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# A detailed study of marine fuel use and its impact on the shipping industry

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# A DETAILED STUDY OF MARINE FUEL USE AND ITS IMPACT ON THE SHIPPING INDUSTRY

by

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## Declaration

I certify all the material in this dissertation that is not my work has identified, and that no material is included for which a degree has previously been conferred on me:

The contents of this dissertation reflect my own personal views and are not necessarily endorsed by the University.

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# Abstract

The dissertation is a study of marine fuel oil; it comprises the origin of crude oil and the associated problems with regards the refining processes. For instance, secondary refining contributes to the origin of diversification of fuel grades. Studies have shown that most diesel engine failures are caused by the use of low grade fuel oil. Furthermore, today's engines are equipped with sensitive and accurate fuel devices like fuel pumps and injection valves. This equipment requires adequate onboard fuel oil treatment. Therefore, a close look at fuel oil treatment equipment is considered, taking into account the responses from Alfa Laval and Westfalia with their latest improvements in cleaning equipment. In addition, some technical and administrative aspects concerning fuel bunkers are also considered. Once fuel oil became a prominent source of energy in the shipping industry, the impact of the oil crises of 1974 and 1979 become a big concern for shipowners and engine manufacturers. However, this triggered off, to some extent, the development of marine transportation, because from the engine design prospect, there was a demand for constructing engines with higher overall efficiency. From the shipowners's side they were scrambling to develop energy saving programs onboard in order to reduce fuel oil consumption. The shortage of crude oil in the 1970s encouraged, on the other hand, the refineries to adopt intensive refining methods such as visbreaking and catalytic cracking converters. Therefore, the fuel oil obtained from these processes was not a straight run product. As a result, the rate of engine damage such as cylinder liner and piston ring wear and fuel equipment deterioration started to increase due to the low grade fuel oil used. In addition, subsequent harm to the environment by SOx and NOx emissions to the atmosphere also increased. To tackle low graded fuel oil problems, experiments and research made by the engine manufacturers and the fuel oil treatment equipment makers, have to be continuously exercised for better performance of the engines with less harm to the environment, thus providing viable solutions for the future.

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## List of Abbreviations

| | |
|---|---|
| **AC** | Alternate Current |
| **BBC** | Brawn Bovery Corporation |
| **CIMAC** | Conseil International Des Machines A Combustion |
| **CRP** | Contra Rotating Propeller |
| **DNV** | Det Norisk Veritas |
| **FBP** | Fluidized Bed Process |
| **FCC** | Fluidized Catalytic Cracking |
| **FO** | Fuel Oil |
| **IHI** | Ishikawajima-Harina Industry |
| **HFO** | Heavy Fuel Oil |
| **IBIA** | International Bunkers Industry Association |
| **IFO** | Intermediate Fuel Oil |
| **IMO** | International Maritime Organisation |
| **ISO** | International Standards Organisation |
| **LV** | Low Viscosity |
| **MD** | Marine Diesel |
| **MIDP** | Mitsui Integrate Duct Propeller |
| **MTBO** | Mean Time Between Overhauls |
| **MTBS** | Mean Time Between Sludges |
| **NOx** | Nitrogen Oxides |
| **OECD** | Organisation for Economic Co-operation and Development |
| **OPEC** | Organisation of Petroleum Exporting Countries |
| **PTO** | Power Take Off |
| **SG** | Shaft Generator |
| **SOx** | Sulphur Oxides |
| **TCC** | Thermal Catalytic Cracking |
| **TEB** | Turbocharger Efficient Booster |
| **VIT** | Variable Injection Time |
| **VLCC** | Very Large Crude Carrier |

# CHAPTER 1

## 1. Introduction

The age of petroleum began over one hundred years ago when Edwin Drake discovered oil in Pennsylvania in 1859. Until the turn of the century, oil was used primarily for lighting and domestic heating , secondarily for lubricants. Around the turn of the century, oil was used for running boilers on ships and in the industry as fuel. By the 1920s the oil came prominently to replace coal and since then it has become the major source of energy.

Meanwhile, with the development of diesel engines steam propulsion plants were slowly being phased out. This situation enhanced the dependence on fossil fuels. Because of the demand for the engine power, the main target for the engine manufacturers was to increase power output. Therefore, fuel consumption was a negligible factor at that time since fuel oil was cheap.

Due to the oil crises of 1973 and 1979 the cost of fuel rose dramatically with the resulting drawback in the world's economy. This situation came to change the thinking of the engine makers, shipowners and the petroleum industry too. As a result, they began to look for constructing engines with higher overall efficiency, taking into account the economic aspects.

In order to reduce the fuel costs, improvements with regards to the engine parts such as cylinder liner in association with the uniflow scavenging principle, bore cooling system, injection system with variable injection timing (VIT), and turbochargers were strongly considered during engine construction. Apart from these, new propeller designs and new hull forms were also developed for increasing the ship efficiency.

The present refining technology has been labelled as "variable quality" of fuels, all commercially available blends from primary and secondary processed feedstocks to no rigorous specifications. The secondary refining contribute partially for originating the diversification of fuel oil grades.

The need for lighter products accelerated the use of cracking catalytic converters. Today's engines are equipped with substantial advanced technology. As a result, many factors are to be considered with regards to the relationship between the engines and the fuel characteristics. Furthermore, the accuracy of fuel systems has become more sensitive, thus seeking more adequate fuel treatment.

As already mentioned above, fuel oil in the shipping industry is the major source of energy and is therefore a determining factor of operational costs for merchant marine. Studies have shown statistically that most engine propulsion failures are mainly caused by poor fuel quality. Not only the engine parts as such, but also the other units, like turbochargers and boilers, are affected by the low graded fuel oil, so the extent of this problem is becoming bigger. Therefore nowadays, this issue is of extreme importance and relevant to engineers and many researchers are involved in this work. In addition, many shipping companies have become concerned about the fuel problems, so these reasons have inspired the writer to study this subject area.

The aim of this dissertation is to draw the attention of those people who are involved in the shipping industry to realise the impact and implications of fuel handling from the technical aspects to some of the commercial aspects.

It consists of six chapters (and the outline of each chapters is shown) as follows:

Chapter one gives a brief overview with regards to this study and its purpose.

Chapter two describes the various types of refining processes that have been employed in the petroleum industry, including the problems with regards to the origin of crude oil. Since it neither has the same proprieties nor the same characteristics in the reserves all over the world.

Chapter three is broken down into three main sections, the first looks at bunker supply and storage onboard ships and the associated problems; the second section gives some guidance related to bunker procedures that ship's staff should know and other related matters like sampling and documentation, that should be carefully analysed; the third section covers the onboard fuel treatment, its importance and also describes *Alfa Laval's* latest developments on fuel cleaning plants including the ultrasonic system (Marissave).

Chapter four seeks to consider the causes and effects of the oil crisis of 1974 to 1979. In addition, it provides an overview of the origin of poor and unstable properties of heavy fuel oil that seem to be progressively decreasing in quality and its subsequent serious damage to engine parts and to the environment through emissions either from ships or from shore-based plants.

Chapter five looks more closely at the economy of the ship in terms of efforts that have been developed over the years by several experts in the field as attempts to lower the fuel oil consumption. This chapter is divided into three main sections; the first deals with improvements in main engines; the second deals with total energy saving in ship operations and the third is concerned with propeller and hull efficiency. In each of these sections the writer tries briefly to cover the subjects that otherwise could take at least a book.

In Chapter six the writer provides a brief summary and draws some conclusions regarding the study.

The research method used was mainly based on the literature covering the topic that was available in the World Maritime University library, although some of the material had be to requested from the other sources through letters and faxes. In addition, field studies and hand-outs from lectures were also used as fundamental tools.

# CHAPTER 2

## 2 Marine Fuel Characteristics

### 2.1 Origin of Fuel

The production of fuels has been experienced since the abandonment of coal as the main source of energy for marine propulsion plants. Fuel oil is a product which is derived from different crude oil and crude oil blends. These have their origins in many parts of the world. In fact, there are many varieties of crude and it would not be practical for this piece of work to cover all of them.

They have different properties as well, which are important to be recognised. For the purpose of this study, five types of crude oil will be considered as examples. These types of crude were chosen to support the statements mentioned above, rather than their country of origin.

Because of the difference in origin and properties of crude oils, there are wide variations in boiling ranges and general chemical nature. For instance, Boscan crude from Venezuela is heavier and predominantly naftenic in character, rich in asphaltenic material but poor in light components. It has a high density and viscosity because of a high contaminant proportion including vanadium, sulphur, nickel and other metal contaminants.

Once the primary product has already contaminant contents its residue will contain higher metal contaminants , after the refining process. Therefore, it requires blending with lighter components. The results of some analyses of typical crude oils are shown in table 2.1. The Brent crude from the UK is typically light and low-pour. It contain comparatively low levels of sulphur and metals. Its residue will be much less viscous than the Boscan. Nigerian Brassriver crude oil has similar properties to the Brent. Only that it has a much lower sulphur content which is reflect in the residue after refining. Iranian crude oil has a fairly high sulphur content and a very low - pour point, high nickel, vanadium components. The residue from this crude will contain high amounts of contaminants. Ardjuna crude from Indonesia has characteristics which are common with the rest of the data as seen in the table below, except for its pour point which is the biggest. Its residue from refining will contain very low amounts of sulphur vanadium and nickel.

***Table 2.1 Some Analyses of Typical Crude Oils:***

| **Country** | **Venezuela** | **UK** | **Nigeria** | **Iran** | **Indonesia** |
|---|---|---|---|---|---|
| **Type of Crude oil** | Boscan | Brent | Brassriver | Iran Heavy | Ardjuna |
| **Density @ 15 °C** | 0.9987 | 0.8336 | 0.8204 | 0.8703 | 0.8414 |
| **Sulphur %** | 5.5 | 0.26 | 0.09 | 1.65 | 0.11 |
| **Viscosity** | 90,000sus @ 100°F | 3.72cSt @40°C | 32.9sus @100°F | 9.81cSt @100°F | 3.74cSt @100°C |
| **Vanadium ppm** | 1200 | 1.6 | | 88 | |
| **Pour Point** | +10 | -3 | +2 | -21 | +24 |

*Source: Fisher C and Lux, J (1994, 44 )*

All crude oils are composed of a series of hydrocarbons ranging from low to high boiling points and their molecular weight. Therefore, there are many thousands of separate and distinct hydrocarbons in then, except for the few lightest ones.

The difference between the boiling points of one compound and its neighbours are submitted only in a fraction of degree as they cannot be separated one from another by ordinary means. For practical purposes it is preferable to visualise the crude oil as a smooth continuous gradation Point Matter rather than a mixture of individual chemical compounds. It appears that all these curds are not usable in their natural state for normal purposes. Thus, it is the task and responsibility of the refiners to convert the product into a series of finished products.

There are many problems regarding fuel oil quality which have arisen on engine operations. To fully understand this issue it is necessary to take into account the processes concerning production . There are:

- Atmospheric Distillation
- Vacuum Distillation
- Thermal Cracking
- Catalytic Cracking
- Fuel Oil Blending

### 2.2 Identification of Marine Fuel Types and Their Characteristics

In the shipping industry fuel is the major source of energy for running most of the power plants and other types of machinery. As the width of fuel issue, the author intends to draw the readers attention only to identifying the marine fuels in use nowadays. According to aims and types of vessels, there is a specific kind of fuel which suites the business transport or the owner of the vessels in terms of fuels costs. The fuels being used in the shipping industry are mainly:

- Fuel oil **(FO)**
- Marine Diesel **(MD)**.

The table 2.2 presents the CIMAC (1990) requirements for residual fuels Fuel Oil for engines (as delivered).

## *Table 2.2 CIMAC Requirements (1990) for Residual Fuels*

| Designation | | | CIMAC A10 | CIMAC B10 | CIMAC C10 | CIMAC D15 | CIMAC E25 | CIMAC F25 | CIMAC G35 | CIMAC H35 | CIMAC K35 | CIMAC H45 | CIMAC K45 | CIMAC H55 | CIMAC K55 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Related to ISO8218 (87) | | F- | RMA10 | RMB10 | RMC10 | RMD15 | RME25 | RMF35 | RMG35 | RMK45 | RMH45 | RMH45 | RMK45 | RMH55 | |
| Characteristic | Dim | Limit | | | | | | | | | | | | | |
| Density at 15C | kg/m³ | max | 950 | 975 | | 980 | 991 | 991 | 991 | 991 | 1010 | 991 | 1010 | 991 | 1010 |
| Kenematic viscosity at 100 | cSt | max | | 10 | | 15 | 25 | 25 | | 35 | | 45 | 45 | 55 | 55 |
| | | min | 6 | | | | 15 | | | | | | | | |
| Flash point | °C | min | | 60 | | 60 | 60 | 60 | | 60 | | 60 | 60 | 60 | 60 |
| Pour point | °C | max | 0<br>6** | | 24 | 30 | 30 | 30 | | 30 | | 30 | 30 | 30 | 30 |
| Carbon residue | %(m/m) | max | 12 | | 14 | 14 | 15 | 20 | 18 | 22 | | 22 | 22 | 22 | 22 |
| Ash | %(m/m) | max | | 0.10 | | 0.10 | 0.10 | 0.15 | | 0.15 | | 0.15 | 0.15 | 0.15 | 0.15 |
| Total sediment after ageing | %(m/m) | max | | 0.10 | | 0.10 | 0.10 | 0.10 | | 0.10 | | 0.10 | 0.10 | 0.10 | 0.10 |
| Water | % (V/V) | max | | 0.50 | | 0.80 | 1.0 | 1.0 | | 1.0 | | 1.0 | 10 | 1.0 | 1.0 |
| Sulphur | %(m/m) | max | | 3.5 | | 4.0 | 5.0 | 5.0 | | 5.0 | | 5.0 | 5.0 | 5.0 | 5.0 |
| Vanadium | mg/kg | max | 150 | | 300 | 350 | 200 | 500 | 300 | 600 | | 600 | 600 | 600 | 600 |
| Aluminium - Silicon | mg/kg | max | | 80 | | 80 | 80 | 80 | | 80 | | 80 | 80 | 80 | 80 |

*Source: Fisher, C. and Lux, J (1994, 45)*

** Applies to region and season in which fuel is to be stored and used (Upper value winter quality, bottom value summer quality)

*Table 2.3 ISO Fuel Standards 8217:1987 (E)*

*Note- The values in this table are maximum values for each property. The actual value for any batch of fuel may vary within these limits.*

| **Characteristics** | **Test method** | **Limit** | **Designation ISO-F** | | | |
|---|---|---|---|---|---|---|
| | | | DMX | DMA | DMB | DMC |
| Density at 15 gk/m$^3$ | ISO 3675 | max | + | 890.0 | 900.0 | 920.0 |
| Kinetic viscosity at 40 °C | ISO 3104 | min | 1.40 | 1.50 | ------- | ------- |
| | | max | 5.50 | 6.00 | 11.0 | 14.0 |
| Flash point °C | ISO 2719 | min | 43 | 60 | 60 | 60 |
| Pour point (upper) °C | | max | ----- | -6 | 0 | 0 |
| Winter quality | ISO 3016 | | | | | |
| Summer quality | | max | ----- | 0 | 6 | 6 |
| Cloud point °C | ISO 3015 | max | -16 | ----- | ------- | ------ |
| Carbon residue, Ramsbotton % (m/n) on 10% residue | ISO 4262 | max | 0.20 | 0.20 | ------- | ------ |
| Carbon residue % (m/n) | ISO 4262 | max | ----- | ----- | 0.25 | 2.25 |
| Ash, % (m/m) | ISO 6245 | max | 0.01 | 0.01 | 0.01 | 0.05 |
| Sediment by extraction % (m/m) | ISO 3735 | max | ----- | ----- | 0.07 | ------ |
| Water, % (v/v) | ISO 3735 | max | ---- | ----- | 0.30 | 0.30 |
| Cetane number | ISO 5165 | min | 45 | 40 | 35 | ------ |
| Visual inspection | ISO 8217 | ------ | ------ | 6.4 | ------ | ------ |
| Sulphur | ISO 8217 | max | 1.0 | 1.5 | 2.0 | 2.0 |
| Vanadium, mg/kg | ISO 8217 | max | ---- | ------ | ----- | 100 |

*Source: Fisher C and Lux J (1992, 42)*

**DMX:** Pure distillate used for engines in emergency equipment, external to the machinery spaces.

**DMA**: General purpose, Bright and Clear distillate, Gas Oil.

**DMB**: General purpose, distillate diesel which may contain trace amounts of residual fuel.

**DMC**: General purpose, blend diesel which may have a significant residual component.

Fuel oil is the most used in the large ships which are involved in foreign sea going business because of its cost effectiveness. It is a residual material from crude oil distillation and cracking processes and rejected materials during the production of lubricating oils. These materials are blended into fuel oil. It is composed of 84% carbon, 11% hydrogen and 0.5% sulphur.

