analysis of various engines and boilers. The more accurately fuel consumption is measured and reported, the more will be the chances for identifying inefficiencies and making improvements.

Although all aspects of fuel management have a close association with energy efficiency, most of the ship-board activities are done to safeguard the engines and boilers from damage. Therefore, fuel management for safety of assets marries well with its aspects of energy saving and there is no conflict between the two objectives.

7.11 References and further reading

The following list provides references for this section and additional publications that may be used for more in-depth study of topics covered in this section:

1. "IMO train the trainer course material", developed by WMU, 2013.
2. ExxonMobile Newsletter, "Fuel stability and compatibility - best practise top tips" http://www.exxonmobil.com/MarineLubes-En/learning-and-resources_voyager-newsletter_2015_may.aspx accessed August 2015.
3. Dimitrios V. Giannakouros, "Technical Aspects of Identifying and Managing Bunker Problems", Presentation to the Marine Club (West England), November 2012, http://www.westpandi.com/globalassets/loss-prevention/loss-prevention-seminars/121108-technical-aspects-of-identifying-and-managing-bunker-problems.pdf accessed August 2015.
4. Gard 2014 "Bunkers and Bunkering", A selection of articles previously published by Gard AS, http://www.gard.no/ikbViewer/Content/72669/Bunkers%20and%20bunkering%20January%202014.pdf published, January 2014, accessed August 2015

8 Ship Maintenance and Energy Efficiency

8.1 Requirements, rules & regulations

International Safety Management Code (ISM) specifies the rules and regulations for maintenance management that influence the shipping industry. The ISM Code stipulates that each ship operator is responsible for the safe and pollution free operation of the ship and that the ship's hull, machinery and equipment should be maintained and operated in accordance with applicable rules and regulations.

The part of the ISM Code on "maintenance of the ship and its equipment" describes in general how ships should be maintained, inspected, non-conformities be reported and corrective actions are taken. Accordingly, the ISM Code states that the shipping company should establish procedures to ensure that the ship is maintained in conformity with the provisions of the relevant rules and regulations and with any additional requirements which may be established by the company. Based on ISM Code, it is a requirement that "the company should identify equipment and technical systems that through sudden operational failure might result in hazardous situations".

When implementing a maintenance management system on-board a vessel as part of the shipping company's safety management system, it is imperative to define the critical systems and equipment. Maintenance instructions according to manufacturers or other policies should be issued to ensure the uninterrupted and safe operation of them at all times.

On the same issue of ship safety, the classification societies are a big player within their classification rules. The major classification societies gradually support more advanced routines for non-intrusive inspections such as condition-based maintenance where equipment and machinery systems can receive a specific class certificate of alternative survey arrangement, if maintained according this alternative method. This approach simplifies classification routines for certain specific ship-board equipment and systems and thus leads to more flexible operation and reduced inspection costs.

8.2 Maritime maintenance management

Like any other continuous improvement activity, the senior management has to be committed to provide required resources, competent crew and a well designed and implemented maintenance management system in order to achieve the above objectives on-board.

The fundamental part of the maintenance management system is normally a database that contains a register of all equipment on-board that need to be maintained. This database then populated with maintenance plans, maintenance activities carried out, etc. thus providing not only the requirements and plans for maintenance but also the fully history of maintenance activities performed.

Effective maintenance planning is essential for ship operation due to its complexity and the obligations on shipping organisations to comply with certain regulations and requirements including ISM. Poor maintenance management could reduce the ship's availability, which may in turn, be reflected in the revenue of the company. Another issue that requires attention is the impact of maintenance on ship's fuel consumption that is highlighted in this section. It is argued and shown that good maintenance leads more energy efficient ship operation, thus the requirement for maintenance and energy efficient operation fully overlaps with each other.

8.3 Type of maintenance

Maintenance has different forms and its practice may vary from one company to other depending on their different requirements. The shipping company usually chooses the most appropriate maintenance type for various ship's equipment based on its maintenance policy or strategy.

Figure 8.1 indicates different maintenance types and policy options with an outline description that follows.

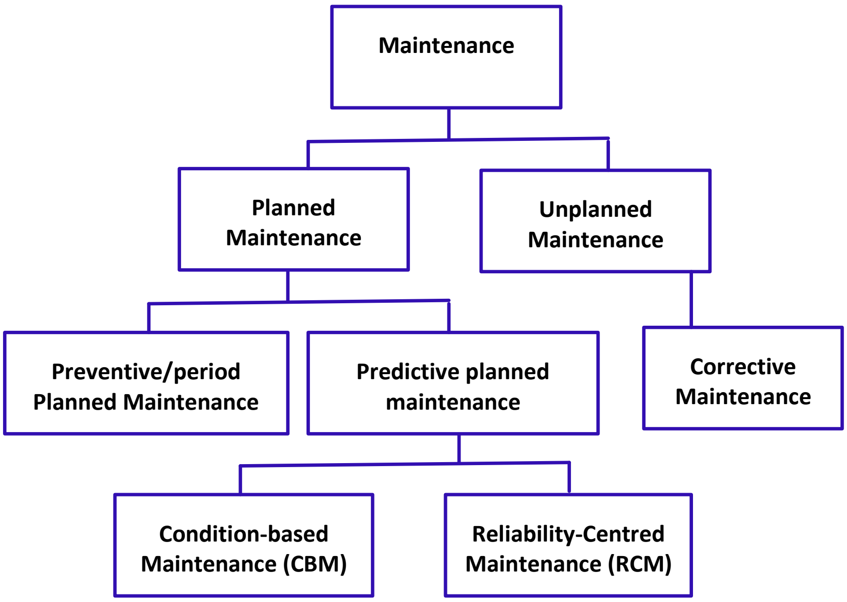


Figure 8.1 – Types of maintenance policy

Unplanned Maintenance: This type of maintenance is basic and simple as it is defined as breakdown maintenance. In this maintenance policy, the repair or replacement is performed only when failure occurs. In this type of maintenance policy, however, basic preventive maintenance routines such as lubrication and machine adjustment are applied to the system at regular intervals.

Planned Maintenance: Maintenance scheduling or planning embraces all activities necessary to plan, control, and record all maintenance activities. Planned maintenance is based on a defined schedule of equipment maintenance. This maintenance policy is normal practice today in the majority of shipping companies. The planned maintenance schedule is decided based on manufacturers' recommendation or use of analytical techniques such as analysis of mean time between failures (MTBF) and reliability analysis. This approach is based on a model of the time that elapses between maintenance periods that takes into account the mechanisms of failures. Therefore, planned maintenance schedule is not necessarily based on fixed-time schedules but could be based on an analysis method that takes into account a number of factors such as reliability characteristics of the equipment.

Preventive Maintenance: This is a subset of planned maintenance **(see Figure 8.1).** Preventive maintenance usually depends on the manufacturer's recommendations and past experience for scheduling repair or replacement time. In this policy, the maintenance is performed on a planned basis within normally fixed scheduled intervals. Preventive maintenance is thus time-driven in that maintenance is performed based on elapsed time or hours of operation. The preventive planned maintenance is still the main strategy for shipboard maintenance. The intervals were based upon the manufacturers' recommendations in addition to past company's or ship-board experience.

Predictive Maintenance: This is a subset of planned maintenance **(see Figure 8.1).** This is generally based on what is referred to as condition-based maintenance (CBM) or reliability-based maintenance (RCM). The maintenance decision is based on the current condition or reliability of the system or equipment. This policy stipulates the monitoring of the machinery and acting upon its condition. Usually, engineers record the system parameters, do condition/performance analysis and use their senses or equipment to hear, sight, and smell the equipment in order to assess the condition of the system. Different techniques are used in condition monitoring, such as visual inspection, performance monitoring, trend monitoring, vibration monitoring, lubricant monitoring, thermograph monitoring, and acoustic monitoring. The advantages of such a policy are that unnecessary maintenance work can be avoided. In this way, the loss of production during scheduled machine downtime can be reduced and components can remain in service if the machine is in good working condition. The industry is gradually moving from preventive maintenance to predictive maintenance.

Reliability Centred Maintenance (RCM): This could be regarded as a subset of predictive maintenance. RCM is a structured way to determine the maintenance requirements of complex systems and assets. It was first developed in the late 1960s, and the approach was derived from the aircraft industry. RCM focuses on the effect of failure with the consequences of a failure being more important than its technical characteristics. The main objective of RCM is to reduce the maintenance costs by focusing on the most important functions of the system and avoiding or removing maintenance actions that are not strictly necessary.

Corrective maintenance: The corrective maintenance may be defined as maintenance which is carried out after failure detection. Corrective maintenance can be subdivided into "immediate corrective maintenance" (in which work starts immediately after a failure) and "deferred corrective maintenance" (in which work is delayed in conformance to a given set of maintenance rules). Corrective maintenance is thus a subset of the unplanned maintenance policy.

The ship maintenance and repair activities can be completed in two different ways.