According to the end use and climate in which the fuel oil is to be stored or used, market requirements of quality as defined by viscosity, pour point and sulphur content, may be considerably different.

### 2.2.1 Density

Density is the mass of a substance divided by its volume at a stated temperature, the SI unit being $kg/m^3$ . This value changes with temperature, depending on the substance's coefficient expansion. For quantity and calorific value calculations, a knowledge of fuel density is needed in order to select the optimum size of gravity disc for purification processes, particularly for conventional treatment plants.

Usually density calculations are measured over a range of temperatures at which the fuel is stored. This value is then corrected by the use of standard tables, to reference temperature, which is usually 15°C. The density of residual fuel can lie in the range of 900 to 1050 $kg/cm^3$ at 15°C, although at present most manufacturers make more than 991 $kg/cm^3$ at 15°C. This value is the upper limit to permit effective purification. However, with the **CIMAC** and the **ISO** standards the density trends for distillate fuel ranges from 890 $kg/cm^3$ for **DMA** and 920 $kg/cm^3$ for **DMC** at

15 °C while for residual fuel it is from 950 kg/cm$^3$, and for **RMA** from 1010 kg/cm$^3$, so the density increases for each specific reference for the same temperature.

### 2.2.2 Viscosity

The viscosity of an oil is a measure of its resistance to flow. In other words, as the oil is heated the viscosity is reduced and the oil becomes more "mobile." Different units have been used for viscosity such as Engler Degrees, Saybolt Universal seconds, Saybolt Furol Seconds and redwood N-1 Seconds.

Fortunately, nowadays, the majority of marine fuels are internationally traded on the basis of viscosity measured in centistokes ( **1cSt = 1mm$^2$ /sec**). The quotation of viscosity must be accompanied by the temperature at which it was determined. The recommended temperatures for viscosity determination of marine fuels are 40°C for distillate fuels and 100°C for residual fuels. The calculations of viscosity measured at one temperature to that at another temperature may not be accurate due to the variability of residual fuels composition. Therefore, the calculated result should be treated with caution.

One difficulty which exists regarding viscosity is that fuel is traded on the basis of viscosity at 50°C but the main standards (**ISO/CIMAC**) give limits at 100°C. These values are referred to in the **ISO 8217** Standards. The tables 2.2 and 2.3 shows the viscosity trends, for instance the distillate fuel ranges from 1.40 to 14.0 **cSt** at 40°C respectively, while the residual ranges from 6 to 55 **cSt** at 100°C.

The maximum viscosity for efficient pumping is considered to be 600 cSt. However, lower viscosity should be maintained where long suction lines are installed.
The desired injection viscosity is normally given by the engine builder and is in the range of 10 to 15 **cSt.** For residual fuels it is essential to use the viscosity

controller for modern low grade fuel oils since the automatic viscosity controller will be sensitive for values other than predetermined values.

### 2.2.3 Cloud Point

The cloud point of distillate fuel is the temperature at which wax starts to crystallise out and this is seen when the clear fuel becomes opaque, for instance fuels as specified in **ISO 8217**. This characteristic is only applied to grade DMX as shown in the table 2.2

### 2.2.4 Carbon Residue

This is the residue left when oil is evaporated and burned under standard test conditions, and is used as a measure of the fuel's carbon-forming properties. The carbon residue provides information about the quantity of coke or carbonaceous deposits which will result from a combustion of fuel.

According to tables 2.2 and 2.3 for distillate fuels, it appears that **DMX** and **DMA** do not have any level of carbon residue, only **DMB** with 0.25 and **DMC** with 2.50 while the residuals are ranging from 12% (m/m) for **RMA10** and 22% (m/m) for **RMH55.**

Fuel which is rich in carbon, high carbon/hydrogen ratio will be more difficult to burn completely resulting in increased deposits in the combustion chamber and exhaust spaces. For instance, generally speaking fuels produced from the thermal cracking process show a high carbon residue percentage. Carbon residue can only be an indicator of the potential deposit-forming tendency of the fuel and operating experience with different fuels at different engine loadings, the fuels which result from the secondary refining process, such as visbraeking, have a higher carbon residue value than those from other refining processes.

### 2.2.5 Pour Point

Pour point is defined as the lowest temperature at which oil will continue to flow when it is cooled under standardised conditions. The result of pour point will give the ship's engineers guidance regarding the lowest temperature at which fuel may be stored.

If fuel is handled at temperatures below its pour point, wax formation will begin out of the solution. This wax formation may cause clogging of filters and deposit on heat exchanges. In severe cases the wax builds up in storage double bottom tanks on heating coils which can restrict them from heating the fuel.

Although marine diesel oil is sometimes received onboard as a clear product for the purpose of wax indication it is considered "black." This is because not all marine diesel oil is clear, and it can also be delivered through the same lines as residual fuels. When dealing with heavy fuels, both pour point and viscosity of fuel are to be considered, if the fuel is to be maintained at a temperature to prevent wax formation and allow pumping. The fuel viscosity should not be above **600 cSt** for efficient pumping.

### 2.2.6 Flash Point

The **ISO** standards requirements for flash point give a minimum of 60°C for all distillate and residual grades except **DMX**. Flash point is the lowest temperature at which vapours from oil ignite momentarily on application of flame under standard test conditions. The Classification Societies rules state that fuels with a flash point of less than 60°C (close cup) are not permitted, except for special services. Exclusively for emergency duty engines outside the main machinery spaces are permitted to have a flash point of 43°C minimum. Permissive temperatures at which the fuel should be stored are also estimated by the Classification Societies. For safety reasons the general rule is that fuel should not be heated above 10°C below the flash point, unless specific requirements are met.

### 2.2.7 Ash Content

The residue fuel from carbonaceous matter, which remains after oil is burned in air, is referred to as ash. The ash value is related to the inorganic material in the fuel oil. The actual value depends upon three factors, firstly the inorganic material naturally present in the crude oil, secondly the refinery process employed and thirdly upon possible subsequent contamination due to sand, dirt and rust scale.

Distillate fuels should have negligible amounts of ash-forming components. If they are present in any appreciable amount this will be due to the contamination after production. Residual fuels, however, will have more of the ash-forming constituents than the crude oil feedstock as they are concentrated in residue.

Ash forming constitutes iron, nickel, silicon including soluble aluminium, calcium, sodium, and vanadium. However, the soluble elements are not included in sediment results. According to the **CIMAC** and **ISO** the level of ash for distillate fuel should range from 0.01 to 0.05. While the residual fuel values range from 0.10 to 0.15 per cent (m/m).

### 2.2.8 Water Content

Water is one of the major contaminants in fuel oils. The water contamination is very rare in fuel when it leaves the refinery. However, contamination by water can occur from a number of sources, which include poor housekeeping during the bunker delivering, condensations within the tank because of temperature differences between in and outside, steam coil leakage, and sea water contamination due to poor installation design.

A maximum volume of 1% of water in fuel oil is acceptable by the majority of fuel quality control laboratories. For instance, distillate fuel has 0.3 per cent of water.

The problems experienced onboard ships for receiving high water levels in fuel deliveries can be complex and range from slugging of fuel tanks, filter blockages, corrosion and fouling of turbochargers. In addition to this, the density and viscosity of the fuel will affect the performance of settling tanks and purifiers with respect to water removal.

### 2.2.9 Sediment Content

Unfortunately marine fuel is not pure hydrocarbon because it contains inorganic matter such as grit, clay, and sand. To some extent these substances occur in crude oil and remain in the residual fuel after refining. Sediment can cause severe abrasive wear problems throughout, derived from the fuel system particularly in fuel injection equipment.

Even though the performance of centrifuges is good some parts of catalytic fines may not be removed completely since the porosity of these fines have a low relative density, thus making separation difficult. This problem is mainly caused by the increasing use of components originating from the catalytic cracking process. In addition, the blending of fuels promotes the possibility of catalytic fines appearing as sediment in the fuel. These materials are usually aluminium and silicon components.

### 2.2.10 Sulphur

The sulphur content occurs naturally in the crude oils which is concentrated in the residual components. There is a wide range of sulphur levels found in crude oils.
Sulphur is associated with higher boiling point compounds and is therefore, at a higher level in residual fuel than distillates.

Typically for residual fuel on a world wide basis, the value of sulphur is in the order of 1.5% to 5%. However, the **CIMAC** and **ISO** recommend values ranging from 1.0 for **DMX** to 2 for **DMC** ; while for residual the values range from 3.5 for **RMA10** to 5.0 for **RMH55** as shown in tables 2.2. and 2.3. Generally, residual fuels tend to contain high levels of sulphur while the distillate has lower viscosity grades and low sulphur levels. The consumption of high sulphur fuel levels has been prohibited by the environmental legislation, see table 2.2

### 2.2.11 Vanadium

Vanadium is a metal that is present in all crude oils in an oil soluble form, and the levels found in residual fuels depend mainly on the crude oil origin. Vanadium has a major significance in fuels burned in marine diesel engines and boilers because it can form high melting point ashes which attack exhaust valve seats and sulphur heater elements.

These problems are largely overcome by good engine design, adequate fuel treatment and correct engine operating conditions. However, the problem will always remain because there is no economic process for removing vanadium from either the crude or residue.

## 2.3 Shore Based Refining Processes

### 2.3.1 Atmospheric Distillation

Atmospheric distillation is a process by which components of a mixture are separated according to their differences in boiling points at atmospheric pressure. Because, this process requires not only pure hydrocarbon but several hydrocarbon components boiling within a certain range, except gases, cannot be separated by simple atmospheric distillation like methane, ethane, propane and butane.

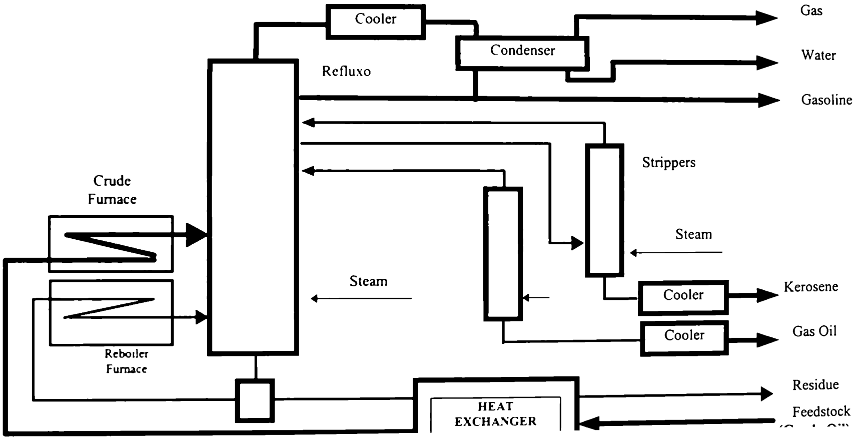
These procedures are referred to as fractions and the process by which they are separated is called fractional distillation. In this section, a distillation process is described as follows:

A feedstock of crude oil is pumped into the a furnace where it is heated to a temperature of 350°C. As a result of the high temperature the thermal decomposition ( cracking ) takes place. The feedstock enters in lower part of the fractionating column, as shown in figure 2.1

From the boiling fractions the vapour rises through perforated "trays" and condensates back down to the column. In this process heat is supplied to vaporise the lighter components in the liquid which rises to the next tray. This continues until the vapour reaches the top of the column. The vapour is removed as gas which is used as refining fuel or as petrochemical feedstock.

Different distillates may be retrieved at several stages in the column, e.g. gas, gasoline, kerosene gas oil and residue. The steam stripping process and the vapour re-entering the column high up, are used to remove each fraction contaminated with light products from the tray above when it leaves the column. After that, the stripped fraction is then cooled. Similarly, the heavier fractions, such as residue descending the bottom of the column as liquid, are also contaminated and injection of superheated steam supplies the heat into the bottom of the column. This has a similar effect as reducing the pressure and enables the high components of the residue to vaporise.

Then, from the bottom of the column, hot residue is collected and enters a heat exchanger through which the incoming crude feedstock is passed before entering the furnace. Fuel oil can be obtained by using straight atmospheric distillation.


Cooler
Condenser
Gas
Water
Refluxo
Gasoline
Strippers
Crude
Furnace
Steam
Steam
Kerosene
Cooler
Cooler
Gas Oil
Reboiler
Furnace
Residue
Feedstock
HEAT
EXCHANGER

However, the demand for lighter components has resulted in modem refineries employing vacuum distillation.

### 2.3.2 Vacuum Distillation

This is a process which consists of removing lighter components from atmospheric residue using high temperature and reduced pressure. Components in the residue are enabled by this process to evaporate at lower pressure than their atmospheric boiling points. In the refining industry there are several types of vacuum distillation processes depending on the type of feedstock. However, for this discussion the author will consider only a typical **"Dray Air"** high vacuum unit as illustrated in figure 2.2.

Here the atmospheric residue passes through via heat exchangers and another furnace, is re-heated and enters at the lower end of the vacuum column .The fractional distillation process is repeated, but because the lower pressure "trays" as used in atmospheric are not suitable, a "Packed beds" system, together with sprays is used. The Packed beds consist of randomly distributed metal rings, usually "Pall rings", which are supported on the grid. Spray sections are located above and distribute the cooling liquid through the packed beds.

The Pall rings enable a good vapour /liquid contact which is important in the distillation process. The function of removing the products is similar to the atmospheric distillation. The products usually collected from this process are vacuum gas oil, waxy distillate, wash oil and short residue. The last product is re-circulated to prevent cracking. Both the residue and distillate from this process can be submitted to other processes e.g. thermal and cracking. These processes are used for obtaining the further lighter fractions and reduce the viscosity of the residue. Both of these process convert the high molecular weight components by means of heat and pressure or by the use of catalysts.

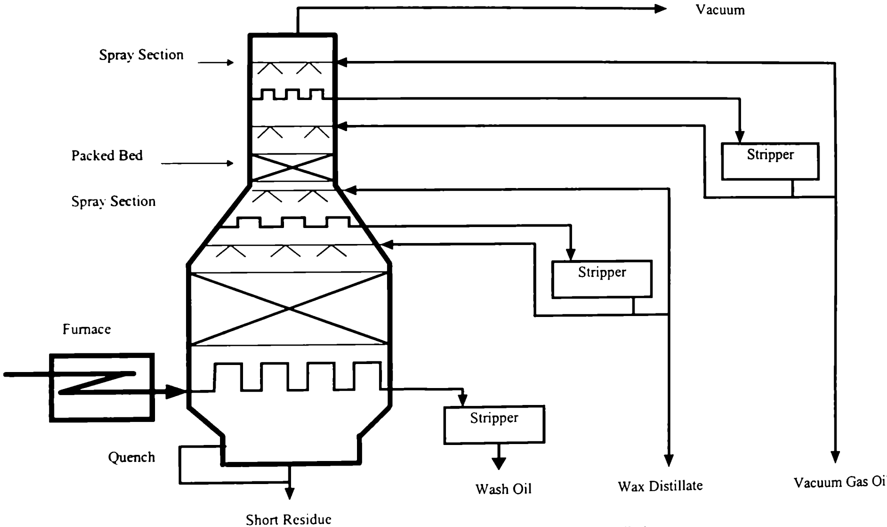



***Fig. 2.2 High Vacuum Distillation***
*Source: Fisher, C and Lux, J (1994, 14).*

### 2.3.3 Thermal Cracking

This is a process which is made of heating surplus heavy oils in a pipe still furnace to high temperatures, ranging from 700 to 1000°F . It is considered as the oldest and simplest way of cracking. However, the truth of this tale is not known, but it is thought to have been discovered by an accident in 1861 in a small refinery in New Jersey. At that time crude oil was mainly distillated for kerosene as lamp fuel. It is alleged that a bake used for this purpose, was left unattended for several hours.

As a result the residue temperature rose to a such extent that cracking occurred and thermal cracked gasoline was found in the kerosene distillate. In fact, this process has relied principally on heating. Once heated, the large molecules of the oil are broken down, "Cracked" into small highly reactive molecules which are subsequently recombined to give a whole range of products from gas to heavy fuel oil. There are two important aspects to consider in this process.

The first is that the residual oil containing bitumen tends to give a high make of coke, and only that part of the feed can vaporise giving a good yield of cracked spirit. It is normal to distillate off in a vacuum distillation unit as much waxy distillate as possible, when the system is operating in heavy fuel oil feed.

The second, if the cracking conditions are too severe, the conversion to gas takes precedence over conversion to compounds in the motor spirit range. When the oil is subjected to a series passes through the cracking zone, and a best overall yield is obtained, each giving limited conversion. Arrangements are therefore made within the plant to recycle any uncracked or insufficiently cracked material.

Although traditional thermal cracking was used high temperatures and pressures, it was popular for producing gasoline. Because of demand on quality distillation this process is hardly used nowadays. However, the milder thermal cracking process is still widely used, known as Visbreaking instead.

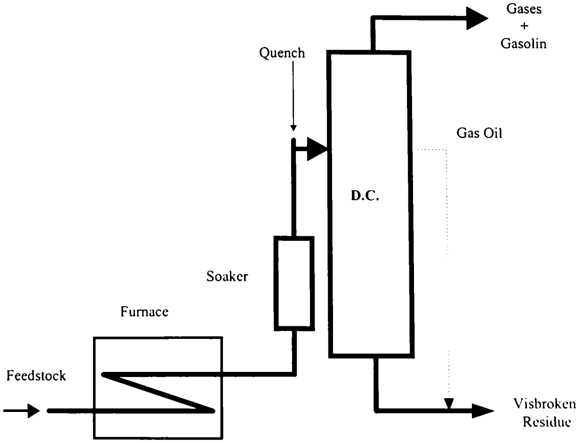
### 2.3.4 Visbreaking

Visbreaking is a process which consists of production of reducing or breaking down the viscosity of feedstock, to produce gas oil and gasoline fractions. The diagram below shows the layout of a visbreaking plant figure 2.3 A furnace heats the feedstock to a temperature of approximately 450°C. Then, cracking begins in the furnace and continues in the soaker. After quenching, at the top of the soaker the product enters the distillation column and side streams are removed.

This process has an advantage because the vacuums residue feedstock may have a very high viscosity, some 20,000 cSt at 50°C, while the residue from the visbreaker will be as low as 3,000 cSt at 50°C.

Thermal gas oil plant is an extension of the basic visbreaking process, which not only reduces the viscosity of the feedstock but also produces a maximum yield of gas oil. The resultant residue from the process has a higher viscosity than the feedstock.

Thermal cracking is even more severe because of delayed coking. In this process the residue is fully converted to coke and the heaviest side stream is heavy distillate.
The visbroken residue is employed in production of residual fuel oil. Although it is more dense than the feedstock, its viscosity is considerably lower.




**D.C- Distillation Column**

***Figure 2.3 Shell Soaker Visbreaking Process***

*Source Fisher, C and Lux, J (1994, 16)*

### 2.3.5 Catalytic Cracking

Catalytic cracking is more preferable to produce gasoline with higher octane and lighter viscosity fuels than thermal cracking. A catalyst is a material which is based in chemical reaction but does not change its own properties.
In the earlier stage aluminium chloride was used as a catalyst, but this method was so expensive and proved difficult to recover for further use.

One of the main problems experienced for using any catalyst in the cracking process is that, the cracking produces coke or carbon which attaches itself to the catalyst. As a result, it reduces the effectiveness of the catalyst. It employed a fixed bed of catalyst for the process. This system constituted three separated vessels, each containing a clay catalyst in pellet form. Cracking was carried out in a cyclic way; if the catalyst in one vessel had deactivated by coke it was steam stripped and regenerated by adding air to burn off the coke. While regeneration was in process in one vessel, the feedstock was being cracked in the other vessels.

The slowness of this process led to the development of the moving bed process. In this process the catalyst, after deactivation in the reactor, was transported to the second vessel where it was de-coked by a regenerator.

This process was named Thermal Catalytic Cracking (TCC). It became commercially operational in the 1940's. The (TCC) plant consists of twin towers with a mechanical arrangement for transporting the catalyst from the bottom of the reactor to the top of the regenerator. Later mechanical transfer of the catalyst pellets was replaced by a high velocity gas flow, and the towers were placed on top of one another giving a high structure of some 100m (meters). Natural clays were originally used for the catalyst and later synthetic catalyst was produced from aluminium and silica.

Nowadays, the synthetic catalyst contains zeolite. However, modern refineries use the fluidized bed process (FBP), the catalyst being in the form of very fine particles; spheres of around 50 to 70 microns which behave as a fluid when mixed in the vapour stream.

The FCC plant varies; in some cases the regenerator is built alongside the reactor and in others the regenerator is placed on top of the reactor. Figure 2.4 shows the schematic arrangement of a typical FCC plant with flow paths of the hydrocarbons and catalyst clearly marked.

Hot feedstock enters the bottom of the riser and is immediately co-mingled with a hot regenerated catalyst from the regenerator which causes vaporisation and "Cracking". After the catalyst is carried to the top of the riser with the hydrocarbons , separation takes place. As the riser is directly connected with the reactor the vapour passes through a cyclone separator to remove entrained catalyst. The following stage occurs in the fractionetor where the side streams are removed. The catalyst is now cleaned steam and passes back to the regenerator fluid bed. The regenerator is supplied with air which promotes the burning off of the carbon from the catalyst. Once regenerated, the catalyst passes back to the riser and therefore passes through a cyclone separator to aid recovery of the material known as catalytic fines. Cracking lower graded feedstock became apparent during the sharp rise in crude oil costs in the mid-1970s.

To reduce metal content and covert asphaltenes, hydrotreating of these feedstocks has improved the yield of high quality gasoline. Developments in refining processes show that hydroprocessing and catalyst conversion are combined. However, there is a slight difference between the catalytic cracking process and hydroprocessing.

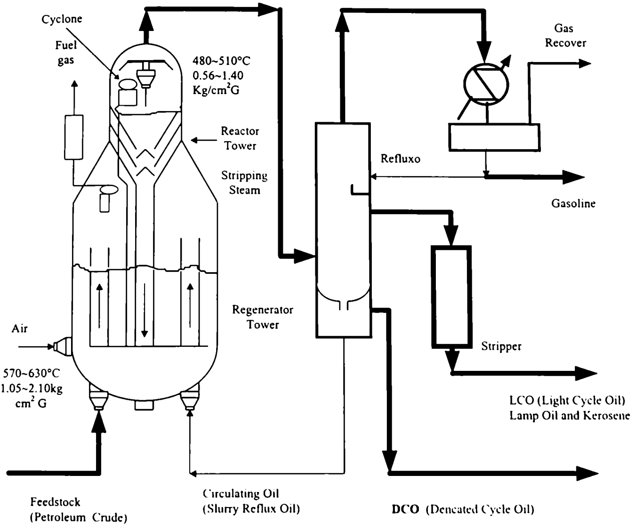



***Fig. 2.4 Fluidized Catalytic Cracking (FCC)***

*Source: Nippon Kaiji Kyokay (1996)*

The catalytic cracking process is used for conversion of atmospheric and vacuum stocks, while the hydrocracker is used to deal with aromatic feeds. Then hydroprocessing is used to cover a wide range of processes from hydrotreating, which does not change the boiling range of feed, through to hydrocraking which is a catalytic conversion process in the presence of hydrogen.

### 2.3.6 Desulphurisation

Studies have shown that sulphur is an undesirable element in finished fuels, because of the formation of sulphur dioxide. Apart from this, it is a detrimental element for internal engine parts and marine boilers due to the chemical reaction, when the temperature is low. However, the outstanding problem is the environmental aspect which relates to the emission of SOx to the atmosphere. Because of these reasons, it should be removed to some extent from the process, otherwise it will poison the catalyst.

The process used to lower the sulphur content is hydroforming or hydrotreating where the feedstock is treated with hydrogen gas. This is an expensive process, therefore, it is only applied for producing high quality products. Since developments go by, new technologies have been experienced, and other arrangements may be found in the future for the conversion of various feedstocks to particular end-product requirements.

The negative effect on marine residual fuels, which have made severe damage to fuel engine parts, is due to the sulphur content. The major harmful effects from this element will be addressed in the following chapters.

### 2.3.7 Fuel Blending and Installations

Today no refinery would be complete if it did not have adequate blending installations for all its products. During the conventional refinery era, the production was made in a small range of simple products, probably only one grade of each type of fuel was required. It was customary to operate various refinery units just to produce specific material as a finished product.

Today almost all the basic product classifications are subdivided, for instance in many different grades of the same material. A refinery may make, for example, seven grades of motor spirit, and perhaps a dozen grades of fuel oil. These variations in grades are only possible to be obtained thanks to the blending process.

A blending installation can be a simple piece of plant which is made of a certain number of storage tanks and a large circulating pump. When it is operating it mixes the blend stocks through a blending tank. One of the advantages of the blending system is that the refiner does not need to make up the finished blend until somebody is called upon to deliver. Thus, the product remains stored in the tank stocks.

Fuel blending is the most important part of fuel oil production. Once it consisted of the conversion of more residual products into marketable lighter components. Perhaps this process will play a very important role in the future, as attempts for improving fuel oil quality are being made so as to avoid declines in its quality. Before being marketable as fuel oil, the residues from the conversion process and distillations require blending with cutter stocks, such as atmospheric and vacuum gas oil heavy cycle oil from fluidized catalytic cracking. The reason for this is that, most of the residues obtained from the refining process are highly viscous and contain large amounts of undesirable materials such as sulphur, asphaltenas and metal complexes. In the blending process the most important parameter is the viscosity.

Fuel oil is generally identified in the market by its grades on a viscosity basis, for instance IFO 180 is about 180 cSt (centistokes) at 50°C. The viscosity of the residue and blending components are ascertained. The use of blending tables which utilise blending indices such as Refutas function, allow a fuel oil of the required viscosity to be obtained. Unfortunately, problems with stability and compatibility of the finished fuel oil may occur if the blending is made by viscosity alone.

It is strongly recommended that the fuel oil should have sufficient aromatic components to keep the materials like asphaltenas in solution and paraffinic components to prevent the deposition of waxes and give good burning qualities. Paraffinic cuter stocks from atmospheric and vacuum distillation are used to supply the required parffinic components.

To prevent materials such as asphaltenes dropping out of suspension there should be a sufficient excess of these blending components when the fuel is mixed with another from a different source or left to stand in storage. These factors are designated as compatibility and stability respectively. These issues will be addressed in the following chapter.

# CHAPTER 3

## 3. Handling of Fuel Oil Onboard Ship

### 3.1 Storage of Fuel Oil

According to the type of fuel oil, the petroleum products after being processed in the refinery need to be stored under the correct conditions, either ashore or onboard. For instance, fuel oil should be stored at the indicated temperature to promote settling of water and sediments and also to prevent wax formation ; this tank is technically called settling tank.

In addition, it requires heat supply in order to keep the optimum viscosity and to maintain pumpable conditions. Therefore, all storage tanks should be equipped with heating coils. The optimum temperature of oil in a tank, is normally given by a chart which shows the relationship between the viscosity and temperature. The figure 3.1 gives an example in which indicates by a bold line how to estimate the adequate temperature for a given viscosity.

Furthermore, the pour point of oil is important piece of data as well. his is a characteristic related to crude oil origin and the subsequent refining process. Basically, pour point is the lowest temperature at which the oil is observed to flow under standard conditions.

For maintaining stored fuel oil a temperature of at least. 10°C above the pour point is recommended. If, for some reasons it cools below its pour point, it will tend to solidify, forming wax.

As a result, it will require more heat and an additional distillate fuel to help the wax-dissolving process. This additive may not be available due to compatibility considerations.

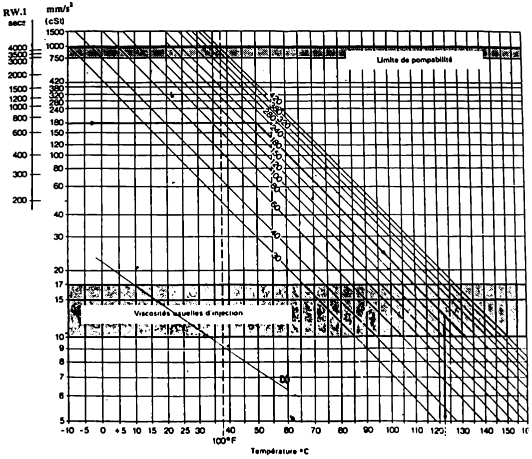



*Fig. 3.1 Fuel Oil (IFO 180 cSt) Viscosity versus Temperature*

This problem of pour point can be easily solved by keeping the fuel at the prescribed temperature from the supplier. With regards to fuel storage water content should also be considered. Under correct conditions the water will begin to settle from fuel. It is good practice for engineers to check the water drain valves every watch or twice a day in unmanned engine rooms.

However, the easy settling depends on the viscosity and density of the oil ( the lower of each the better, and therefore some heating can be helpful), and also the size of droplets. The smaller the size, the more difficult it is to separate the water from oil, and this can progress as far as the formation of an emulsion, both unstable and stable. At the later point a sludge can be the result. On the other hand, fine water droplets are unlikely to harm ignition and combustion proprieties of the fuel. Centrifuging, is also widely used to separate water from oil, as is filtration.

Investigations should be carried out immediately if the drain displays large amounts of water than usual to find out the source of water ingress into the tank. It is also necessary to identify also if the water is fresh or salt .

Salt water contamination is the most undesirable and should be avoided at all costs because it can cause severe corrosion and damage to oil pumps and injectors.

## 3.2 Bunker

All the propulsion plants fitted onboard ships need to be supplied with fuel which is delivered on board either in ports or at sea.

The term "bunker" comes from the shipbuilding twin terms "coal bunker" describing the spaces where coal was stored on the vessel. This term has remained in use although it now refers to viscous liquid marine fuel oil which is used for refuelling vessels.

At the beginning of the twentieth century, an International Bunker Industry Association (**IBIA**) was created in order to provide a clear understanding of how ships should be refuelled, and details covering fuel quality, delivery and changing trends.

The bunker buyer should know all the technical details about the efficiency and limitations of onboard fuel treatment equipment. Then, he can order according to the indicated specifications which will give him the necessary freedom to negotiate the price.

Unfortunately, in many cases the necessary specifications indicated in the contract are not always obtainable. Therefore, specifications obtained from the supplier often cannot be trusted. To support the validity of previous statements it should be appreciated that after fuel leaves the refinery it may be bought and sold several times and subsequently blended before it reaches the vessel.

In order to achieve the desired viscosity, and density the proportion of components for specific grades are calculated from the formula or determined from charts. Therefore, good blenders rely on experience and knowledge, to ensure that the nominal viscosity is not exceeded as a safety factor.

The bunker is usually delivered on board after being purchased by the shipowner company agency or by the bunker brokers. There are three ways of bunker delivery in the shipping industry namely: truck, barge and pipeline. In the following section the author intends to address only the delivery by barge since it is very common.

**3.2.1 Received Onboard**

Bunker quality has been in a steady decline for several years, particularly the heavier residual oils are increasingly becoming the sink for waste refined products. There is a number of procedures which should be followed for bunker being received onboard. Further problems may be encountered such as waste lube oil which does not contain any hydrocarbons necessary for combustion, but may contain water and wear debris which cannot be removed by a ship's purifier system. There are cases on record of a ship's engine damaged because of careless on receiving of bunkers.

Although the low flash point incidents are unusual there is a growing tendency for density. This occurs when the density stated on the bunker receipt is higher than that found after analysis from the representative samples.

To alleviate some of the problems with quality, and to reduce the risk of disputes, it is strongly recommended that the buyer should obtain specifications acceptance from the fuel supplier; the fuel oil purchaser should advise the ship's engineers what grade of fuel they expect to receive.