- They can be undertaken in the ship repair yard when the ship is due for dry docking for regulatory or class surveys. Certain type of maintenance activities are carried out at shipyard when the ship is at berth.
- Maintenance can be conducted during the ship's day-to-day operations of the ship; either while at sea or when in port.

Figure 8.2 shows this way of dividing the maintenance and repair activities.

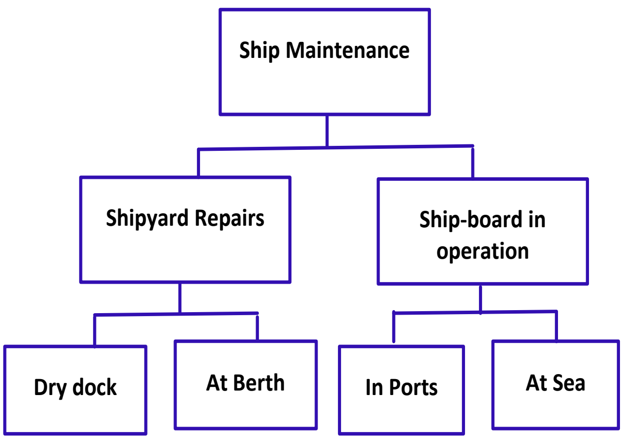


Figure 8.2 – Ship maintenance by location

8.4 Maintenance and energy efficiency

Maintenance operations are fundamental for energy efficient operation of machineries and systems. Deterioration of ship systems' condition takes place due to normal wear and tear, fouling, mis-adjustments, long periods of operation outside design envelopes, etc. As a result, equipment downtime, quality problems, energy losses, safety hazards or environmental pollution may results. The end result is a negative impact on the operating cost, profitability, customer satisfaction and probable environmental impacts if maintenance is not properly done.

The major challenge of maintenance optimization is to implement a maintenance policy which maximizes availability and efficiency of the equipment, controls the rate of equipment deterioration, ensures the safe and environmentally friendly operation and minimizes the total cost of the operation which includes energy cost. Fortunately, most of the machinery maintenance activities are simple adjustments, cleaning, part replacement, or elimination of adverse conditions which means preventive maintenance.

Studies by a variety of industries and companies have shown that a company can cut energy consumption at its facility by about 5% to 10% by focusing on its preventive maintenance effort [Terry Wireman 2011]. As indicated earlier, the main strategic aim of a maintenance programme is to safeguard the safety of ship and its assets and increase the ship's availability for highest operational returns. Luckily, the good maintenance of a ship generally leads to improved performance of the hull, propeller and machinery, thus provides a more energy efficient operation as well.

In this section, various aspects of benefits of good maintenance for energy efficiency are further demonstrated.

Hull and propeller cleaning

The impact of hull or propeller fouling and roughness on ship energy efficiency has been discussed in **Section 5**, demonstrating the significant negative impacts. Thus keeping hull and propeller in clean good condition can lead to major energy saving. The techniques for improving hull and propeller conditions are discussed in **Section 5**.

Engines' adjustments and tuning

Engines are the subject of frequent maintenance actions for a variety of reasons; one of the main reason being the impact of burning low quality fuel and its impact on engines. Engine condition monitoring is normal practice on-board ship and engine adjustments and tuning could lead to energy saving. This topic has further been discussed in **Section 6**.

Mechanical transmission systems

On board ships, a variety of mechanical transmissions systems are used. The most complex and important one is the propulsion shafting and the simpler ones include all the mechanical linkages between drives / motors and the machinery. The energy savings in mechanical transmission systems would be influenced by the type of maintenance performed and adjustments made. For example, the following would influence the energy efficiency of the mechanical transmissions systems depending on the type:

- Shaft and couplings alignment: Any shaft misalignment will not be good for machinery maintenance as well as for transmission energy efficiency. This would lead to extra losses in the system in the form of heat.
- V-belt slippage: Improved tension in belt-driven transmissions would prevent slippage during loading on the belt as well as during high loading. This would reduce frictional losses due to slippage.
- Chain and gear misalignment: In chain-driven systems, any misalignment will lead to loss of energy and at the same time will not be good for upkeep and maintenance of the system.
- Proper bearing lubrication: Over-lubrication and under-lubrication are not good for energy efficiency. If bearings have excessive lubrication, it may need to churn more of the lubricant,

increasing the fluid friction in the lubricant and thus energy losses. The opposite is definitely not desirable as the lack of enough lubrication not only will increase energy use but also will lead more maintenance due to extra wear and tear due to metal to metal contact.

Electrical systems

Similar to mechanical systems, the energy losses in electrical systems can also be influenced by state of maintenance of the system. Typical energy losses occur in poor operating conditions for electric motors. For example, when a motor is fouled with dirt and moisture, this would inhibit the thermal heat transfer process. This condition results in increased resistance of the wiring which further increases the temperature of the motor and subsequently its energy consumption. This could lead also to early failures as compared to a better maintained electric motor. For electric motors, improper or insufficient maintenance on mechanical transmission system (as explained above) will also increase the amount of energy required by the motor to drive the system.

Steam system

Steam generation systems (boilers) have long been recognized as having potential to produce substantial energy savings for most plants. There are a number of EEMs (energy efficiency measures) in this area as covered in **Section 10**. Most of the relevant EEMs are directly influenced by state of the steam system maintenance. Examples of such cases are:

- Steam trap maintenance and inspection programs
- Reduced fouling of boilers with direct improvement in its energy efficiency.
- Adjustment of combustion air in relation to fuel flow in boilers (so called control of excess air). This is part of the performance-related maintenance activities that could yield significant energy saving.
- Leak detection programs for hot water and steam. All leak reductions directly will support the energy efficiency aspects as well.
- Insulation inspection programmes to reduce heat losses from the system due to loss of insulation.
- End-use steam optimisation via improved cleaning of the heat transfer surfaces, etc.

All the above measures can be only achieved by an effective maintenance programme.

Compressed air system

Compressed air systems can experience similar problems as steam system such as air leaks, excessive end-use air consumption and air compressor conditions. Maintenance not only will look at compressed air production (air compressors) but also the compressed air distribution and end-use areas. Aspects to cover include:

- <u>Compressors:</u> Poor maintenance of compressors or incorrect pressure settings would lead to extra running hours and thus more energy use.
- <u>Air leaks:</u> Any air leakage in the system would require the compressors to run more than necessary. This would lead to additional energy use by the need for compressors to operate for longer periods.
- <u>End use devices maintenance:</u> The compressed air is used for end-use devices that may have a poor state of maintained. This will lead to extra need for compressed air generation.

The above examples are part of a longer list where proper maintenance could support energy efficiency. All of the above require planned or condition-based approaches to maintenance of the compressed air system.

8.5 References and further reading

The following list provides references for this section and additional publications that may be used for more in-depth study of topics covered in this section:

1. Darabnia B and Demichela M, 2013 "Maintenance an Opportunity for Energy Saving" Chemical Engineering Transactions, Vol. 32, 2013.
2. Terry Wireman 2011, "Tips on saving energy using preventive maintenance techniques", http://www.pem-mag.com/Features/Tips-on-saving-energy-using-preventive-maintenance-techniques.html#sthash.F31kH9iP.dpuf accessed August 2015
3. Gösta B. Algelin 2010, "Maritime Management Systems - A survey of maritime management systems and utilisation of maintenance strategies", Department of Shipping and Marine Technology, Chalmers University Of Technology, Gothenburg, Sweden, 2010.
4. Yousef Alhouli 2011 "Development of Ship Maintenance Performance Measurement Framework to Assess the Decision Making Process to Optimise in Ship Maintenance Planning" PhD Thesis, School of Mechanical, Aerospace and Civil Engineering, University of Manchester, 2011.
5. "IMO train the trainer course material", developed by WMU, 2013

9 Technical Upgrade and Retrofit

One effective way of improving the energy efficiency of a ship is to upgrade ship-board technologies to more energy efficient ones. Upgrading of technologies is not a ship-board activity but nevertheless, the ship-board staff could always engage in proposing such technologies. For this reason, this topic is covered under this module.

A number of technology upgrades can be considered for energy efficiency. It should be noted that applicability of such technologies will depend on ship type, ship size, operation profile and other factors. Thus the decision making for each technology will need to go through the normal process of technical feasibility aspects and economic cost-effectiveness analysis for the specific ship that is under consideration. The technologies described here only shows a good sample, but the list is not comprehensive as there are other potential technologies that may be included.

9.1 Devices forward of propeller

9.1.1 Mewis Duct

The Mewis Duct[12] and other similar devices are designed for installation forward of the propeller as appendages. They have successfully been adapted for the larger scale commercial vessel. **Figure 9.1** shows such devices.

Figure 9.1 – Mewls Duct **[Becker Marine Systems]**

Since its introduction to the market in 2010, the Mewis Duct has gained acceptance by both ship owners and ship builders. A large number of vessels of the order of few hundreds are currently fitted with this sort of duct. They are mainly used on tankers and high block coefficient ships.