It is also good practice to segregate the fuels from different deliveries as far as possible; all receiving tanks should be gauged and the results recorded before taking delivery of the fuel; no document should be signed before witnessing the actual event and always the supplier's representative should be present. The fuel sample should be taken by continuous drip method through the bunkering line. This sample should be sealed and labelled in each bunker operation.

If the origin and method used for obtaining the supplier's sample is unknown, no receipt should be endorsed.

### 3.2.2 Barge

Barges are the most common means of bunker delivery in many ports, once providing a good caring capacity for supplying ships. The barges are usually equipped with pump units and sometimes heating system for discharging purposes. Unfortunately, some barges cannot provide steam for their cargoes and consequently fuel may be overheated prior to loading on the barge to ensure that the fuel has a reasonable temperature and viscosity to allow good pumping when the barge reaches the vessel.

There is a need to take measurements of existing quantity onboard before the bunker is received. Because some operators are sometimes troublesome, they try to shortest the bunkers, as a result it arising disputes afterwards.
Precaution should be taken on pumping velocity, therefore a good adjustment of pumping discharge is needed to avoid oil spills.

**3.3 Compatibility of Fuel Oil**

Compatibility may be defined as lack of asphaltenic sludge formation after two types of fuel being mixed. For instance if one type of fuel is mixed with another (these may be distillates or residual) and the final blending does not precipitate solids such as sludge or asphaltenes which cause "layering" of the fuel storage, it is classed as compatible.

Stability is another term which is often used in connection with compatibility, but this property should be considered as regards to the fuel characteristics, namely: thermal stability and storage stability.

Thermal stable fuel may be considered as such if the fuel is able to stand chemical changes when it is heated to a reasonable level. After long periods of storage, some fuel oil tends to change its composition, therefore storage stability is a measure of resistance to that change.

The compatibility and stability of fuel are not measurements of asphaltene and carbon residue content but, the capability of fuel to hold the asphaltene particles in suspension. If the aromaticity of fuel is maintained, the asphaltenes are held in suspension. The thermal cranking process has an effect on the asphaltene phase which causes a need of a greater aromaticity in order to remain in suspension. This is the reason why fuel which has been produced from the thermal cracking process must only be cut with a paraffinic dilator under careful controlled conditions, and the compatibility of the final blend should be established. The aromatic and asphaltene phase of each fuel needs to be considered because of complexity of mixing one blended fuel with another.

If the intention is to reduce the compatibility problems, it is therefore clear that mixing fuels of unknown origin on board a vessel should be avoided, in order to prevent the engine from serious damage.

Mixing of fuels is inevitable at the same stage during the voyage. For instance new bunkers are transferred to the settling tank where some of the original fuel will be held. It is good practice to always isolate a new bunker from those which are already on board. Once a mixture of oil occurs, it should not be stored for long periods in the settling tank but should be processed and burned as quickly as possible before it starts to deteriorate.

### 3.3.1 Incompatibility

The problem of incompatibility, may become apparent in the fuel lines between service tank and the fuel injection pumps. This phenomena may create blockage on filters and lines with sludge and fluctuations in pressure and the temperature as well.

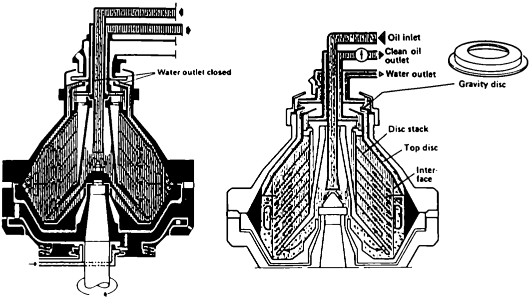
## 3.4 Analyse of Treatment Means

Generally all diesel powered ship which have been designed to burn heavy fuel oil or marine diesel should be equipped with means of removing impurities from the fuel system. Older ships may have equipment which are not particularly suitable to deal with modern low grade fuel oil. As fuel oil quality deteriorates, fuel purifies have been specifically designed to treat the lower grade fuel and of course, reduce the man hour spent on maintenance and cleaning routines.

This equipment can be ordered by the shipowner or by shipbuilder after discussing with the supplier, in order to select the separator system which will suit his particular requirements, regarding to fuel quality and cleaning frequency The term clarifier refer to that process whereby the solids are separated from liquid and a centrifuge is operated to discharge a single liquid (clean oil). When it is operated as a purifier the centrifuge will discharge clean oil and water from two different outlets.

For on board fuel treatment the operators should maintain the equipment in optimum conditions. In addition, they should be aware of the construction and the equipment performance limitations.

The Alfa Laval company is well known manufacturer of fuel treatment plants. As regards to on board plants the figure 3.2 shows the inner parts of the Alfa Laval fuel separator clarifier and purifier units.




CLARIFIER PURIFIER

*Fig. 3.2 Centrifuge Units: Clarifier and Purifier*
*Source: Alfa Laval (1996 )*

The units are basically composed of the following components: The bowl which is rotated by an electric motor driven through a worm and wheel arrangement. This bowl is set inside a casing and framework and is supported on a shaft which is held in position by bearings. The whole rotating assembly is built and balanced to reduce vibrations and noise. Inside the bowl conical stainless steal discs (up to 150) are mounted.

These discs have a spacing thickness of 0.5mm between them. The disc stack assembly is encased within the sliding bowl bottom and bowl hood. When the bowl is rotated at high speed, a centrifugal force of some 6000 to 7000G is developed. As a result the heavier components in the fuel oil flow outwards. The heavier components such as sludge and water, will travel around the bowl periphery. Then the space between the outside of the discs and the bowl wall accumulates the sludge separated from the oil.

As it is running continually a point will be reached where the solids have filled the bowl and then the cleaned oil is passed through the clarifier quickly. At this stage there is no separation process taking place. If the purifier remains working in these conditions even the light deposits in the bowl may be carried over with the untreated oil making the fuel dirtier on exit than it was before entering the purifier.

### 3.4.1 Conventional Cleaning with Purifier Systems

The conventional cleaning system is based on purifier type separators. Practical experience on operation has proved that the purifiers generally accept as a maximum density limit 991 $kg/m^3$ at 15°C for operation. However, at bunkering this maximum density limit for fuel oil may occasionally be exceeded. When this happens it normally results in operational difficulties with the cleaning system.

Currently fuel oils with densities above 991 $kg/m^3$ at 15°C are available on the market. A diesel engine can burn such fuels as long as it is properly cleaned. Consequently, the purifier type of separator restricts the use of available fuels for diesel engines because of its limitations on cleaning.

## 3.5 Effect of Interface Position on Separation Results

In this section the writer intends to address the effects of interface results on the separation process as one of the important factors in the separation system. The term interface position means the area of contact or boundary layer between two forms of matter; for instance oil and water. Therefore, this aspect is the most important to consider in the separation process.

In the purifier type of separator, cleaned oil and separated water are continuously discharged during operation. An interface is formed in the bowl between the oil and water. However, this interface position is affected by several factors such as density, viscosity, temperature and flow rate as well. To create a correct interface position it should be located between the outer edge of the top disc and the disc stack. This will enable the operator to achieve the best possible separation.

When the interface position is correct, the dirty oil can enter the narrow channels of the disc stack along its entire height. This is essential, since separation takes place in these channels. If the interface is in the incorrect position the oil to be cleaned will pass only through the lower part of the disc stack. Once the upper part is blocked with water, the separation is inefficient because only the disc stack is being used.

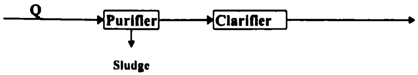
The separation efficiency is decreased not only with respect to water but also to the same degree with respect to solids particles. To enhance separation efficiency it is therefore essential that water from the water seal or separated water never enters the disc stack. This principle is applied to both purifier and clarifier type separation.

### 3.5.1 Mode of Separator Operation

The separation onboard can be operated in the following modes with different outcomes as illustrated in figure 3.3

__Series flow__

i)



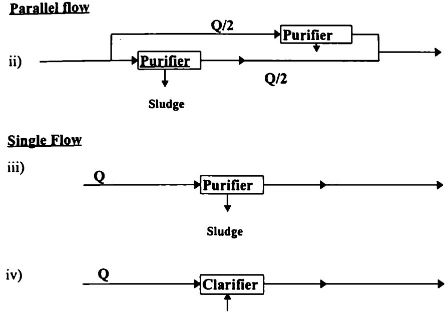



*Fig. 3.3 Modes of Centrifuging Operation*

The following operational modes tested by the manufacturers are:

i) Series operation means that one purifier is handling the total flow followed by one clarifier.

ii) Parallel operation consists of two purifiers each handling 50% of the total flow.

iii) Single operation means that one single purifier is handling the total flow.

iv) Single operation means that one single clarifier is handling the total flow.

### 3.5.2 Analyse of Separation With Purifiers

To achieve optimum separation results with purifiers, the interface between oil and water in the bowl must be outside the disc stack. The gravity disc is the key element for adjusting the interface position in a purifier. Thus, to get a correct interface position the purifier should be fitted with the correct gravity disc which varies according to the density of the fuel. However, this presents an operational dilemma with changing in oil properties.

Today's technologies enable the petroleum industries to squeeze as much as possible out of the conversion products by using visbreaking and catalytic cranking processes. Consequently the density of fuel oil has increased, therefore to maintain optimum separation results by means of gravity disc becomes increasingly difficult.

The interface position can be affected by changes in fuel density viscosity, flow rate and temperature. The figure 3.4 shows the interface sensitivity to the disturbing factors. When the density increases the optimum separation become progressively more sensitive for these factors.

Unfortunately, gravity discs experience the same progressive sensitivity to these factors. The gravity disc capability to cope with these disturbing factors therefore declines progressively with increasing fuel density as shown in figure 3.5.

Once the interface position becomes more sensitive to disturbing factors, each successive gravity disc has a smaller capacity to cope with them.
In practice, there is swiftly growing problem well before the fuel density reaches 991 $kg/m^3$. The disturbing factors cannot be entirely eliminated. As the settling tank is topped up with oil bunkered on different occasions, properties and changes in density and viscosity magnify the problem.

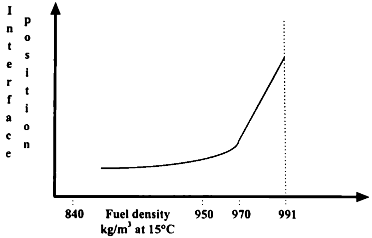



***Fig. 3.4 Interface Position's Sensitivity to the Disturbing Factors***

*Source: Alfa Laval (1996, 3)*

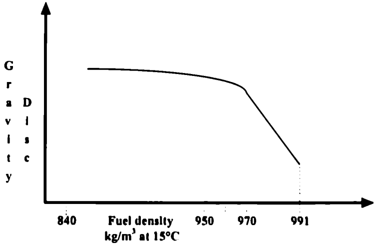



***Fig. 3.5 Gravity Disc's Capability to Cope with Disturbing Factors***

*Source Alfa Laval ( 1996, 3)*

In addition the fluctuations in temperature have been reflected directly to the viscosity even with temperature control. However, a P.I. temperature controller will be used to reduce this source of disturbance, (see figure 3.6).

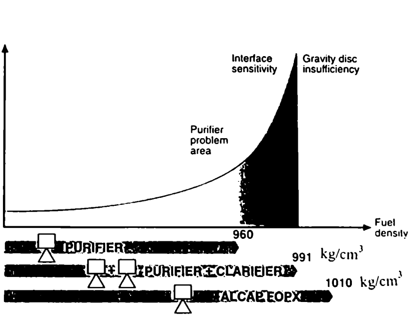



***Figure 3.6 Purifier Problem Area***
*Source: Alfa Laval (1996, 4)*

### 3.6 Effect of Flow Rate

The effect of flow rate is the single most important factor for any centrifuge operation. An experiment was made with a single purifier as mode of operation. The flow rate was 100% of rate capacity for 380 cSt fuel as 50°C . A correct interface position was maintained and the results shown in the table 3.1 indicate that the number of solid particles in the cleaned oil decreases with reduced flow rate.

*Table 3.1 Influence of Flow Rate in Centrifuging Operation*

| Size Range (micron) | 5-6 | 6-8 | 8-10 |
|---|---|---|---|
| **Cleaned Oil at Flow Rate** | | | |
| **100 %** | 1600 | 1100 | 440 |
| **50 %** | 910 | 760 | 400 |
| **25 %** | 1505 | 90 | 60 |

*Source: Alfa Laval (1994)*

### 3.7 Conventional Units Limitations

**a) Purifier**

- The basic problem in treating heavy fuel oil is the gravity disc.
- It restricts the use of diesel engine fuels to oils with a maximum density of 991 kg/m$^3$ at 15°C.

Selection of the correct gravity disc is a pre-requisite for getting optimum separation, which is a difficult task to achieve in practice as density and viscosity fluctuate, particularly with high densities. Checking and fitting the gravity disc is a time-consuming and unpleasant task. In practice it results in fitting smaller diameter gravity discs to avoid overflow and reduce alarm conditions. Therefore, the oil cannot be adequately cleaned in a purifier alone.

In order to ensure satisfactory cleaning a second separator is required in series operation, e.g. a purifier followed by a clarifier as a safety net. Thus this system becomes expensive and the maintenance costs as well. However, it is still restricted to oil with a maximum density of 991 kg/m$^3$.

The basic problems when treating fuel oil of any density in a clarifier are:

The entire contents of the separator bowl are emptied, including not only sludge and separated water but also the oil between the water layer and the centre of the bowl. With a partial discharge type clarifier the losses are smaller. The bowl is operated for shorter periods in this type to permit the sludge to be discharged together with only part of the remaining liquid in the bowl.

- Limited water handling capability

For optimum separation efficiency the separated water must never enter the disc stack. The separated water can only be discharged with the sludge through the sludge ports and the bowl periphery, see figure 3.7 as the water outlet is closed off in a conventional clarifier. This necessitates extremely short intervals between sludge discharges as there is no other method of discharging water.

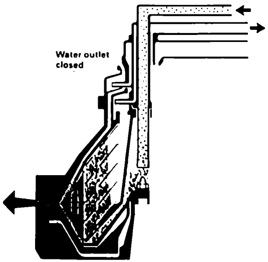



***Fig. 3.7 Conventional Clarifier-Water Discharge***
*Source Alfa Laval (1996, 5)*

A sludge discharge causes turbulence in the bowl. As a result too frequent discharges lead to less than optimum separation efficiency. Consequently, the water handling capacity of a conventional clarifier is insufficient for cleaning fuel oil.

### 3.8 Latest Development in Centrifuge Design

As the modern fuels exceed the conventional density limitation of 991 $kg/m^3$ and reach a value of 1010 $kg/m^3$ the major centrifuge manufacturers like ***Alfa Laval*** and ***Westfalia*** have responded by introducing the ***Alcap*** and ***Secutrol*** systems respectively. The ***Alcap*** system uses a clarifier unit as the base on the following unit and the theory utilised separates water from oil with a higher density unit of 1010 $kg/m^3$.

The significant feature is the abandonment of gravity disc, which was sometimes troublesome, as the means of controlling water discharge from a centrifugal purifier.

In effect the equipment was designed to suit the influence of fuel variables. As the bowl gradually fills up with sludge the water content in the clean oil outlet senses high water discharge through a water transducer. This relies on a high capacitance di-electric constant and differential between oil and water content. The CPU has also a timer unit which activates the sludge discharge sequence as required.

#### 3.8.1 EPC-400CU

Apart from the Alcap system there is another system called *Westfalia* which has basically the same approach for this problem of abandonment of gravity disc. This system uses a clarifier unit as already stated but the sensing mechanism to activate sludge discharge is different because the clarifier has a special top disc and pressure monitoring system. This equipment senses the contaminant when it reaches the outside edge of the top disc, at which point self-cleaning of the machine is initiated.

reaches the outside edge of the top disc, at which point self-cleaning of the machine is initiated.

### 3.8.2 Advantages of the *Alcap* System

The Alcap system has been used successfully in cleaning high density fuel oils. Its performance proved to be a highly reliable system and simple to operate. Conclusions were drawn after the system was tested in a laboratory , onboard ships and in power plant stations, see fig. 3.8

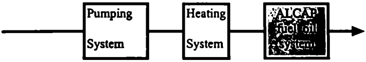



***Fig. 3.8 Alcap Cleaning System Concept***
*Source: Alfa Laval (1996, 6)*

The following items were taken from the *Alfa Laval, (1996)* documents.

- Constant optimum separation efficiency since separated water never enter the disc stack in the FOPX/MFPX separation
- Single operation one Alcap does the job
- Greater flexibility since any fuel with density up to 1010 kg/m$^3$ at 50°C and viscosity up to 700 cSt at 50°C. Can be efficiently cleaned with respect to water and solid particles. The fact that oil with density up to 1010 kg/m$^3$ at 50°C has a density below that of water between 50 and 100°C makes it possible to separate water from high density oils as shown in figure 3.9
- Potential to reduce fuel costs by bunkering high density and high viscosity fuel.
- Less man-hours as the system is simple to operate. No gravity disc, or adjustment cleaning plant are required due to fluctuation in density, viscosity and other factors. Fewer alarms occur because there is no water seal to be broken, for

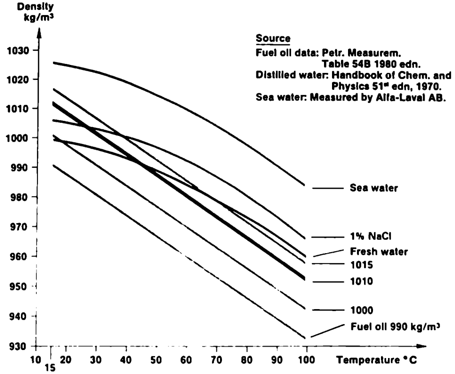



*Fig. 3.9 Density of Fuel Oil and Water Versus Temperature*

- Reduced maintenance costs owing to fewer and better components resulting in high system reliability. Emphasis has been placed on planned preventive maintenance schedules for better operation safety.
- Less need for manual cleaning due to increased cleanliness of the bowl.
- Lower installation costs fewer and simple components installed.
- Simplified installation as there are fewer points and components, critical for reliable operation, that have to be considered. For instance high pressure water is used for opening water and water addition to ensure proper operation of the system.

### 3.8.3 The ALCAP Composition

According to figure 3.10 the Alcap fuel oil concept includes four main parts as follows:

- An FOPX/MFPX separator
- An EPC-400 control unit
- A WT200 water transducer Ancillary equipment

### 3.9 Elements description

In this section a brief description is adapted from the *Alfa Laval Documents (1996).* With regards to ALCAP parts the system is composed by following:

**i) FOPX/MFPX Separator**

The FOPX/MFPX is the separation unit which has almost the same configuration as an ordinary centrifuge purifier. Only that it has special arrangements to cope with the additional devices.

**ii) EPC-400 Control Unit**

Is based on solid-state electronics incorporating microprocessors with memory chips *(PROM).*

**iii) Water Transducer (WT-200)**

The WT-200 consist of two pipes and a box fitted to the outer flanged pipe. The two pipes are insulated from each other, forming a cylindrical capacitor through which the full flow of the cleaned oil passes.

### 3.9.1 Functions of The *Alcap* Components

The following descriptions is adapted from the *Alfa Laval Documents* (1996).

- Interprets the signals from the water transducer and controls draining of separated water from the FOPX/MFPX separator bowl. Initiates sludge discharge either signal reaches the trigger point or after the maximum time between sludge discharge elapses, and controls and monitors the sludge sequence.

## The ALCAP Fuel Oil Concept

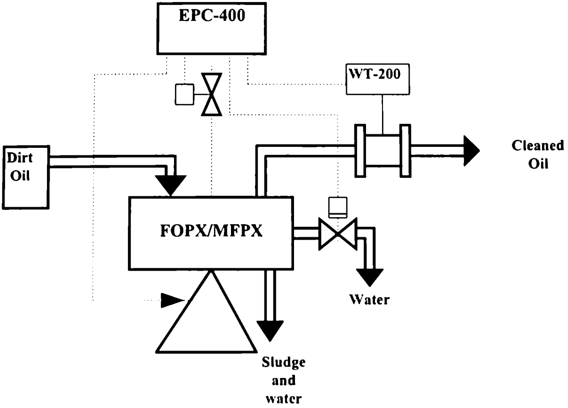



*Fig. 3.10 ALCAP Fuel Oil System*
*Source: Alfa Laval Marine (1996, 8)*

- Checks the function of the water transducer every 6 seconds.
- Determines it and when water should be added and the duration of the water pulses , thereby controlling the volume of water added.
- Monitors the addition of displacement water.

### 3.9.2 Principle of Operation

The FOPX/MFPX separation is continuously fed with dirt fuel oil. The flow of oil is not interrupted when sludge and water are discharged. This system basically operates as a clarifier unit. The clean oil is continuously discharging oil. Due to the centrifugal force, separated sludge and water are accumulated at the periphery of the bowl. See figure 3.11

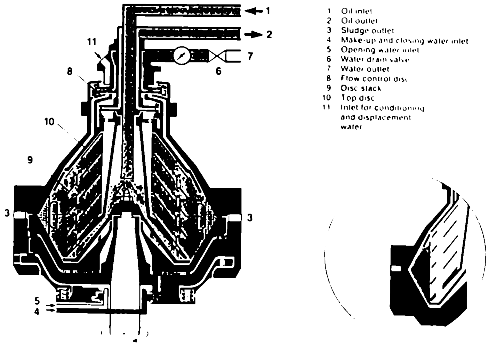



*Fig. 3.11 FOPEX/MFPX Separator.*
*(Source Alfa laval 1996, 9)*

When separated water approaches the disc stack some water droplets tends to escape with the clean oil. An increase in water content in cleaned oil is then immediately sensed by the water transducer installed in the clean oil outlet. Increased water content in the cleaned oil is a significant sign of reduced separation efficiency of not only water but particles too.

The signal from the water transducer is continuously transmitted and interpreted by EPC-400 control unit. It only measures the changes in water content, and no water content values are involved. It is the deviation of water transducer signal from non-calibrated reference value that is measured.

The allowed deviation range is the trigger range. A new reference value is stored by the EPC-400 control unit. The reference time follows every sludge discharge sequence. The possible separation result is obtained during the reference time. The trigger point is reached when the water transducer signal has reached is maximum allowable deviation equal about 0.2%. See figure 3.12

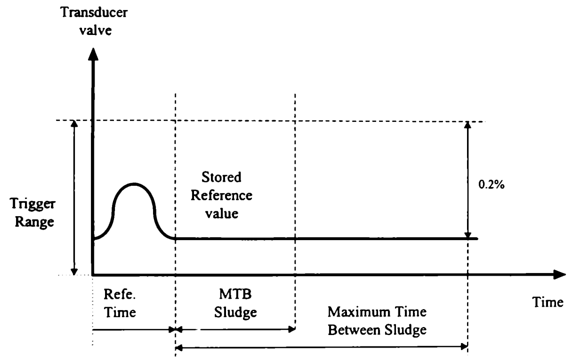



***Fig. 3.12 Signal versus Time Definition for Water Transducer.***
*Source: Alfa Laval (1996, 10)*

According to figure 3.13, when the water content in the cleaned oil reaches the trigger point, the EPC-400 unit initiates an automatic discharge of water that has accumulated in the FOPX/MFPX bowl. The water is discharged either with the sludge through the sludge ports at the periphery of the bowl or through the water drain valve. The diagrams below illustrate the water discharge.

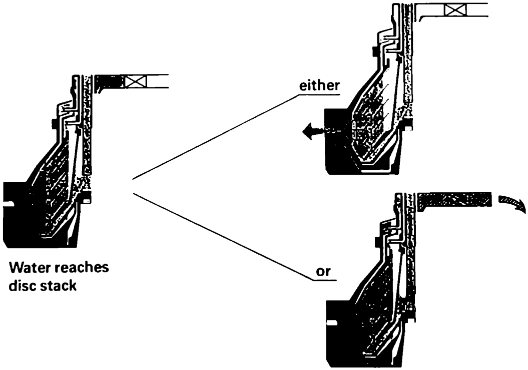



*Fig. 3.13 ALAP Fuel Oil -Discharge of Separated Water*
*Source Alfa Laval (1996, 10)*

### 3.10 Fuel Oil Filtration and Filters

The existence of catalytic fines in fuel oils has been blamed for many cylinders and piston ring causalities over the years. It should be considered that centrifuges, despite their efficiency, cannot remove all the fines particles of contaminants in fuels, especially residual fuel. Therefore, an additional filtration is needed. To cope with the upgrading fuel purification issue, different types of filters have been widely employed in fuel system before the fuel pumps. Filters are devices used in fuel systems to provide the final cleaning of the fuel prior to use.

In fact, it has been found that almost all the wear problems are caused by abrasive fine particles like sand and metals. Concerning wear in the fuel engine parts, this may be as much to blame as the catalytic fines. However, many cases of abrasive wear have been investigated by expertise in the field who have found that the level of aluminium and silica in fuel oil were low.

The size of abrasive particles has become a big concern to the engine operators and filter designers. If the fuel separator can effectively deal with particles in the 20-30 micron range, but allow through a small number of particles in the order of 70-90 microns, then the filter system must be designed to remove these particles before the fuel injection pump. Apart from the ordinary filters there are various specially designed to deal with distillate fuel and the residual fuel system.

For this discussion the author will take as example, three types of filters. The are: Suction filter, Coalescer filter and "hot" filters. For distillate fuels the system is often incorporates a Coalescer filter while for residual fuels the system uses the "Hot" filters.

**I) Suction Filters**

The suction filters can be coarse mesh filters which may have to be cleaned manually or an "Auto-Klean type figure 3.14. This filter is made of a stack of thin steel annular discs fitted on a central spindle. Each disc is passed by number of guide rods and it carries thin steel washers which separate the discs by a small clearance.

On top of the bottom disc there is a blank circular plate and as arrangement is mounted so that the oil flows through the places between the discs. In these spaces between each pair of discs project thin cleaning blades.

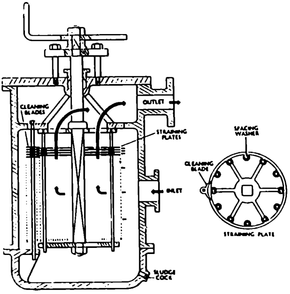


***Figure 3.14 Auto- Klean Type Filter***
*Source: Clark, G H (1988, 196)*

The discs are fixed close to the stack by means of a square sectioned spindle. The plate stack is rotated past the cleaning blades and these are shaped so that whichever way the stack is rotated, the dirt lodged between the plates is shaped out and falls to the bottom of the chamber. Sometimes magnetic elements are incorporated in suction filters to trap any loose, ferrous particles.

**II) Coalescer Filter**

The coalscer filter is a device which is used for distillate fuels on removing water and solid impurities. As it is static equipment little attention is required. However, the renewal cost of the cartridge filter becomes expensive if large amounts of water are present. A two stage process takes place in the filter cartridge, which is a single replaceable assembly. The fuel to be treated flows rapidly outwards through the cartridge, firstly through a pleated inner element, and secondly through the outer coalescer stage.

The inner element which is made from synthetic fibre, is pleated with folds separated by spacers. This inner element removes particle matter down to 5 microns from the fuel, thus protecting the outer coalescer element from excessive quantities of contaminant. In the outer coalescer, which is made from inorganic fibres suitably pressed to a predetermined density and depth, any fine droplets are agglomerated to such a size that they fall by gravity to the sump.

The water from the sump may be drained either manually or automatically.

**iii) Hot Filters**

The hot filters have a special arrangement which consists of two separate filter chambers and a distributor driven by a hydraulic motor. One of the filter chambers is for full flow filtration, whilst the other is a diversion chamber.

The actual filtration takes place through disc type elements and is divided into eight sections. When assembled, the ribbed elements form eight independent filtering columns.

It is advisable for the engineers to study carefully the literature and technical specifications supplied by the filter designers. Once being aware of this instructions it will enable them to purchase the suitable type of filters for the engines. In addition, the parameters like pressure and temperature at which the filters are to work require carefully consideration and the maintenance levels as well as the cost of spare parts.

It is important that engineers are fully aware of filter limitations too. Scheduled maintenance and correct procedures should also be adopted. The damage to the engine parts can be severe if a given filter collapses in service. A blockage of a filter may cause a high differential pressure in the system.

### 3.11 Ultrasonic Fuel Treatment System

Although substantial performance of the purifiers and newly designed filters for cleaning the fuel oil before it enters the fuel pumps some chemical components known as soluble residues still remaining and can hardly be removed by above the mentioned equipment; (purifiers and filters). Thus many experiments have been carried out with ultrasonic vibration to break up wax crystal formation.

This system consists of an ultrasonic generator driven by a high electric motor which passes ultrasonic waves through the fuel in a chamber where the molecular motion of the two main components, carbon and hydrogen, are greatly accelerated. As a result the agglomerated asphaltenes, made up primarily of carbon and hydrogen molecules tend to separate into smaller molecular groups, in the order of 2 to 5 microns.

There is a number of ultrasonic fuel treatment types, but the principle of operation is basically the same. For instance, a recent system was developed by Volmax. This equipment was placed in the fuel line before the centrifugal separators to reduce the amounts of sludge containing combustible asphaltenes extracted during the centrifuging process.

Another ultrasonic heavy residue fuel treatment system developed in Japan, the ***Marisave Fuel Oil Reformer***, has now been in use in a number of diesel installations since 1977. It has apparently given satisfactory results. Until the present moment the main purpose of this system has been to disperse and homogenise any sludge or asphaltenes remaining in residual fuel after separation. For this case the unit was located between the engine daily service fuel tank and the engine.

This system could be used in connection with the conventional centrifugal separators, and is possibly beneficial also for large land and marine boiler plants where fuel is not centrifuged.

The MARISAVE system is basically composed of a motor-driven ultrasonic wave generator, an ultrasonic horn and a cylindrical rotary filter. The fuel supply to the engine enters the filter compartment and passes through the five micron mesh filter to the inside. The rotating filter carries any particles retained on the outer surface to a disposal area below the ultrasonic horn.

At the top of the compartment the ultrasonic horn is fitted, which transmits intensive ultrasonic waves of very high frequency. These are emitted through the disposal area, causing liquid and semi-solids to expand and form a cavity. This is followed by a compression stage in which the cavity collapses, producing an impulsive compression wave which disperses any broken down asphaltenes into the liquid fuel. Then it passes through to the engine.

# CHAPTER 4

## 4. Impact of Energy Crises of 1974 and 1979

### 4.1 The Effects of the Oil Crisis

The oil crisis of 1974 and 1979 had a very big impact on the world's economy, particularly in the shipping industry. This critical situation put a lot pressure on the engine manufacturers, shipbuilders and shipowners. The shipowners were compelled to develop the energy conservation programs, for instance their fleets were running on slow-steaming speed in order to save some fuel and at the same time keep their ships on the market.

Due to the increase in density , viscosity and level of contaminants in marine fuel oil the way was paved for enhancing the development in design of purifier performance.

Shipowners concerned with scarcity of fuel oil had experimented by using fuel additives and improved general fuel handling onboard. While the ship's engineers had become familiar with treatment on handling residual fuels.

During this period a great number of ships were being built, since the shipbuilders had not suspended the construction because of this problem only that the demand for new orders has dropped sharply. On the other hand, the engine designers started on improving the engines to work in a more economical way, (this issue addressed in detail in the following chapter).

The scarcity was artificially contrived rather than being a physical shortage of an energy source. The situation was instigated by various forces that operated within the overall framework. Some of these forces may have had basically divergent targets, but at least in the short run, they may have co-operate for immediate self interests that was successfully achieved with a sharp world-wide increase in oil price.

### 4.2 Causes of Oil Crisis

As far as the world energy crisis is concerned there have been a number of reasons and many different opinions with regards to this issue. Analyses made on the world energy crisis show that at the origin of this catastrophic situation were the economic problems associated with political elements.

The crisis of 1973/74 should be regarded as two separate sets of actions which where inter-related. The first element was the unilateral price increase of oil; the second was the embargo of October 1973, initiated by a group of Arab countries and the oil exporting countries, in response to the US support of Israel during the Arab-Israel war of 1973. The Arab states reduced their oil production as a weapon to compel the US to stop supporting Israel.