It is claimed that the Mewis Duct produces energy saving through three major impacts:

- Wake field equalisation: The installed duct straightens and accelerates the hull’s wake into the propeller and also produces a net forward thrust.
- Reduction of propeller hub vortex: An improved flow behind the duct significantly reduces the propeller hub vortex with corresponding thrust deduction, leading to improved thrust and better inflow to the rudder.

[12] Developed by Becker Marine System

- Contra-rotating swirl: Due to individually placed fins, a pre-swirl in counter direction could be generated, reducing the rotational flow losses of the propeller.

The way it improves the propeller efficiency is via a better streamlined and directed flow into the propeller thus reduces the propeller losses. The level of energy saving is claimed to be about up to 8%; however this maximum potential may be applicable to certain ship types and designs. The potential saving for each vessel will depend on a number of factors and thus any decision should be made on a ship-specific basis after performing a good deal of ship hydrodynamic analysis and model tests.

9.1.2 Wake-equalizing duct

The wake-equalizing duct consists of one half-ring duct with foil-type sections attached on each side of the after body forward of the propeller (see **Figure 9.2**). The half-ring duct accelerates the flow into the propeller in the upper quadrant on each side and retards the flow in the lower quadrants. This results in a more homogeneous wake field in front of the propeller, while the average wake is almost unaltered. The improved power consumption that is obtained from well-designed wake-equalizing ducts can be attributed to the following:

a. Improved efficiency because of more axial flow and a more homogeneous wake field;
b. Reduced resistance because of reduced flow separation at the after body;
c. Orientation of duct axes so that the inflow to the propeller is given a small pre-rotation;
d. Improved steering, due to straightened flow over the rudder and more lateral area aft.

Similar to Mewis Duct, it is placed to the fore of the propeller with the aim of accelerating water in-flows. This device is ideally suited to vessels with full hull forms (such as tankers) and containers operating at lower speeds (under 19 knots).

Figure 9.2 – Typical wake equalising duct [Scheneekluth]

9.1.3 Pre-swirl stator

These are stators located at the fore of propellers as shown in **Figure 9.3**; acting like guide vanes for the flow into the propeller. The aim of guide vanes is to eliminate or reduce the cross-flow that is often observed in front of the propeller. These vanes are fitted in front of the propeller on both sides of the sternpost. The vanes straighten the flow in the boundary layer in front of the propeller, thereby improving its efficiency. Cross-flow appears mostly in ships with stern bulbs and full hull forms that operate at relatively low speed. The benefit is therefore largest for tankers and bulk carriers. The improvement decreases with decreasing fullness of the hull form.

Thus pre-swirl stators (guide vanes) aim to provide a favourable pre-rotation of the water flow into the propeller. They are alternatives to ducts as explained above.

[Fathom]

DSME system [SPPA]

Figure 9.3 – Pre-swirl stator

As shown in **Figure 9.3**, in general:

- This arrangement enhances propeller efficiency via fitting of the bladed stators on the hull immediately forward of the propeller.
- The stator improves propeller efficiency via better adjusting the flow into propeller as the same happens in in normal pumps with guide vanes.
- A gain of 4% in propulsion power is claimed by proper tuning of stator blade angle.
- Better cavitation performance and supress of cavitation generated pressure pulses on the propeller is the other advantage.

As with the ducts, the device is especially suitable for the larger ships and hull forms. Its first installation on a 320,000 DWT VLCC has resulted in a 4% reduction in fuel consumption with more installations afterwards.

9.2 Devices aft of propeller

The propeller operation involves flow losses that appear at the rear of the propeller in the form of axial flows and rotational flows. The typical levels of such losses are shown in **Figure 9.4**. These flow losses mostly appear in the slipstream at the back of the propeller.

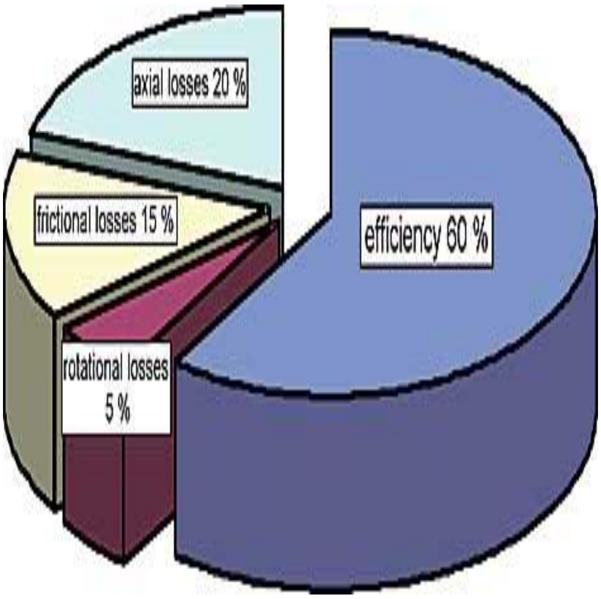
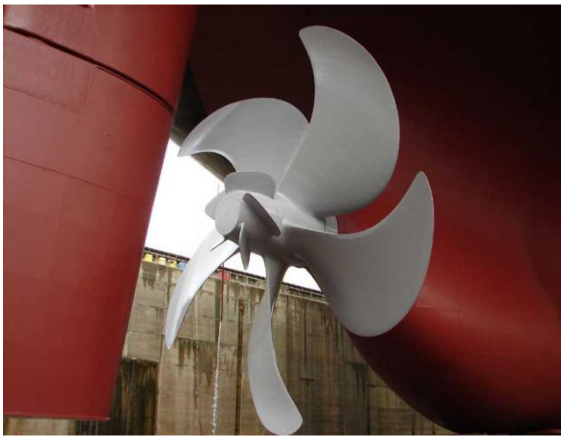


Figure 9.4 – Typical propeller efficiency and losses

There are devices that can be placed at the aft of the propeller to recover some of the lost energy thus increase the overall efficiency of the propeller. These devices are normally cost effective as a retrofit option with a short payback period, provided they can be fit correctly. A number of devices belong to this category. Some of them involve modifications to the rudder. The most important among these devices are described below.

9.2.1 Propeller Boss Cap Fin (PBCF)

One of such devices is the Propeller Boss Cap Fin (PBCF) (see **Figure 9.5**) that can be added to the propeller's rear in place of the normal boss cap. This performs the function of recapturing some of the rotational energy lost by the propeller.



[Fathom]

[MOL Techno-Trade]

Figure 9.5 – PBCF at the back of propeller

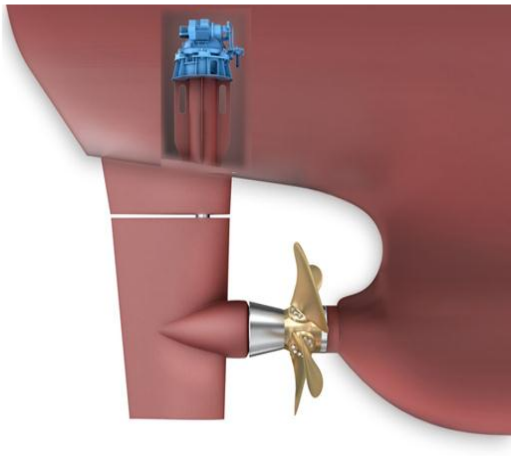
PBCF consists of small fins attached to the propeller cap. It was first developed and manufactured at the end of 1980s and so far has had some few thousands installed on ships worldwide. Therefore, there is significant experience with this device. The PBCF is relatively low-cost and non-complicated additions to a propulsion system. The return on investment of one year or so has been claimed and with installation time of only few days without the need to dry-dock.

The following are to a large extend the agreed benefits of using such a device:

- PBCF eliminates or reduces the hub vortices generated. As a result, PBCF can play an important role in reducing propeller generated noise and vibration.
- It is suitable for slow speed vessel.
- PBCF boost propulsive efficiency by about 5% and ship fuel efficiency by about 2%.
- PBCF can be retrofit easily to an existing ship.

9.2.2 Integrated propeller and rudder units

As the name implies, the propeller and rudder are designed as an integral unit. Part of the design is a bulb behind the propeller that is fitted to match similar configuration on the rudder. There are a few patented designs for such an arrangement (see **Figure 9.6** as main examples). The effect of these units has been reasonably well documented in tests on models and in full-scale trials. A reduction of about of 5% in required power of the vessel for design speed can by typical savings. The units are applicable to general cargo vessels, RoPax vessels and container vessels operating at relatively high speed. As with all other devices that impact ship hydrodynamic and resistances, the choice must be done after significant flow analysis and testing as the claimed savings are not universal. However, the potential for such a savings always exists for certain ship types and sizes.



Promas efficiency rudder [Ship Technology]

[VICUSdt 2015]

Figure 9.6 - Integrate propeller rudder

9.3 Ducted propeller

The ducted propellers, as the name implies, refer to a two-component propulsor consisting of a propeller located inside a nozzle (duct) as shown in **Figure 9.7**.