The increase in oil prices from 1974 to 1979 the OPEC revenues was not large enough to compensate for inflation on the prices of goods and services purchased by the producing countries from the industrialised nations. Apart from this situation huge amounts of money were particularly used for purchasing armaments that seem to have their own super-inflation rate; thus each year more barrels of oil were required than the previous year for the same end.

Most of conditions that preceded the 1973 price increase were once again developing such as pressure on revenues of the OPEC countries reflected on demand for foreign currency tending to drive down the exchange rate, making all imports more expensive and exports cheaper, at least the relative goods of oil exporting countries.

These were the main factors that made a scenario of shortage in oil supplies that seem credible and it only requires a political incident like the Arab-Israel war of 1973 to trigger a second oil crisis.

> *For instance, Raymond Vernon argues that the energy crisis is the result of the low cost of crude oil relative to other sources of energy. Consequently, he asserts that as the national incomes of consuming nations increased during the last two decades, their demand for energy increased correspondingly. But since crude oil was cheaper than other sources, demand for crude oil grew faster than the demand for other sources and this in combination with the supply interruption resulted in crisis.*
>
> ( Cyrus Bina, 1985)

**4.3 The Role of OPEC**

The Organisation of Petroleum Exporting Countries, universally know as (OPEC), was established in 1960 by five major producers and holders of about 40% of the crude oil reserves proved to exist in the world. It included Saudi Arabia, Kuwait, Iran Iraq and Venezuela. This Organisation was mainly established to form a united front against the multinational oil companies which had previously controlled the world's oil industry with a major share of the oil market. The major oil companies were: ***British Petroleum (BP), Esso (now Exxon), Shell, Mobil, Texaco, Standard California (Chevron)*** and ***Gulf***. These companies were regarded as "*the seven sisters*".

They had a high percentage of the refining capacity, large international marketing organisations and abundant reserves of crude oil in detriment of the OPEC countries.

The main goal of OPEC was to increase the price of crude oil by controlling production and by negotiating with the major companies. The other major oil producers, such as Libya, Algeria, and Indonesia were later to become members of OPEC until the cartel totalled thirteen.

Oil in the OPEC countries is now controlled by the state. In some cases, it is controlled by their country's Royal family. This policy is totally different from the multinational oil companies, which is applied in some of the main non-OPEC oil producers such as USSR, Mexico and China. OPEC had a little influence until the end of the 1960's on the world oil market, since the major companies dominated the market.

At the beginning of the 1970's the OPEC demands for high prices and greater participation in oil extraction and refining was declining. Tired of such exploration, OPEC started gradually to acquire technical expertise and began, especially in Libya, to use cartel-breaking independent oil companies such as Occidental supply outlets.

**4.4 Cost of Crude Oil**

In the early stage the fossil fuels such as coal and crude oil were so abundant, specially in the Arabic countries. Large amounts of crude oil were supplied by the Arabic countries with very competitive prices. Therefore, many importing and some of the producers countries were depending on those Arabic suppliers countries, these situation remained until the foundation of the OPEC.

By the beginning of the 1970s, with regard to the crude oil business, the OPEC started to adopt a new policy. This was because OPEC deplored the operations of the multinational companies.

However, the average price of crude oil was from about $ 1.7-1.9 per US barrel; (traditional unit in which oil was traded), and depending upon its quality. The Arab light crude oil was widely used as a yardstick for good quality crude.

In 1970, the first impact of growing strength of the OPEC cartel was felt, when the original members were able to increase typical Middle East crude oil by $2.7-2.9 per barrel.

Due to the oil ban declared by the OPEC countries the situation worsened, since this created a world wide shortage and the prices of crude oil increased again by the end of 1973 and the beginning of 1974 by $11 to $12 per barrel.

As a result of global scrambling for scarce oil this situation enabled the non- Arab members of OPEC to take advantage of this situation and quickly adopted the artificial vast increase in crude oil prices. By late December 1980 the prices of crude rose from an overage of about $ 13 per barrel to as higher as $ 34 per barrel.

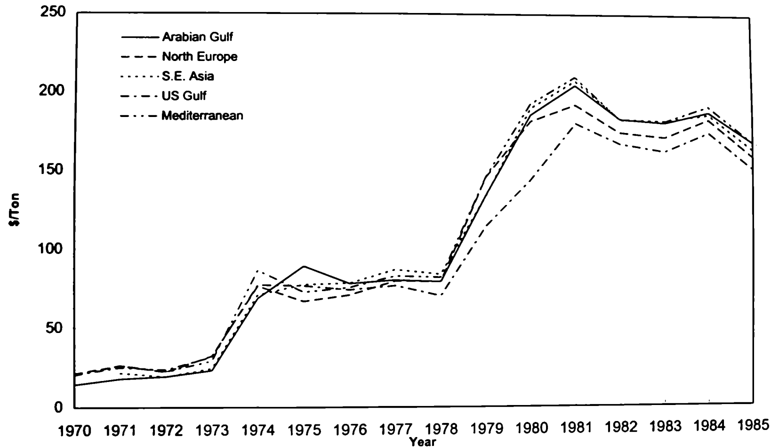
Another major factor was that OPEC demanded the expropriation of the proprieties and concessions of oil fields owned by the major western oil companies, to bring all oil production under state ownership or control, thus strengthening OPEC's position in the cartel.

Finally, in the last analysis, the escalation in oil prices had far reaching economic effects, particularly between the poor OPEC countries and the industrialised countries, especially the OECD (Organisation for Economic Co-operation and Development), since huge financial resources were transferred from the relatively rich industrialised oil-consuming countries to the poor oil-producing ones. As a result this created a sudden reversal in the world's economic balance.

### 4.5 Cost of Fuel Oil

Generally speaking the cost of fuel oil was primarily estimated according to the price of crude oil in the first instance, and secondly by its viscosity taking into account the quality. However, apart from these parameters the price of fuel in general has fluctuated over the years.

Figure 4.1 shows the prices of fuel oil IFO 180 cSt in tons versus the time, in the Arabian Gulf, North Europe, South East Asia, the US Gulf and the Mediterranean. The graph presents the twin oil price jumps that occurred in 1974 and 1979, the prices are slightly different from one another, but in general all of them were followed the same trends.




**(IFO180 cSt)**

***Fig.4.1 Annual Average of Bunker Prices from 1970-1985***

*Source: Drewry Shipping Consultant (1986)*

## 4.6 Quality of Fuel Oil

The quality of fuel oil is normally different by the origin of the crude oil and its characteristics. In chapter two are stated the main characteristics and properties of fuel oil and marine diesel as well as the ISO and the CIMAC requirements.

The problem regarding quality of fuel oil has became a big concern after the twin oil price shocks of 1973 and 1979. For instance, years before the world energy crisis there was a fairly safe assumption that, wherever in the world the vessel might take on bunker, the quality of fuel oil available would be such that none of the engine manufacturers recommended limits for any fuel characteristics or proprieties because the quality was acceptable.

The changes that occurred in the petroleum industry triggered the widespread introduction of secondary refining and fluidised cranking catalytic (FCC) plants at many of the world's refinery centres. These new techniques have been enabling the refineries to reprocess the straight run fuel oil as refinery feedstock and to maximise their yields of more profitable lighter products such as kerosene, naphtha, gas oil and gasoline. As a result of these high efficiency refining processes have caused handling problems and also substantial damages to the machinery were reported, followed by complaints and claims directed at the fuel suppliers.

### 4.6.1 Relationship Between the Quality of Fuel oil and Refining Processes

Figure 4.2 shows the evolution of the refining processes of which the disadvantages are the following:

- higher viscosity up to 700 cSt at 50 °C
- higher gravity in excess of 1
- bigger percentage of impurities such as in sulphur, vanadium, and asphaltenes decreased infallibility characteristics at presence of catalyst fines in the fuel oil

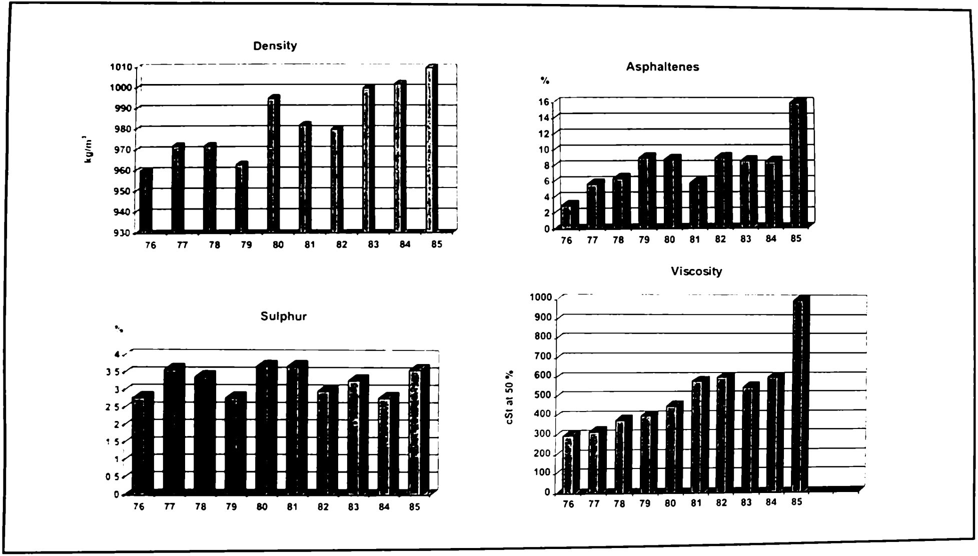



*Fig. 4.2 Evolution of Fuel Quality*
*Source Gallios, J (1986)*

Due to this situation the engine manufacturers had to cope with all of these disadvantages. For instance the viscosity increase has been partially solved by the increase of the fuel heating temperature. This temperature rising up to 150°C is necessary in order to prevent any risk of fire to pressurise the fuel circuit at about 5 bars.

The main refining processes are stated in chapter two including the proprieties of fuel oil. However, it worth emphasising that some of these processes have been developed to respond to the imposed scarcity by the oil producers, and the level of demand for high quality products such as aviation fuel gasoline and lubricants through the employment of intensive refining methods like thermal cracking, visbreaking, and the fluid catalytic cranking.

The extent of this problem had gone far until drawn to the attention of the classification societies and the (DNV) Det Norisk Veritas, Norwegian Classification Society responded by introducing a fuel quality testing program in 1981.

Figure 4.3 shows the flow of the feedstock to the various refining processes and the range of residues and dilators which may be used to produce residual fuel oil. The residues produced by various processes can be either squeezed for further extraction or may be blended to form residual fuel.

As a result of the use of a wide range of crude oil, associated with multi-stage refining, it is hard to state the typical proprieties of the marine heavy fuel oil and blended diesel oil. However, some general aspects can be considered. For example a paraffinic crude oil subjected to atmospheric distillation would generally provide a residue which would meet the ISO standards for 380 cSt fuel. This residue would have a relatively low density and good calorific value.

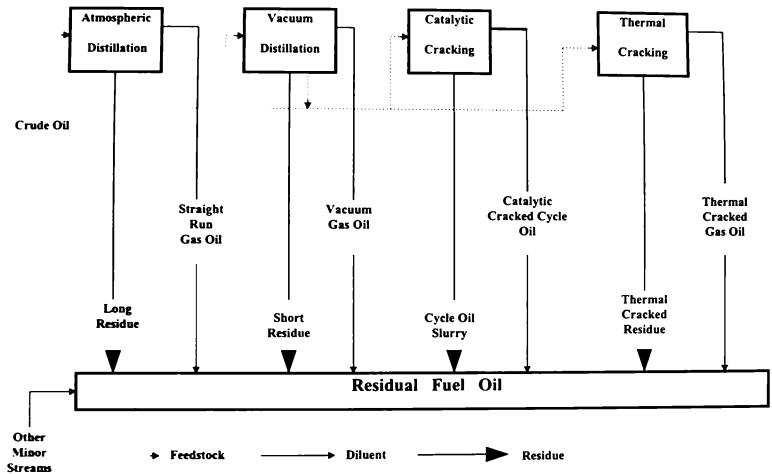



***Fig. 4.3 Residual Fuel Manufacture***
*Source: Fisher, C and Lux, J (1986, 22).*

If the same type of crude oil is subjected to vacuum distillation the viscosity would be increased and it would require a distillation the viscosity would be increased and it would require a dilution with a distillate to produce a 380 cSt fuel. While the carbon level and sulphur of the residue would be high but residue up to acceptable levels by the addition of the dilator.

The catalytic process typically has a viscosity around 200 cSt at 50°C but a density above 991.0 kg/m$^3$. This produces a "slurry oil" or bottom residue.

The carbon level will have been reduced but the pour point and ash content would have increased. Special attention should be paid to the ash content because of the particles fines that can be significant in fuel oil. As new technologies on fuel treatment exist, the use of low fuel quality has directly affected ship machinery; main engines and auxiliary motors and the subsequent harm to the environment through emission.

For example, the use of fuel oil, rich in sulphur, means abnormalities are likely to occur such as:

- low temperature corrosion wear of piston rings and cylinder liners
- adhesion of black liqueur on the inner surfaces of cylinder liners
- low temperature corrosion wear of exhaust passages and turbocharger casings, and surging of turbochargers
- clogging of fuel heaters
- high temperature corrosion of exhaust valve

These emissions are a product of engine combustion that are finally exhausted to the atmosphere.

Although the environmental issues are not within the scope of this chapter, it is worth to mentioning some important aspects regarding air pollution.

The ozone layer as been depleted over the years because of various types of air pollution, such as the burning of solid fuels and fossil fuels from industrial plants like boilers, furnaces, large marine and stationary diesel engines.

As a result of the ozone layer depletion, the world has been experiencing a global warming phenomena. In addition, air pollution can be harmful to physical and mental health, can also contribute to smog, and in extreme cases, it may cause death due to respiratory sickness. Polluted air increases soil acidity, retards the growth of crops and adversely affects animal health. Because of its growth acid rain is causing damage to forests in many parts of the world.

As far as deterioration of the environment is concerned some important measures for reducing the injurious effects are to be considered:

- to burn only selected fuels having low pollutant proprieties, particularly sulphur content;
- to remove or reduce the sulphur content of the fuel before combustion;
- to treat the flow of gases after combustion to remove the pollutants such as smoke, ash, $SO_2$, and NOx and convert them into harmless compounds;
- to use tall chimneys feasible only for large plants;
- to burn the fuel efficiently in suitable burners under nearestochiometric conditions

In the early 1980s the international community, began to be more aware about the air pollution problem, probably because of wide use of low quality fuel oil.

At the end of the 1980s the International Maritime Organisation (IMO) began to direct the impact of shipping on air pollution by discussing the possibility of controlling the emissions of gases from ships. These emissions are mainly generated by a ship's machinery such as the main engines, auxiliary motor and the boilers on board or ashore.

With regards to the uptaking of emissions, the main concern has been evolution of combustion products like (NOx) Nitrogen and (SOx) Sulphur oxides. Engine designers are also doing their best to reduce the amount of emissions to the atmosphere. For example, they have been trying to tackle the NOx problem by making improvements on fuel injection systems like the electronic fuel injection system, emulsified fuel with water and the injectors units as well. The SOx issue is directly related to the quality of fuel oil nowadays in use.

IMO produced, in 1990, a draft report regarding the development of a new annex of Marpol 73/78, concerning air pollution from ships. Although the draft covered various types of air pollution the target was the reduction of SOx emissions from ships by 50 per cent within a decade. For instance, there is considerable measures for the mandatory introduction of a regional cap on sulphur oxide emission from residual marine fuel oil in the Baltic Sea as low as 1.5 per cent.

For environmental protection the Regulations for the prevention of air pollution from ships are now under deliberation by IMO. Regulation 19 of the draft provides requirements for fuel oil quality. The contents are that a Bunker Delivery Note is to be issued by the fuel supplier, and retention of the note for three years after issuance is compulsory to ensure and certify the quality of fuel oil. It is required for the fuel oil supplier to indicate the properties and specifications of bunker fuel oil in the ISO grade and declare it in the Bunker Delivery Note.

# CHAPTER 5

## 5 Efficiency Improvements in Ship Propulsion Systems

### 5.1 Measurers for Reducing Fuel Oil Consumption on board Ship

As explained in the previous chapter, the impact of oil crises had a substantial effect on the shipping industry. The technology regarding marine diesel engines had been developed over several decades, but was mainly triggered as a result of the oils crises. However, in the early stage, because of fuel abundance and low price, the engine builders were devoted merely to constructing engines simply to generate power for displacing cargo from port A to port B and vice-versa.

The economic factors such as efficiency and durability were left behind. These issues became a big challenge for the engine builders after the outbreak of the first fuel oil crisis in 1974. Although these measures covered the low speed and medium speed diesel engines as well, the writer intends to address mainly the subject with regards to low speed engines. Many steam ships with diesel propulsion plants started to phase out.

#### 5.1.1 Main Diesel Engine

As a result of the oil scarcity, the engine builders began to step up efforts towards the improvements in engine design to respond to the crisis situation. The main target was to design an engine with lower fuel oil consumption by upgrading the specific engine parts and operating parameters. This issue was successfully fulfilled by a number of leading engine builders often assisted by their licensees such as ***Sulzer, B&W-Man*** , ***Mitsubishi*** and ***Wärtsilä*** and many others. However, in this chapter the author intends to address the improvements on design based on a ***Sulzer, RTA 62*** diesel engine. On the other hand, the extent of oil scarcity was concerning deeply the shipowners as well. Thus to attain improvements corrective measures were taken on board such as reduction of ship speed. Due to the engine manufacturers attempts to lower fuel oil consumption after 1979 a big drop of consumption was registered, see figure 5.1.

The main parameters which have increased the **Sulzer RTA** engine type efficiency were:

- lowering engine speed increasing the stroke
- higher combustion pressure
- alternation of scavenging process
- introduction of efficiency booster
- introduction of **VIT** system

To tackle the problematic situation the Sulzer company set some parameters which governed the **RTA** engine.

With regard to the figure 5.1, from the beginning of the diesel engine era the most important factor that was always considered during the construction was the power output. Taking a look at diagram until 1979 there was sleight decline fuel oil consumption. After that the thinking of the engine manufactures changed then, the main target became efficiency and decrease of fuel oil consumption.

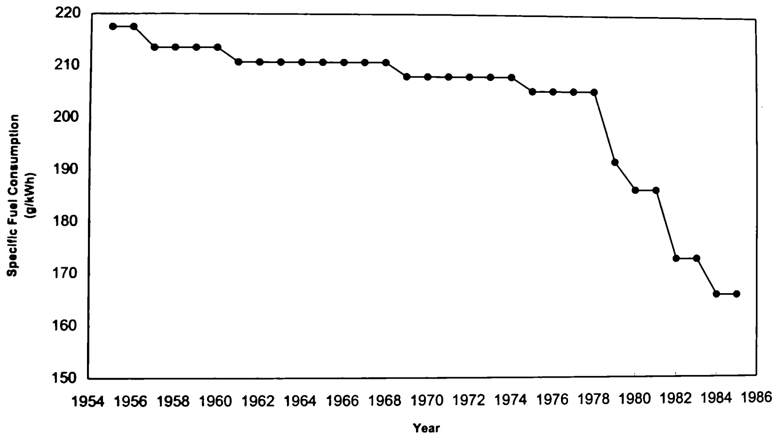



***Figure 5.1 Trend of Specific Fuel Consumption***
*Source: Society of Mechanical Engineers (1987)*

### 5.1.2 Reduction of Engine Speed

The trend of lowering the engine revolutions and large diameter propeller has proved to be feasible and applicable for better engine and propeller performance. Generally speaking the lowering of the engine speed first of all allowed an increase in propeller efficiency. Since engine parts move slowly it appears to be more reliable and of course the Mean Time Between Overalls (MTBO) can be extended as well. The thermal efficiency surpassed the 50% limit which was considered unattainable by reducing the revolutions per minute. The thermal efficiency of 50% is equal to specific fuel consumption of 168.6 g/kWh or 124.0 g/bhph.

### 5.1.3 Fuel Injection System (VIT)

The fuel injection system has been designed in such a way that the fuel pumps can convey some advantages, especially in connection with low quality fuel. The use of a big central exhaust valve increases the efficiency of the engine, since the exhaust gas removal is more complete. However, this requires a new peripheral location of injection valves on the cylinder cover.

Due to this arrangement, one fuel injector became insufficient to deliver adequate spray into the cylinder. Therefore the cylinders are usually equipped with two or four injection valves; for example in the case of the Sulzer RTA engine, some fuel valves are installed on the top of the cylinder head, it is depending on the size of the engine. As a result, separated cooling systems of fuel nozzles were also eliminated for better access during maintenance.

The current technology of the fuel injection system use the circulation of fuel in the injectors when the engine is not in operation, thus allowing the operators to use heavy fuel oil from pier to pier without major problems. The variable injection timing (VIT) has been developed and tested for use in future designs, because of its advantages such as allowing the use of poor quality oil and the possibility of adjusting the time of injection.

In addition, the specific fuel consumption is lowered by controlling the maximum permissible combustion pressure with different loads through adjustment of the fuel injection timing. The reduction of fuel consumption at 85% of the engine load is about 2g/bhph when carrying the maximum combustion pressure at its normal value.

The VIT system changes automatically the injection timing according to the load to maximum combustion pressure at loads between 85 and 100%.

This system has a mechanism which allows the engineers to make a manual adjustment of the fuel injection and it is known as fuel quality setting by a separate lever of the VIT.

When burning heavy fuel oil it is necessary to make a readjustment of the fuel quality lever towards earlier injection, then the pressure rises and fuel consumption is lowered to its best possible value. On the contrary, heavy fuel oil can result in an ignition delay and consequent drop in the maximum combustion pressure which in turn increases the fuel consumption in the engine. To confirm that the engine is operating at the correct maximum pressure at a given load, peak pressure cards can be taken by the engineer after adjusting the equipment.

### 5.1.4 Superlong Stroke

The superlong stroke concept means increasing drastically the stroke thus the stroke to bore ratio is ranges from 3.0 to 4.2. Obviously, with this value the engine size will slightly increase in dimensions. This is a result of the short piston in connection with the uniflow scavenging principle. The compact structure design of the running gear components enables the reduction of revolutions per minute up to 55 rpm, while still maintaining or even increasing the engine power output per cylinder. On the other hand the specific fuel consumption can be reduced as well. By increasing the stroke the gain could be up to 160.5 g/kWh.

### 5.1.5 Uniflow Scavenging Principle

In this section the author intends to address the uniflow scavenging principle, however, for a better understanding a description of the loop scavenging principle is described in advance.

Generally speaking the scavenging system is only applicable to two-stroke engines, and is the process of clearing from the cylinder any remaining products of combustion from the previous cycle. Efficiency scavenging is the effectiveness with regards to the air on clearing the cylinders.

The loop scavenging system consists of inlet and exhaust ports located in the cylinder liner. The opening and closing of these is regulated by the piston in its reciprocating movements. From the construction view point, this system simplifies the design of the cylinder head for the loop scavenging engines.

The uniflow scavenging principle has been adopted by many engine builders, since it is capable of achieving 100% scavenging efficiency. Therefore it is absolutely appreciated and employed in modern long stroke engines. It is composed by the inlet ports located at the lower part of the cylinder liner and an exhaust valve on the top of the cylinder head.

Uniflow scavenging is the change from the loop scavenging principle which is a consequence of the superlong stroke design. Loop scavenging posed some operational difficulties because of the location of the inlet and exhaust ports in the cylinder liner. For instance, with the stroke elongation the loop scavenging system was not efficiently removing the exhaust gases.

Figure 5.2 Shows the comparison between the loop and uniflow scavenging principles in terms of performance of scavenging efficiency ratio that proves once again that the uniflow principle has better efficiency than the loop scavenging principle, since it can maximise the amount of oxygen in the cylinder.

Furthermore, for equal specific fuel consumption the loop scavenged engine requires somewhat higher maximum combustion pressure compared to a uniflow scavenging design. As a result, special care was given at Sulzer to develop the technology to

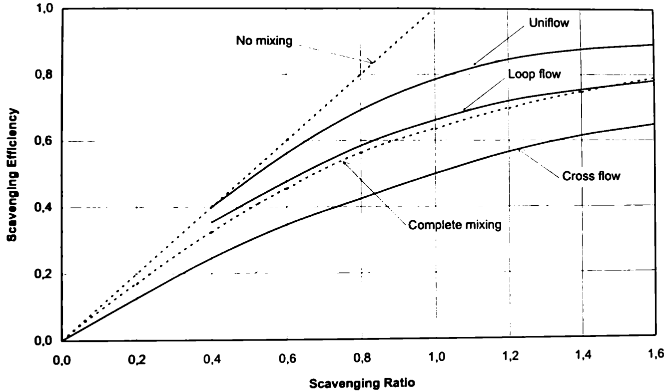



***Fig. 5.2 Relationship Between Scavenging Efficiency and the Types of Scavenging***
*Source: Woodward, J B (1988,88)*

withstand high pressures with moderate stresses and strains ensuring excellent reliability for the whole engine.

This arrangement of an exhaust valve increases the efficiency with which the exhaust gases are completely removed from the cylinder. It is quite common to have the inlet ports angled tangentially to the liner in such a way that, air develops a swirling characteristics that not only helps to maximise the flow of exhaust gas removal from the cylinder liner, but also provides an aid for better combustion, as a result of improved air/fuel ratio, thus improving the engine performance.

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Figure 5.3 shows one of the scavenging model tests which relates the Purity (volumetric) versus the Stroke bore ratio, where the weakness of loop scavenging systems is clearly apparent compared to the uniflow scavenging system. For instance, when the stroke bore ratio is 2.5 the loop scavenging starts to decrease while the uniflow is steadily increasing. At point 3.5 the loop curve falls sharply while the uniflow reaches the maximum value. This shows that for the long stroke diesel engine efficiency increases with an increase of the stroke bore ratio.

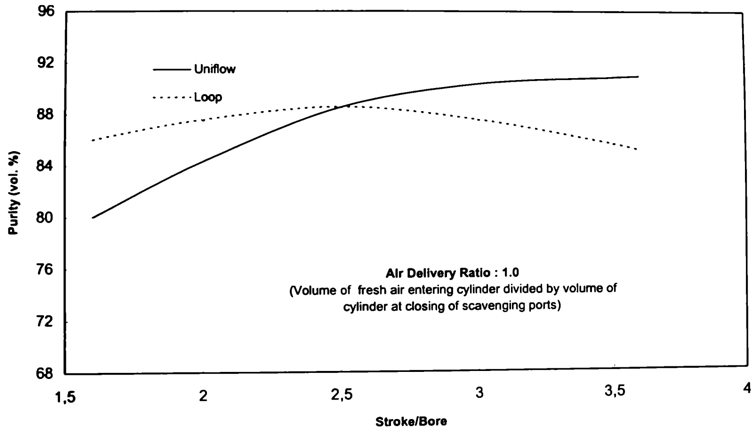



***Fig. 5.3 Influence of Stroke/Bore Ratio Scavenging Model Test***
*Source: Prof. Listewinik, J Ships Machinery Lecture Notes (1996)*

### 5.1.6 Bore Cooling Design Principle

The bore cooling principle is one of the most important techniques which used for today's engines. In order to achieve good performance of the engines, the engine manufacturers have designed the bore cooling system. Generally speaking, the bore cooling system can be applied to cylinder liner, piston crown and cylinder head.

This will keep the surfaces at safe temperatures. If the water is properly treated the scale formation will be avoided in the inner parts of the engine. The bore cooling concept allows the combustion pressure in the engine to rise hence increasing the engine efficiency.

$$\eta_{th} = 1 - \frac{T_L}{T_H} \qquad (5.1)$$

Where:

$T_H$: *High temperature during the cycle*

$T_L$ : *Low temperature during the cycle*

*Formula 5.1 expresses the thermal efficiency that can be achieved by use of the bore cooling principle.*

The more $\mathbf{T_H}$ increases the better the thermal efficiency of the engine, since the system is such that it allows the engine to withstand higher pressures and temperature and strains because the bore cooling can moderate these parameters.

### 5.2 Total System

The total system is reflected by the overall economy of the ship. It includes the improvements with regards to the main engine efficiency, and the related factors such as increasing the propulsion efficiency, exhaust gas temperature (waste-heat recovery), including main engine specific fuel consumption through shaft generators, propeller design and hull improvements. The above factors can be translated as the overall ship propulsion efficiency expressed by the following equation:

$$\eta_{Prop} = \eta_H \cdot \eta_{FRP} \cdot \eta_P \cdot \eta_{SH} \cdot \eta_g \cdot \eta_e \qquad (5.2)$$

Where:

$\eta_H$ : *Hull efficiency or hull factor*

$\eta_{FRP}$: *Free rotating propeller*

$\eta_p$: *Propeller efficiency*

$\eta_{SH}$: *Efficiency of the shaft line*

$\eta g$: *Efficiency of the reduction gear (if present)*

$\eta_e$: *Overall efficiency of the engine*

The $\eta_e$ can be expressed further as:

$$\eta_e = \eta_t \cdot \eta_i \cdot \eta_m \qquad (5.3)$$

$\eta_t$: *Theoretical efficiency*

$\eta_I$: *Indicated efficiency*

$\eta_m$: *Mechanical efficiency*

### 5.2.1 Power Recovering

The power recovering system is a principle widely employed in large propulsion plants in order to reduce the energy losses and, of course to lower the fuel consumption. It is known that marine diesel engines are machines which work through internal combustion, whereby each full cycle ends at the exhaust gas phase. The exhaust gases are discharged with temperatures ranging from 150 to 250°C for slow speed and 150 up to 350°C for medium speed with pressure ranging from 6 to 9.0 bars.

Following the principle of power recovering the designers found out that it could be possible to recover some of the energy of the exhaust gases. For example, about 12% of the energy is recovered by using the turbochargers. Generally, the turbochargers are really superchargers for supplying air for the engine. They are driven by heat from the exhaust gas which may otherwise be wasted or lost. Hence, not only is it possible to increase the boost air pressure through combustion efficiency, but it can be used for recovering heat from exhaust gas, and the overall thermal efficiency of the plant is also improved.

The effect of supercharging is to increase the air density in the cylinder allowing a proportionate increase in the fuel injected and thereby give a corresponding increase in power. For example, the Sulzer **RTA 62** engine with a Turbocharger Efficiency Booster (TEB) can be used for other applications as shown in figure 5.4.

The Efficiency Booster is a system which is applicable especially for the ***Sulzer RTA*** engine but generally it can be employed in all large diesel engines as well as medium speed engines.

This equipment is fitted in parallel with the engine turbocharger where it is directly connected with an exhaust gas pipe to recover the surplus energy.

When the engine is running at high load the flap installed in the exhaust gas pipe of the engine opens automatically giving access for the exhaust gas energy to operate the power turbine **BBNTC-4** thus converting the exhaust gases in mechanical power which is supplied to the engine through the crankshaft. If the load is low then the pressure of exhaust gases decreases, consequently the flap closes automatically. The turbine shaft is cobnected with **BBC Epicyclical** gear. The hydraulic coupling connects the turbine shaft, and the **BBC Epicyclical** gear with the power take off gear which is engaged with the crankshaft of the engine.

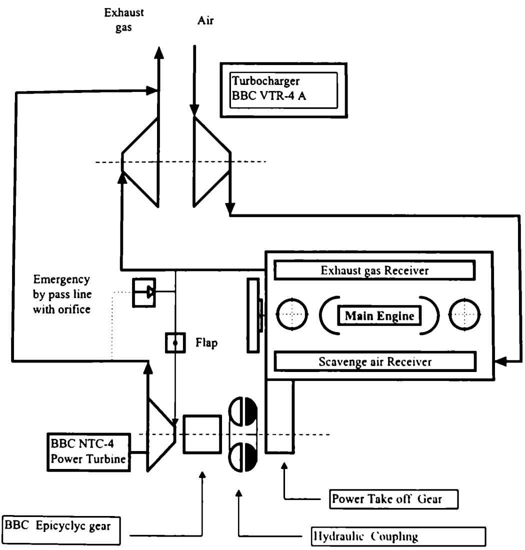



***Fig. 5.4 Turbocharger Efficiency Booster (TEB)***
*Source Prof. J.Listewinik Ships Machinery Lecture Notes (1996)*

Because of the sensitivity of this connection, closer tolerances for alignment are now specified in order to minimise wear of the resilient blocks in the elastic coupling. This system has proved to be consistent and saves energy in the range of 4% of the main engine output.