[Chatterjee 2012]

Kort Nozzle [FathomShipping 2012]

Figure 9.7 - Ducted propeller

Compared to the conventional propeller of the same diameter and thrust, the ducted propeller arrangement allows a larger mass of water to be supplied to the propeller, improving the operating conditions around the propeller, thus its improved efficiency leads to corresponding potential for reduced power and fuel used by the ship propulsion.

Although, the reported benefits claim of the range of 5–20% is generally high, similar to Mewis Duct, it may have significant positive impact on certain ship types and designs. On the negative side, use of additional appendix in the form of a duct will increase the skin frictions thus flow resistances. Additionally, ducted propellers are prone to fouling of the system that may lose some of the advantages. As a result, there may be more need for propeller and duct underwater cleaning. This is regarded as one of their main weaknesses.

Ducted propellers are suited for ships operating at high propeller loadings, such as tankers, bulk carriers, tugs and different offshore supply and service vessels. The advantages of the ducted propellers in addition to fuel efficiency, could also include aspects such as reduction of propeller cavitation, vibrations and noise, better manoeuvrability if used with azimuthing thrusters and more safety for the propeller for example in ice operation or while grounding.

9.4 Fore-body optimisation and bulbous bow

Fore-body optimization includes consideration of the bulb design, waterline entrance and so on. The reason is that when a ship sails, the fore-body generates waves. These waves then hit the front side and increase the ship resistance and thus required power. The faster the ship sails, the more is the wave making resistance and the more energy it needs to overcome the waves.

A properly designed bulbous bow thus reduces wave resistance by producing its own wave system that is out of phase with the bow wave from the hull, creating a cancelling effect and overall reduction in wave making resistance (the concept is shown in **Figure 9.8**). A bulbous bow works best at a certain speed range and is sensitive to ship draft as well. If the ship sails at a different speed and draft ranges than the ones the bulbous bow is designed for, the bulbous bow has no, or in the worst cases even a negative effect.

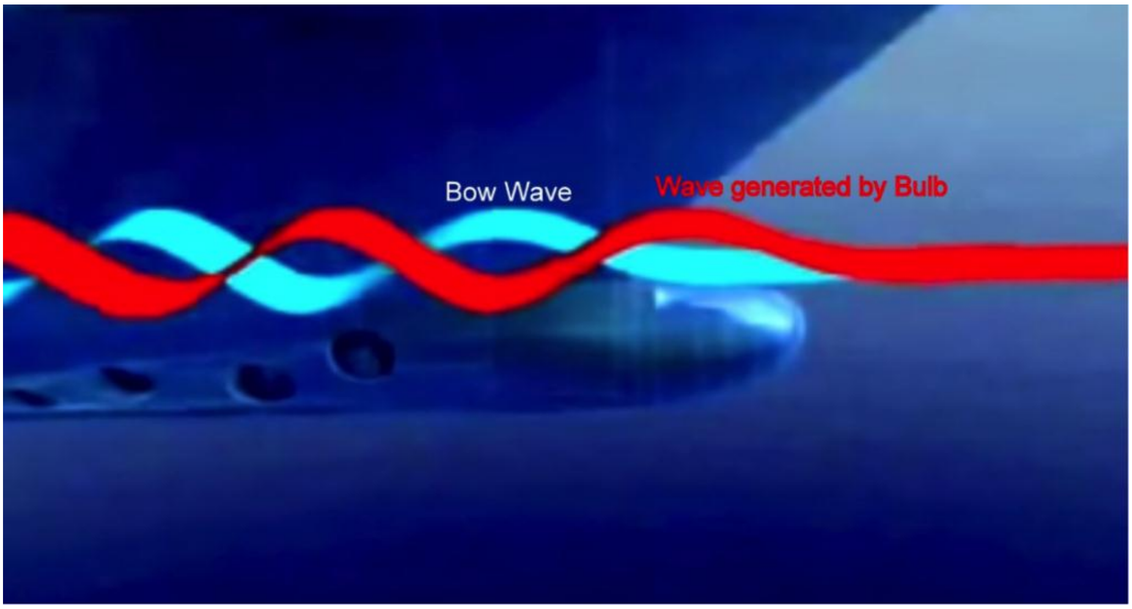


Figure 9.8 – Concept of bow waves and bulb waves that cancel each other [Soumya Chakraborty]

Design of the bulbous bow involves significant level of flow and hydrodynamic analysis. A bulb with a reverse pear shaped section is primarily effective at the design condition; pear-shaped bulbs work best for drafts below the design draft (i.e. ballast draft or partial load draft) and cylindrical shaped bulbs offer a compromise solution [ABS 2013].

A V-shape may be introduced at the base of the bulb to mitigate slamming impact loads. Faster and more slender vessels favour larger volume and forward extension of the bulb (more pronounced bulbs). Fuller ships such as tankers and bulk carriers are often arranged with bulbs having a large section area and V-shaped entrance, such that it behaves as a traditional bulb at loaded draft and acts to extend the waterline length at ballast draft [ABS 2013].

Commercial vessels normally do not operate solely at the design draft, thus, compromises in the bulb design are needed to provide good performance over the expected range of operating drafts and speeds. Depending on operation profile of a ship, retrofitting a new bulbous bow could be quite attractive from energy efficiency point of view. Maersk Lines has reported fuel savings of over 5% by modifying the bulbous bow from the original shipyard design that was optimized to the design draft [Jonathan Wichmann]. This change took place because of the reduction in operating speed of the vessels relative to their design speed for slow steaming. This provided more favourable performance over the anticipated actual operating profile compared to design assumptions.

Retrofit of bulbous bow simply involves the cutting off of the old one and replacing it with the new design. This takes place in shipyard and during dry dock (sees **Figure 9.9**). As mentioned, this has practiced by major liner operators due to the need for changes to ship operation profile.

Figure 9.9 – Bulbous bulb retrofit on Maersk ships [Jonathan Wichmann]

9.5 Waste heat recovery

Waste heat recovery can be carried out to produce hot water, steam or electricity from the hot exhaust gases or hot water from engines cooling system. The main candidate areas of waste heat recovery are from exhaust of the engines where the temperature is high. Also, low grade heat recovery from engine cooling system is possible and need to be considered for specific ship applications.

Exhaust gas economisers are the usual waste heat recovery system currently used on many ships. This is a shipbuilding issue and not subject to retrofit. It has been covered as part of discussion on “steam system” in **Section 10**. Also, more sophisticated exhaust gas steam system with steam turbine is used in larger ships; this is not normally a subject of retrofit but mostly applicable to new buildings. For ships in operation, the scope for extra heat recovery needs to be reviewed, and generally if lower grade heat is needed on-board, then waste heat recovery system could be used.

9.6 Auxiliary machinery and systems

9.6.1 High efficiency electric motors

Electric motors are not 100% energy efficient but generally have energy efficiency that could be anything from 75% to 95%. Thus choice of energy efficient electric motors for a ship will make energy saving over the long term. These days, there are standards for energy rating of electric motor and efforts are made to make these motors more energy efficient. **Figure 9.10** shows an example of rating practiced by Europe.

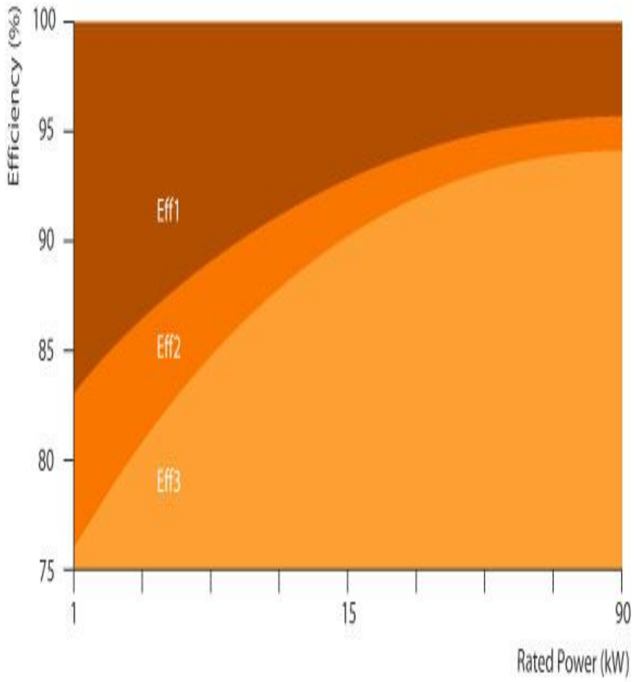


Figure 9.10 – Example of energy efficiency rating of electric motors

In choice of electric motors for ship, the idea of energy efficiency needs to be taken into account early and during the shipbuilding stage. For existing ships, when an electric motor needs to be replaced due to maintenance requirement, procurement of an energy efficient electric motor should be considered.

9.6.2 Fuel oil homogenisers

Fuel sludge may constitute up to 1% of fuel used on board. The sludge disposal is normally done either via burning on board (incinerator) or transfer ashore. The whole process is waste of energy and money. Finding ways of reducing sludge thus could be desirable.

A homogenizer assists the process of fuel homogenizing and thereby a reduction is sludge level. It also helps with the supply of more uniform fuel to combustion systems. The main job of a homogenizer is to create a uniform structure of all solid and non-solid materials present in heavy fuel oil. A homogenizer also breaks down large water elements into small homogenous structure, resulting in an emulsion consisting of water molecules spread evenly throughout the whole fuel.

A homogenizer mainly works by agitating and milling of the fuel. Agitation can be done by using a mechanical arrangement which pumps the liquid through an orifice plate. Such a system is shown in **Figure 9.11**. Agitation can also be done by an acoustic medium which uses ultrasonic frequency to agitate a surface over which the liquid is pumped.

Figure 9.11 – Typical homogeniser

A conventional homogenizer is like a milling machine which churns the liquid as it passes through it. The design consists of fixed stator housing with a rotor which is generally driven by a motor. The mating surface of stator and rotor has specially designed channels. Both rotor and stator are conical in shape and have a specific clearance between them through which the fuel is passed.

Moreover, the design is made in such a way that the liquid accelerates as it moves through the channel, making the dissolved components uniform in nature. It should be noted that although the unit looks like a pump, it doesn't have a pumping unit. A separate pump needs to be installed to pump the fuel through the system.

The operation of a homogeniser has the following advantageous effects:

- Reduction in sludge production (up to 75% has been claimed but a number of 40% is more realistic). This causes an increased amount of burnable fuel, thereby fuel saving and fuel cost. Also, this reduces the cost of disposing of the sludge.
- Influence on purifier efficiency.
- Less wear and tear of engine components.

In case, a homogeniser is used for some water emulsification into fuel, it could positively impact exhaust pollutants as well. Both NOx and smoke reduction can be achieved if the system is used for water-fuel emulsification.

9.6.3 Other technologies

There are other technologies that may be used for upgrade and retrofit that includes:

- Energy saving lamps.
- Card controlled or occupancy sensors lighting system for accommodation.
- Variable speed drives for pumps, fans and compressors.
- HVAC system control upgrade and also pre-cooling of incoming air using outgoing cold air.
- Engine de-rating: This is a significant area and only applies for extreme slow steaming.

9.7 References and further reading

The following list provides references for this section and additional publications that may be used for more in-depth study of topics covered in this section:

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10. Soumya Chakraborty, “What’s The Importance Of Bulbous Bow Of Ships?”, http://www.marineinsight.com/marine/marine-news/headline/why-do-ships-have-bulbous-bow/ accessed August 2015.
11. ABS 2013 “Ship Energy Efficiency Measures, Status and Guidance“, http://ww2.eagle.org/content/dam/eagle/publications/2013/Energy%20Efficiency.pdf, accessed August 2015.

10 Boilers and Steam System

10.1 Introduction

The steam system plays a major role in energy efficiency of certain ship types (such as steam driven LNG ships) and a medium role in ships such as oil tankers carrying liquid cargo that require cargo heating or there is a need for cargo transfer using steam driven pumps but also need to generate Inert Gas for cargo tank cleaning, purging or tank top ups. **Figure 10.1** shows typical level of fuel use in boilers as compared to main and auxiliary engines for a VLCC vessel.

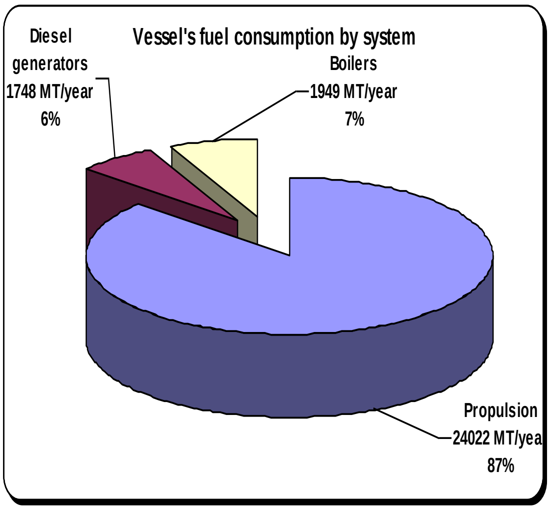

Figure 10.1 – Overall annual fuel consumption and boiler share [Bazari 2012]

Figure 10.2 from IMO 3rd GHG Study 2014 also reveals the level of energy use in marine boilers for the whole of international fleet.

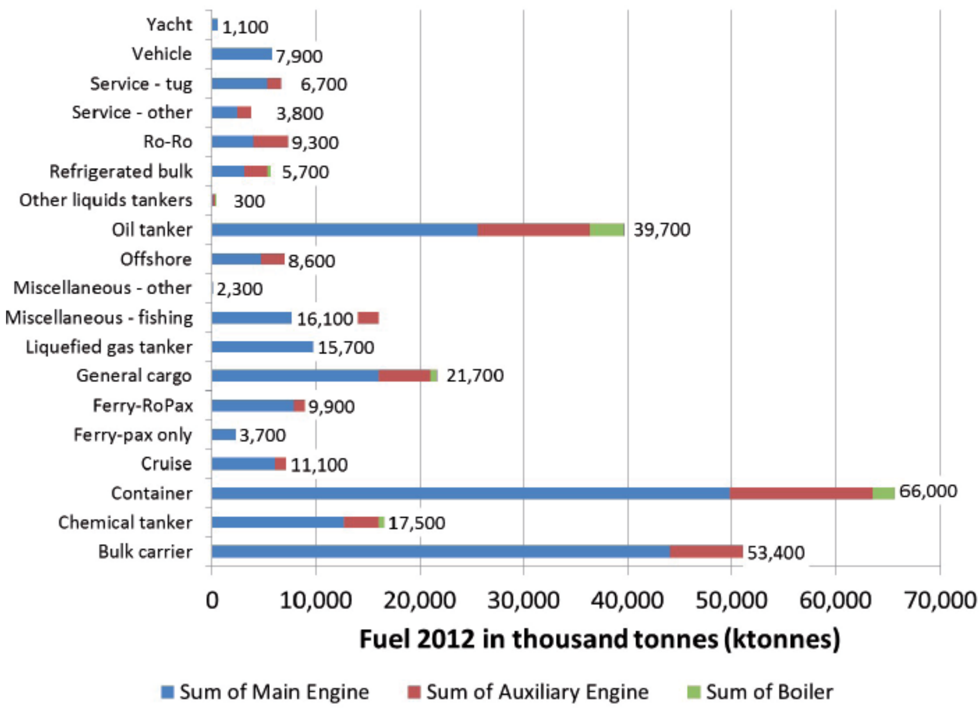

Figure 10.2 - Annual shipping fuel consumption per ship type and combustion system [Third IMO GHG Study 2014]

It can generally be stated that an overall average number of up to a maximum of 6% of shipping fuel consumption could be attributed to the use of boilers. As stated, for steam turbine propulsion ships such as steam LNG ships, more than 80% of energy use is due to boilers.

10.2 Overview of a ship's steam system

In commercial ships, the steam system normally includes the following equipment:

- Auxiliary boilers
- Exhaust gas economisers

As the names imply, the exhaust gas economiser is a waste heat recovery system that recovers heat from exhaust of main or auxiliary engines and thus does not use fuel. The more the second system is used, the less will be a need for use of the auxiliary boilers, thus good maintenance and operating conditions of exhaust gas economiser should always be regarded as part of energy saving in the steam system. **Figure 10.3** shows a typical steam system for a ship.

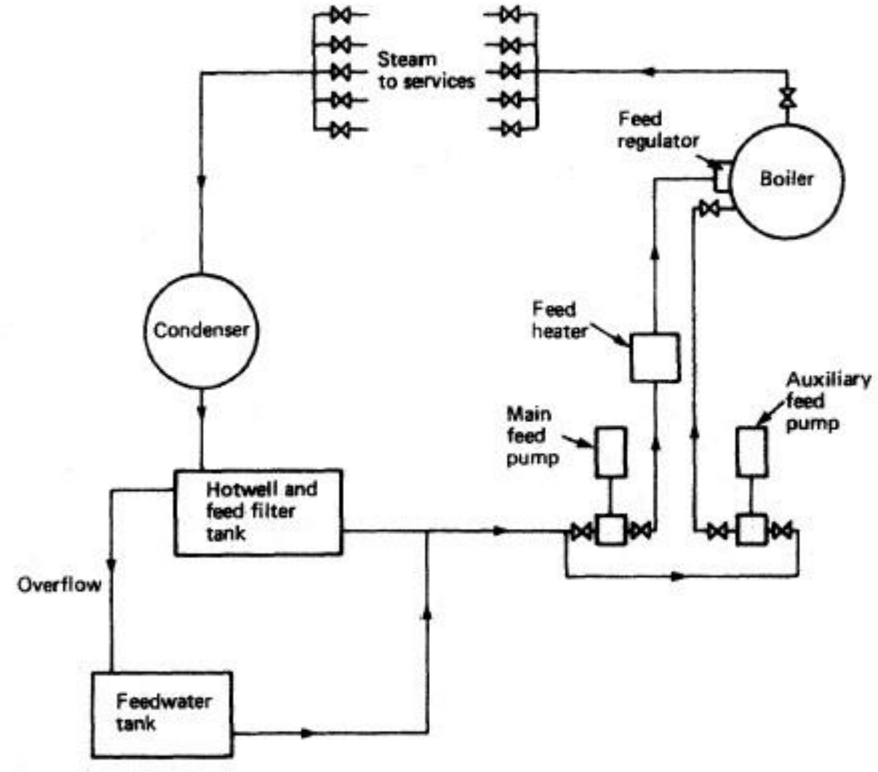

Figure 10.3 – A typical auxiliary boiler steam system configuration [Machinery Spaces.com]

For the sake of presenting the energy efficiency case, the ship-board steam system will be divided into the following parts:

- The auxiliary boilers: This is where the steam is produced using fuel.
- The exhaust gas economiser: This is where the steam is produced via waste heat recovery.
- The steam distribution system: This refers to steam piping system and relevant instruments and devices used for steam controls.

- Steam end-use: This refers to all the steam consuming systems such as steam turbines, fresh water generators, steam heaters, etc.

Figure 10.4 shows a typical arrangement for such components.

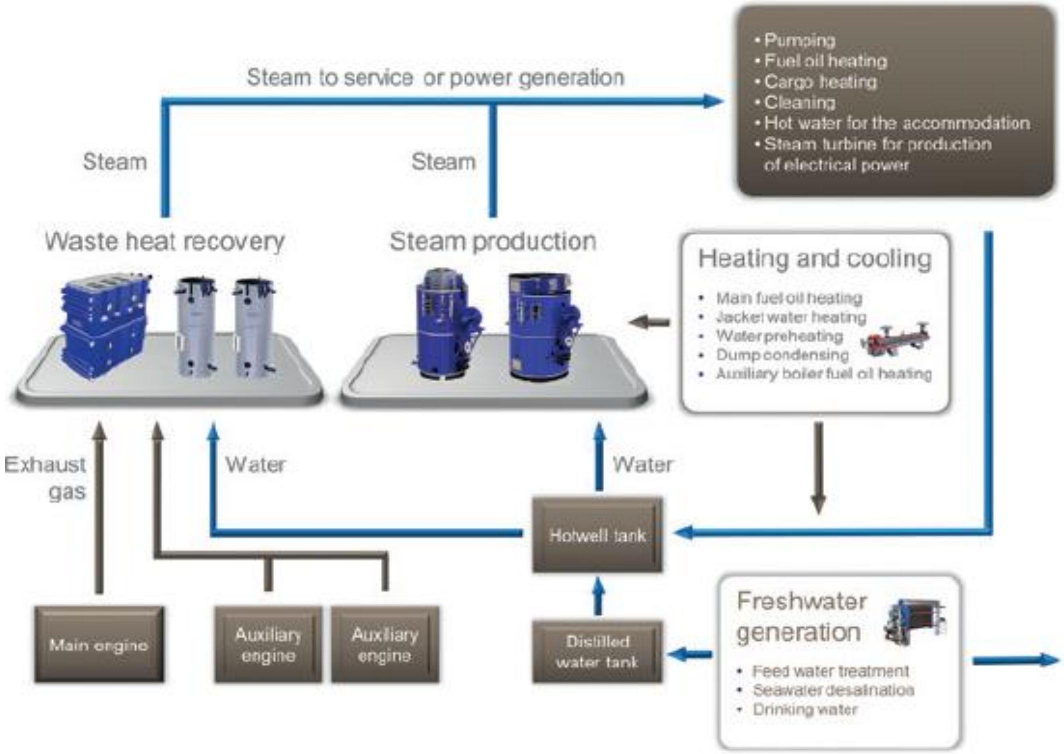

Figure 10.4 – Overall ship-board steam system [Alfa Laval]

10.3 Boiler energy efficiency measures

Figure 10.5 shows typical energy efficiency characteristics of a boiler that is normally specified by boiler manufacturer. As can be seen, the boiler efficiency is a factor of its load.

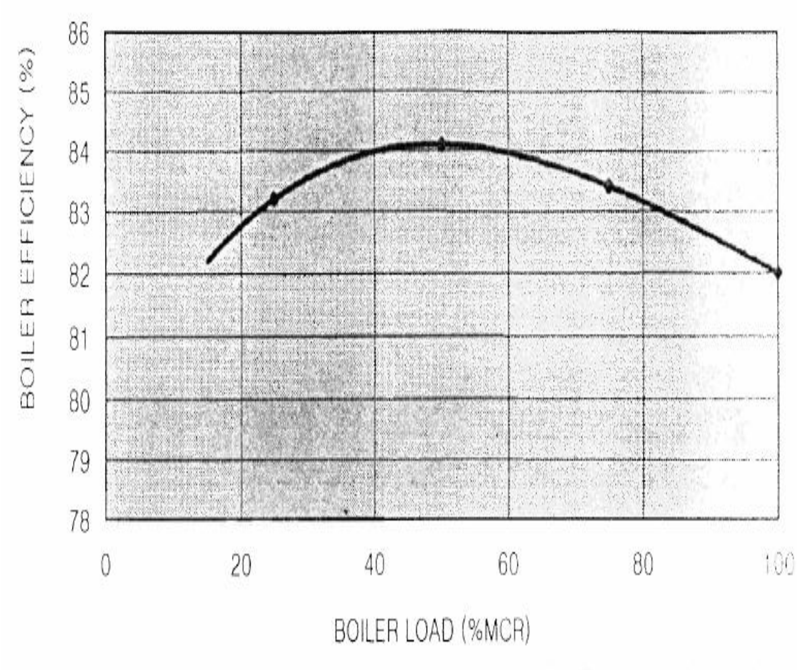

Figure 10.5 – Boiler efficiency characteristics

In operation, the efficiency tends to be lower than the above design values. There are a number of major areas that need to be managed in order to keep the auxiliary boiler at its highest energy efficiency levels as signified by **Figure 10.5**.

10.3.1 Fouling of surface

The boiler main function is to generate steam at correct pressure and temperature and with best energy efficiency. Optimal energy efficiency means optimal transfer of fuel energy to boiling water via various boiler pipes and heating surfaces. Aspects that could lead to a reduced rate of this heat transfer include:

- Fouling of boiler tubes and heat transfer surfaces on the gas side
- Fouling or scaling of boiler tubes on the water side.

The above will normally translate into a less heat transfer from gas and more heat retention by the exhaust gases as they leave the boiler. Thus high boiler outlet exhaust gas temperature could be a good indication of such fouled conditions. To remedy the case, maintenance practices should include boiler's soot blowing, de-scaling, good water, combustion adjustments (to reduce soot formation) and son on.

For this purpose, the heat transfer areas of the boiler must be monitored. The soot blowing of the boiler must be done regularly as build-up of soot acts like an insulator and reduces the heat transfer rate. The same goes for the buildup of scale in the water tubes. The stack temperature must be monitored regularly and any increase in it means that heat recovery is not optimum. High increases of exhaust gas temperature beyond those experienced after the last cleaning would indicating build-up of fouling and would require another cleaning action.

10.3.2 Optimum hot well temperature and blow-down levels

There is a hot well (see **Figure 10.3**) that collects all the condensates from steam system end-users plus where water treatment and cleaning may take place. It is from hot-well that the feed water is supplied to the boiler. Hot well temperature must be maintained at temperature specified by manufacturers. A low temperature (e.g. below 80-85 C) will cause colder feed water to enter the boiler thus increasing the fuel cost due to the need for more heating for evaporation. An overheated hot well may cause evaporation of water at the suction of feed pump (e.g. cavitation) and cause vapor lock in the feed pump and loss of suction. For heat retention in the hot well to keep temperature higher, heat losses due to poor insulation can be reduced. Also, control of make-up water is important as excessive need for make-up water will be indicative of leak in the steam system as well as more heating for make-up water that is normally at low temperature.

The blow down of the boiler is required for controlling the amount of dissolved solids as a result of evaporation and impurity of make-up water or addition of other chemical. Blow down must be calculated and done after measuring the level of dissolved water. In some cases, the engineers blow down the boiler excessively, thus not only loose hot water, but also increase the need for make-up water and make-up water generation.

10.3.3 Excessive combustion air

In order to burn the fuel, air needs to be supplied to the boiler. The excess air unused in the combustion gets heated and then discharged through the chimney. This is waste of energy. Thus, any excess air that is not needed for combustion will cause energy loss as it will take away heat from boiler and discharge to the atmosphere, thus normally should be avoided.

Boilers normally have certain amount of optimal excess air and the air input must be adjusted to this level. It signifies a balance between combustion efficiency and amount of air supplied. Excessive "excess air" is identified in the form of either high O2 concentration or low concentration of CO_2 in the boiler exhaust gas. These two parameters thus need to be monitored as part of controlling boiler excess air thus its energy efficiency. **Figure 10.6** shows the boiler efficiency as a function of CO_2 concentration. As can be seen, it is desirable to maximise the CO_2 concentration in the exhaust gas for best efficiency. As indicated, the optimum level would normally be specified by the manufacturer.

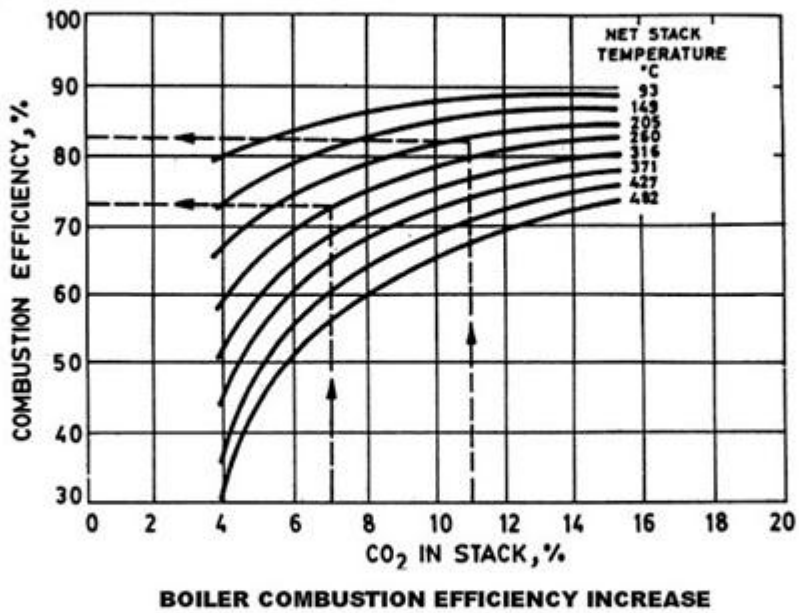

Figure 10.6 – Boiler efficiency as a function of CO_2 level in the exhaust gas [Mohit Sanguri]

10.3.4 Exhaust gas economiser efficiency

The Exhaust gas economiser in a ship is like a huge heat exchange that exchanges heat between exhaust gas from engines to water and produces steam for the same purpose that auxiliary boilers produce steam. The revered energy and amount of steam generate by exhaust gas economiser is normally sufficient for routine ship-board steam requirements, thus normally a ship with exhaust gas economiser does not need to fire the boiler while in passage. As far as improving efficiency by avoiding the fouling on the gas side and water side, the same principles discussed under boiler applies.

The efficiency of an exhaust gas economiser can be improved by increased soot blowing frequency (once or twice a day while at sea). Recording the exhaust gas temperature difference and pressure drop can provide an indication of economiser cleanliness. Water washing should be scheduled into major repair periods. The exhaust gas economiser maintenance will not only improve energy efficiency but also reduce maintenance overall costs and reduce safety risks associated with soot fires. Occasionally use of fuel additives may improve the cleanliness of the economiser (see **Section 7** on fuel management).

As for ship design, the maximum waste heat recovery is desirable. For exhaust gas economisers, the funnel stack temperature must be as low as possible but with sufficient margin to be above the dew point to avoid sulphur corrosion. Generally a funnel temperature of 165 to 195 deg C when using fuel oil is considered optimum.

10.3.5 Boiler efficiency and load factor

Like any other devices, the boiler energy efficiency is a factor of its load factor. **Figure 10.5** and also **Figure 10.7** show typical of such efficiencies.

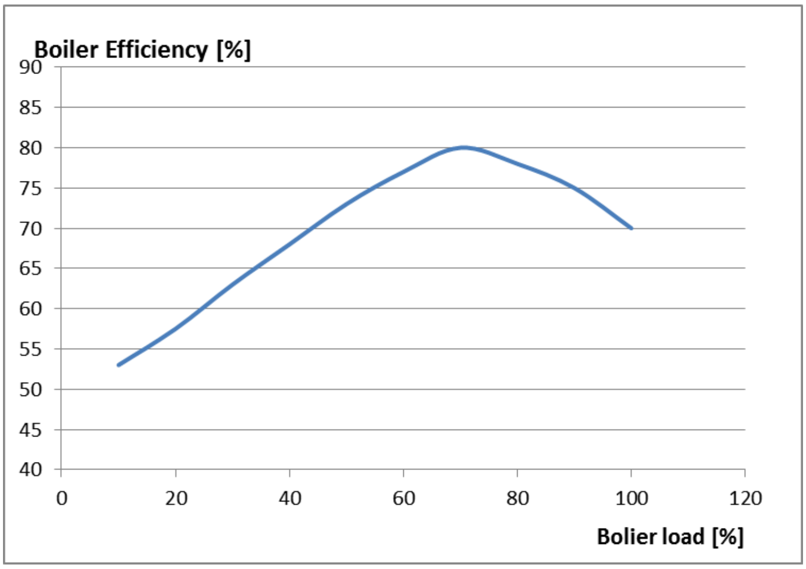

Figure 10.7 – Impact of load factor on efficiency

Accordingly, for this boiler the efficiency is highest at certain point and then drop off with changes in load. Thus boiler load management could be considered as one aspect of energy efficiency. **Figure 10.7** shows that at 70% load, the efficiency is 80% and at 30% load, the efficiency is 63%; a significant drop.

Operating the boiler at low load is thus inefficient. Avoiding low load boiler operation will depend on ship type, number of boilers and where the steam is used. Generally, if there are two auxiliary boilers on a ship, they must not run in parallel if one can supply the whole steam demand; unless safety issues dictates the need for such a parallel operation case.

10.4 Steam distribution system energy efficiency measures

The steam distribution system maintenance makes a significant contribution to energy efficiency in steam system. Measures to consider include:

- Steam loss through open bypass valves
- Steam loss through failed open steam traps
- Heat loss through un-insulated or improperly insulated piping and equipment.

To determine if your ship could benefit from a steam distribution system maintenance program, normally steam lines and steam traps surveys need to be done at regular intervals. The inspection activities will include steam pipes, insulation, traps, steam supply/discharge on or around heat exchange devices etc. Fundamental to such inspections is the collection of good data. Aspects to consider include:

Reduce steam leakage: As part of day routines, checks should be made for steam leaks. The steam leaks should be rectified as soon as observed.

Heat loss due to inadequate insulation: The boiler and steam lines along with condensate return to the hot well must be well insulated. Over a period of time insulation is damaged or worn out. Any analysis by thermography or any other thermal measurement system could identify the hot spots. Improvement of damaged insulation due to repair work must be done. All these will reduce the heat losses from the system thus improve energy efficiency.

Steam trap losses: Steam traps are used to discharge condensate once it is formed, thus the main function is to prevent live steam from escaping and to remove air and non-condensable gases from the line. However it is a largely neglected part of the steam distribution system. Steam traps that are stuck open allow live steam to escape thus resulting in loss of heat and also increasing the load of the condenser. Steam trap that is stuck shut results in reduced capacity of the equipment it is being supplied to. Overall, steam traps must be checked at planned intervals to show their good working conditions.

10.5 Steam end-use energy efficiency measures

Steam end-use could vary according to ship types. The main users of steam include:

- Steam-driven cargo pumps in tankers.
- Steam driven ballast pumps
- Cargo heating
- Fuel storage, treatment and condition system
- Fresh water generation especially in cruise ships
- HVAC system in particular in cruise ships

Every efforts should be made to economies on steam-end use as this would eliminate the need for extra steam generation thus very effective in energy saving.

10.5.1 Cargo heating planning and optimisation

In some ships, the cargo requires cooling to maintain quality; e.g., refrigerated or frozen cargo. With other cargoes such as special oil products, special crude oils, heavy fuel oils, etc. may require heating in particular in winter and cold climate regions. Some of this heat required can be supplied by exhaust gas economiser. However, in many cases an additional auxiliary boiler is needed to supply sufficient steam. Steam from exhaust gas is generally sufficient to heat the heavy fuel oil that is used on most ships; in port, however, steam from an auxiliary boiler may be needed.

For cargo heating purposes and in order to reduce fuel consumption and the heating costs, a voyage-specific cargo heating plan should be developed by the shipboard team with support from operation department at head office. For a proper plan, the following should be considered:

- Vessel tank configuration.
- Whether deck heater or tank heating coils are provided.
- Number of heating coils and surface areas.
- Cargo details including specific heat, pour point, cloud point, viscosity, and wax content.
- Weather en route including ambient air and sea water temperatures.
- Estimated heat loss and drop in temperatures.
- Recommended return condensate temperatures.
- Estimated daily heating hours and consumption.

Various parameters such as daily air/sea temperatures, weather, cargo temperatures at three levels, steam pressures, return condensate temperature, actual against estimated consumptions and temperatures are discussed between shipboard team and head office. The heating plan should be reviewed and revised appropriately throughout the voyage.

The optimum temperature to which cargo should be heated for carriage and discharge largely depends on the following factors:

- **Pour point:** It is the lowest temperature at which the liquid will pour or flow under prescribed conditions. It is a rough indication of the lowest temperature at which cargo is readily pump-able. General principle is to carry cargo at 10 ^{0}C above pour point temperature.
- **Cloud point:** It is the temperature at which dissolved solids are no longer completely soluble, precipitating as second phase and is synonymous with wax appearance temperature. Once separated, it requires temperature over 80 ^{0}C to dissolve the wax. Cargo temperature should not be allowed to fall below the cloud point.
- **Wax content:** High wax crude tends to deposit sludge, and therefore require to be maintained at a higher temperature to prevent wax fall out.
- **Viscosity:** High viscosity oils do not necessarily deposit sludge and may be carried at lower than the discharge temperatures. However, for discharge purposes, the heating will be done to reduce the viscosity to acceptable levels for cargo pumps.
- **Ambient weather and sea conditions:** This will also influence the cargo carriage and discharge temperatures as these impacts the level of heat transfer from cargo tanks or fuel tanks.

The cargo heating plan would need to take into account the above parameter. As part of cargo heating planning, relevant instructions will be developed. Heating instructions should be reviewed after loading cargo, based on charterer requirement. Permission to carry and discharge the cargo at optimum temperatures should be requested from charterer or cargo owner. The heating plan should be made soon after loading cargo and reviewed/updated on daily basis considering the various factors that affect the heating and customer requirements.

A review of the heating log abstract with the following will help with better future planning and identifying the gaps:

- Actual vs. planned temperature
- Actual vs. planned fuel oil consumption
- Actual vs. planned heating hours

Vessels should complete the heating abstract (daily basis) after completion of each voyage and send it ashore along with the Cargo Heating Log, also identifying any gaps.

Figure 10.8 shows a typical cargo heating patterns graph.

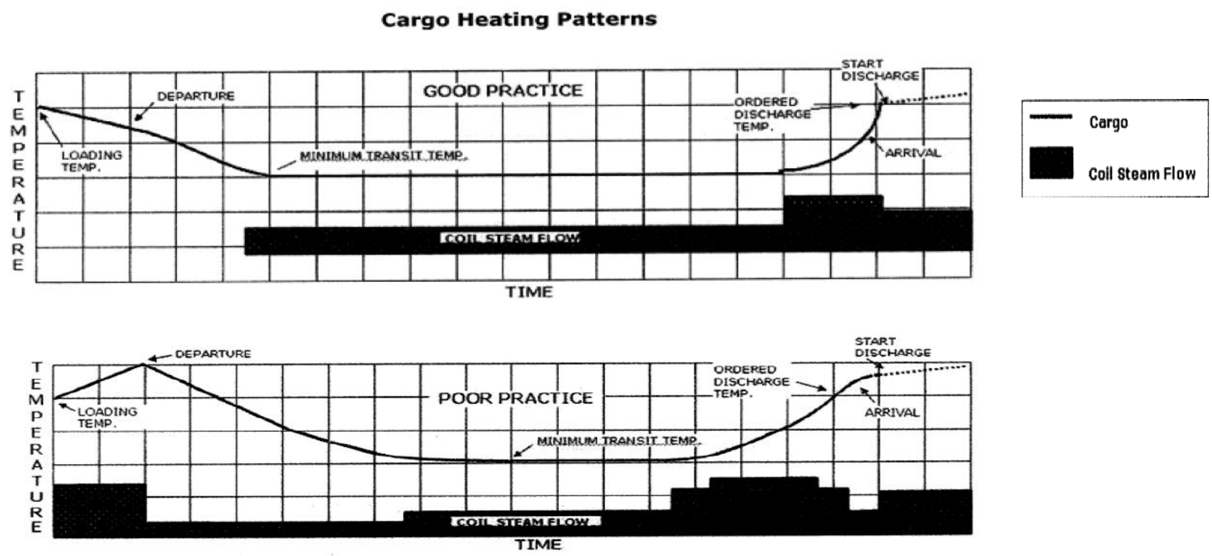

Figure 10.8 - Example of a cargo heating process [OCIMF 2011]

Operational control and best practice

For best practice cargo heating planning, the following should be noted:

- Vessels should have a greater understanding of the voyage manager/charterer's heating instructions.
- Seek the receiver/charterer's permission for allowable range of cargo temperatures.
- Avoid heating during adverse weather period.
- Create and follow the proper cargo heating plan to verify the effectiveness of actual heating progress.
- Closely monitor and analyse cargo heating reports. Monitor heating daily to address deviations from the heating plan.
- Do not heat for short frequent periods and running boiler at low loads.
- Follow the recommended condensate temperature and optimum boiler settings for efficient cargo heating. Heating instructions, accompanying the heating plan, should further highlight these points.
- Maintain efficient and good communication between the vessel and the voyage manager/charterer about the plan and execution.

Cargo heating may also benefit from the use of effective insulation. For example, using lagging on heating coil water / condensate return pipes as well as steam, thermal oil and hot-water lines on deck area. This could be significant energy saving option as it has been observed that some ships lack insulation of branch lines and cargo tanks. It is important that the insulation material is of good quality. A poor quality of insulation material is likely to rot or lose its effectiveness.

10.5.2 Steam for cargo discharge or ballast water operation

Certain ships such as large crude oil and product tankers as well as ships for the need for large ballast pump may use steam-driven turbines to drive the cargo and ballast pumps.

In these ships, extra boilers are operated to drive the cargo pump steam turbines as well as for inert gas generation. Cargo pump driven steam turbines are highly inefficient (with an overall efficiency of about 10-15%) and care should be exercised in their usage level.

During cargo discharging operations, vacuum should be maintained properly in the vacuum condenser. This will ensure better work transfer across the steam turbine thereby increasing output at the same boiler load. During cargo discharging operation, better coordination and planning must be maintained with the terminal personnel (loading master, terminal representative(s)) as also on board with deck and engine department so as to reduce idle firing period of main boilers; reducing unnecessary / prolonged cargo oil pumps' warm up period, idle running of inert gas plant etc.

10.5.3 Inert Gas Generation (IGG)

In various type of crude oil and product tankers, IG is needed for cleaning, purging and top of the cargo tanks for safety reasons. The IGG (Inert Gas Generation) system produces exhaust gas with minimal O_2 concentration for this purpose. The IGG operation resemble that of boilers and consumes fuel thus its management is required for saving energy. The IGG usage needs to be monitored to ensure that it is not used excessively. Also, optimising of the cargo tank cleaning, gas freeing and inspection intervals will reduce the usage of IGG system. When IGG system is used, the level of discharge to atmosphere (blow off of not needed IG) should be minimised via optimal operation of the system.

10.6 Shipboard best practice guide

The need to maintain clean surfaces on all exhaust gas economiser and auxiliary boilers is emphasised. The differential pressure across the economiser and its gas inlet and exhaust temperatures should be constantly monitored and appropriate action taken if measurements are out of optimum range.

Additionally, steam traps are to be checked regularly for functionality and steam leaks are to be identified and stopped. Boiler control settings such as burner start/stop and water level setting for feed pump start/stop shall be chosen in a way to reduce energy consumption.

Cargo tank heating (if applicable) shall be carried out according to the specification of the cargo and control temperatures shall be set as low as possible. Also, fuel oil temperature in various storage tanks must be monitored and kept within acceptable limits.

For evaluation of insulation and steam traps, thermal imaging may be used as a tool.

To demonstrate compliance to the above guidelines, the following need to be carried out:

- Steam pipes insulation should be kept in good condition.
- Boiler insulation should be kept in good condition.
- Steam traps are to be checked regularly for functionality.
- Steam leaks are to be identified and stopped.
- Boiler pressure setting for burner start/stop is to be as wide as practicable.

- Cargo tank heating (if applicable) shall be carried out according to the specification of cargo and control temperatures shall be set as low as practicable.
- Fuel temperature in storage, settling ad supply tanks shall be monitored and kept at acceptable lower limits.

Other activities will include:

- Steam trap maintenance should be carried out regularly. Steam traps which are not working correctly may lead to the loss of an excessive amount of additional energy.
- All steam leakages to be minimized.
- Auxiliary boiler is to be used during anchorages and other relevant opportunities.
- Starting of auxiliary boilers too far in advance of intended use is to be avoided.
- Steam dumping when possible is to be avoided.
- Pipe/ valve lagging is to be maintained in good order to minimize heat loss.
- Steam tracing is to be used judiciously.
- Bunker tank heating is to be optimized.

10.7 References and further reading

The following list provides references for this section and additional publications that may be used for more in-depth study of topics covered in this section:

1. Mohit Sanguri, "Energy Conservation in Boilers and Making an Audit Report" http://www.marineinsight.com/marine/marine-news/headline/energy-conservation-in-boilers-and-making-an-audit-report/ accessed August 2015.
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