Apart from supporting the engine this system can alternatively be connected with a generator through a shaft or by a special coupling where the turbine will drive the generator to produce electricity power.

### 5.2.2 Shaft Generator (SG)

The shaft generator was one of the great achievements of improving energy management on board ship. To some extent this reduces the high fuel, personnel and maintenance costs. Generally speaking the shaft generator is an alternator which is directly connected to the crankshaft of the main engine or it can be connected via a gearing system. Since this equipment is engaged it will run simultaneously and produce a power supply.

The individual components comprising a shaft generator plant vary according to the arrangement of the main engine and its mode of operation. The most common feature is the three-phase AC synchronous generator driven from the propeller shaft.

There are two ways to connect the shaft generator with regards to the constant or varying speed of the shaft:

If the ship is propelled by a controllable-pitch propeller; the speed of the propeller shaft is mainly constant since there is no variation of the shaft speed. Hence, the generator speed necessary for the frequency of the supply system can be kept constant through simple, suitable gearing. For this arrangement, a parallel operation with an auxiliary diesel generator, there is no need of any extra automatic control device. Therefore, it is only possible for a short period when transferring load.

If the speed of the propeller shaft can vary within wide limits, like on ships with fixed-pitch propellers, a frequency converter will be needed to produce a constant supply-system frequency. With the actual capacity of most modern shipboard supply systems it is normal to use a static converter. Thus it is necessary to prove any generator speed matching. The shaft generator can run in parallel with auxiliary diesel generators. A mechanical-hydraulic constant frequency system (**RCF**) with a planetary gear also exists.

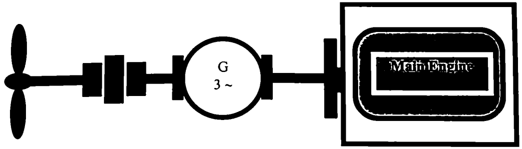
### 5.2.3 Physical Arrangement of Shaft Generator on Board

The positioning of the components of a shaft generator (SG) plant on the ship depends entirely on the designer, since he enjoys considerable freedom to place it. On the other hand, the shaft generator itself depends on the arrangement of the main engine and the propeller shaft.

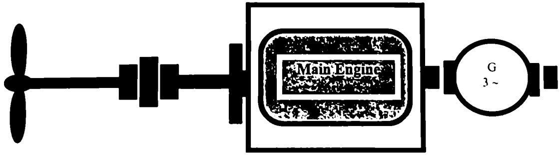
There are several alternatives for connecting shaft generators as mentioned bellow:

I) The shafting system between the maim engine and the propeller
II) The generator designed to be driven by the main engine through a flexible coupling system, separated from the propeller shaft
III) Shafting through gears with propelller shaft connected
Iv) Shaft through gear without propeller connected shaft

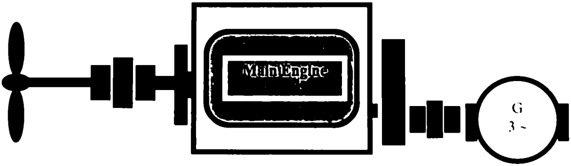
These alternatives employed for driving a shaft generator are illustraed in figure 5.4.



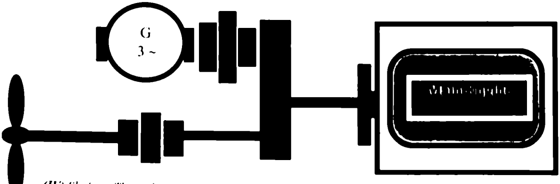

*(I) Shafting System Between Main Engine and Propeller Shaft*




*(II) Generator Designed to be Driven by the Main Engine through a Flexible Coupling System Separated from the Propeller Shaft*




*(III) Shafting Through Gears Without Propeller Shaft Connected*




*(IV) Shafting Through Gears with Propeller Shaft Connected*

***Fig. 5.4 Shaft Generator Arrangements***

*Source: Siemens (1996)*

### 5.3 Propeller

The propeller is defined as one of the most important parts of the ship propulsion plant, except some ships which are using other means of propulsion. In terms of working modes the propellers are classified in two main groups:

- Controllable pitch propeller
- Fixed pitch propeller

Over the years many types of propeller have been developed in order to improve their performance. These propellers are designed and constructed for various applications, and selection of the best technical solution depends on the particular applications. For example, a VCCL propeller cannot be applicable for high speed craft or frigate.

#### 5.3.1 Propeller Speed and Diameter

There is a strong relationship between the propeller size and the shaft revolutions. The propeller's efficiency is increased when its speed is decreased and the diameter increased.

The formula 5.4 expresses the propeller efficiency:

$$\eta_0 = \frac{TVa}{2\pi nQ} \qquad (5.4)$$

Where:

$\eta_o$: *Efficiency*

***T***: *Thrust*

***Va***: *Advanced speed*

***Q***: *Torque*

***n***: *Revolutions(rps)*

In addition to the previous equation, the relationship between the thrust and propeller diameter is given by the following formulas:

$$T = \rho A V (v_b - v_a) \tag{5.5}$$

$$T = \rho \frac{\pi}{4} D^2 V (v_b - v_a) \tag{5.6}$$

Where:

*V: velocity through the propeller*

*$v_a$: velocity ahead of the propeller*

*$v_b$: velocity behind the propeller*

*A: area of projected propeller*

*D: propeller diameter*

According to the below experiments, the results of different size propellers tested on a VCCL ship had the following characteristics: Engine power propulsion of 10,185 bhp; propeller speed of 82 rpm; propeller diameter 7.3 m; overall length 228.6m; width 32.24 m; draught 12.5m; dead weight 600,000 ton; service speed 14 knots. The trial was performed as follows are:

With a 7.3m diameter propeller at 80 rpm, the power required was 7,600 kW. When the diameter was increased to 8.5 m, the speed was reduced to 60 rpm., and the power required was 7,273 kW, giving 4.3% of power saving. When the propeller diameter was further increased to 10.3 m, the speed was reduced to 40 rpm. with a further reduction on power required of 640 kW, giving a final power saving of 15.6%. To sum up we can say that with a bigger size propeller and slow running propeller the efficiency of the propeller improves significantly.

**5.3.2 New Propeller Design to Achieve Efficiency**

As far as propulsion efficiency is concerned, the propeller manufactures have devoted a lot of efforts on experimenting and research which have resulted in a number of different propeller types of higher efficiency. With regards to the propulsion efficiency it is worth mentioning that the relationship between the wake and relative efficiency can be expressed by the formula 5.7

$$\eta_o = (1 + W_F)(1 - t) \cdot \eta_R \cdot \eta_o \qquad (5.6)$$

*$\eta_O$: Propeller open efficiency*

*$\eta_R$: Relative rotative efficiency*

*$t$: Thrust deduction*

*$W_F$: Wake*

There are a number of design changes, that have been carried out in the stem of the vessels namely:

- Semi-duct design
- Inclusion of the propeller flow arresting vanes and shrouds
- Introduction of the vane wheel design
- Redesigning of the propeller

The propeller efficiency can be improved by many factors that indirectly influence propeller efficiency. Therefore, the propeller efficiency philosophy is based on the so-called Quasi propulsion efficiency and the engine factors. The hull form and its weight, the aftership contour and the asymmetrical after ship of Nönnecke are significant parts for achieving good propeller efficiency.

### 5.3.3 Types of Propellers

Over the years many type of propeller have been introduced as attempts to improve the efficiency of propulsion and reduce fuel oil consumption on board. In this section some types of propeller arrangement will be addressed as a complement of the whole chapter.

**i) Contra Rotating Propeller (CRP)**

Propulsive gains of up to 15% are claimed for contra-rotating propellers. Prolonged trials have been completed by the Japanese company Ishikawajima- Harima Heavy Industry (IHI). The contra rotating propeller, is composed of two coaxial propellers positioned one behind the other and rotating in opposite directions.

This has been traditionally associated with the propulsion of aircraft. The advantage of the contra rotating propulsion system is the hydrodynamics using the ship's stream rotational energy that would otherwise be lost with a conventional single screw system. Furthermore, because of the two configurations, the contra rotating propeller possesses a capability for balancing the torque reaction from the propulsion.

In marine applications of contra-rotating propulsion it is also normal to consider the aftermost propeller to have a smaller diameter than the forward propeller and in this way accommodate the slipstream contra-rotating effects.

This system has been a subject of experiments and research. It has proved to be one of the efficient systems which can recover energy savings of 10 to 14%. The loads of both propellers are reduced and the efficiency is improved by the necessary thrust being shared by the propellers. Due to the satisfactory results, this system has been already fitted to a 37,000 dwt bulk carrier, and subsequently to a 258,000 dwt VLCC four years ago.

**ii) The Spanish Designed CLT Propeller**

The CLT propeller was conceived by the Spanish specialist G. Perez Gomes and developed by Compania Auxiliar de Navegacion. This type of propeller achieves a special radial circulation (distribution law), thus it is loaded and designed to adapt to the fluid vein crossing its disc.

The propeller tip is fitted with end plates which create an appreciable pressure difference between the pressure end suction side of the propeller, thus achieving high efficiency.

**iii) Grim Vane Wheel**

The grim vane wheel propeller has been in service for the largest period of time. This unit was manufactured by the West German company Schalfran propeller Lehne & Co. The system consists of a free rotating turbine-like propeller element which is mounted aft of the ship's main propeller.

The inner turbine parts extract from propeller slip stream a large amount of wasted energy that would be directly converted into useful thrust by the outer turbine parts of the wheel thus resulting in energy saving and reducing power required for a given speed. According to researdh work developed in a vessel by the Schafran company in 1980, it has recorded fuel savings of 9% per year.

**iv) Mitsui Integrated Duct Propeller (MIDP)**

The MIDP propeller was designed by the Japanese manufacturer. The system consists of locating a duct in an asymmetric configuration constituting an integral part of the ship's hull resistance and at the same time, a propulsion force is generated by the duct itself, thereby the efficiency of the propeller is increased because of the overall propulsion efficiency. For instance, in the case of a VLCC up to 5% of fuel cost savings had been verified. However, it depends on ship type, speed and laden conditions.

### 5.3.4 Hull Efficiency ($\eta_H$)

The hull efficiency is among the others affected by the after ship contour design. The hull efficiency is defined by the following formula:

$\eta_H$ = Effective horsepower/ Thrust horsepower

$$\eta_H = \frac{1-t}{1-w} \qquad (5.6)$$

Where $t$ and $w$ mean thrust deduction coefficient and wake friction, respectively. According to the formula the efforts for increasing $\eta_H$ are achieved by decreasing the thrust deduction coefficient $t$ and the wake friction.

Hull efficiency is also achieved by controlling the flow of the aft wake. It is known that when the propeller is rotating, eddy currents are produced around the wake area. These produce resistance thus resulting in an uneconomical running of the vessel. Hull efficiency was raised by better shaping of the hull forms- bulbous bow, for instance the development of the low viscosity (LV) hull form where in practical use the bulbous were part of bow section is removed for reducing the viscous resistance generated at the bulb part.

Self-polishing type, anti-fouling parts provide a good maintainability for smooth surface conditions of the painted coat under the system that the paint coat dissolves by itself through hydrolysis on coming into contact with sea water while dissolving the anti-fouling agent always leaving a smooth surface. When paints of this type are applied, the ageing effect of deterioration on the surface roughness can be controlled, and in the long run , a fuel cost saving effect of 10%.

The reduction in hull weight is also an important factor, since the use of high tensile steel will greatly contribute to the improvement of propulsion efficiency and energy-saving achievements. Once the hull weight is reduced more carrying cargo capacity and less power demand for the engine in unloaded conditions is required.

### 5.3.4 Other Alternatives for Raising Efficiency

Apart from designing propeller aspects, the efficiency can rise by controlling the undue growth of hull and propeller surface roughness that effects the propeller and hull efficiency. Thus polishing propeller blades and by preventing the increase in surface roughness of propeller blades due to corrosion though the provision of the external power supply system, the propulsion efficiency can be maintained at a high level with a resultant fuel cost saving of about 3%.

# Chapter 6

## 1. Summary and Conclusions

Looking at the past and future, we obviously find that fuel oil has become the backbone of the global industry as the main source of energy particularly in the shipping business. It is credible and predicted that the shipping industry will continue to rely on this kind of energy in the foreseeable future.

As described in chapter two, crude oil has its typical characteristics and properties. It varies according to the differences concerning the origin. Therefore, for the finished product, which in this case is fuel oil onboard ships, it cannot have the same composition after being refined although improvements in the refining processes have been taking place with the application of advanced technologies. Due to the reasons stated above, difficulties still remain in how to get fuel oil with the same characteristics.

The intensive refining process will always constitute serious problems, for low grade oil users, since its quality had been progressively declining. To tackle this problem of low grade oil the new technology introduced by Alfa Laval and Westfalia for onboard treatment has played an important role in the shipping industry. However, the problems with regards to the fuel quality cannot be totally overcome only with onboard treatment. This is because fuel equipment is bound to have some limitations since it is only effective for removing solids particles and water to a certain extent. Because of this reason, the ideal solution would be the use of clean-oil to slow down all these problems brought about by the use of heavy fuel oil such as engine parts wear and the emissions to the environment.

The problems between the multi-national companies and the OPEC countries, led to a world wide economic disaster, in the 1970s popularly called the *oil crises*. As a result, many events have taken place in the shipping industry since 1974. For instance, a lot of efforts that have been made over the years by the shipbuilders and engine manufacturers in order to reduce specific fuel consumption have been successfully accomplished.

As discussed in chapter five, it is the concern of engine designers and shipowners to reduce fuel oil consumption and to turn the engines to operate economically. Fortunately, a number of alternative solutions were found throughout the 1980s and improvements are still being carried out. For instance, the uniflow scavenging principle in association with stroke bore/ratio was introduced. The comparison made in figures 5.2 and 5.3 shows clearly the prominence of the uniflow scavenging principle compared to loop scavenging. This means that better results in terms of performance of the engine can be achieved with the uniflow scavenging principle. Therefore, today, the uniflow scavenging principle, due to its distinguished efficiency when applied in engines, is becoming very popular with engine designers and manufacturers for slow speed engines.

Apart from the scavenging principle, variable injection timing (VIT) came to optimise the combustion into the cylinder, specially with the use of low graded fuel oil. In addition it does reduce the specific fuel oil consumption. However, one of the drawbacks in this matter for now is the maximum pressure (Pmax) cannot be increased any more.

Auxiliary equipment connected with engines like Turbocharger Efficiency Booster (TEB) and Shaft Generators (SG) influence to some extent energy savings onboard ship.

According to the research made with different sizes of propellers and the variation of the engine speed, the conclusion reached was that; with bigger propeller diameter and low revolutions per minute, the efficiency of the ship is increased.

The market is flooded with a wide range of different types of propellers. Although all have their particular performances the difference of propeller efficiencies among them may be negligible. However, the water jet propulsion system may come to replace the variety of propellers in the future for small and high speed craft.

The most remarkable concept is that all the factors that are mentioned above when combined, provide an optimum overall ship efficiency and total energy savings are greater increased.

However, a look to the future by asking questions if there are any future implications in the development of shipping industry is productive:

- The association of higher viscosity, higher specific gravity and higher levels of ash, sulphur content and sludge will definitely present particular problems for the fuel oil treatment system on ships and the engine itself. Consequently, fuel quality is decreasing, and it will remain decreasing thus maintenance demands will also increase as time goes by.

- Emission of SOx and NOx will require a search for more rejuvenation of the engines and the setting of strict laws, in order to enhance the degree of environment protection.

- More sophisticated cleaning equipment will be required in the future to respond to the decline of fuel quality.

- Due to this chain of problems such as economic, environmental protection and the need for reliable engines and boilers, the designers will be committed to continue their research in the development of engines and boilers that can withstand a wide range of variation in fuel oil quality with less emissions.

In considering possible solutions in this area and particularly the environmental aspects, it must be bearing in mind that in order to keep the environment clean and healthy, it will cost money. However, it would be convenient if all shipowners would apply either primary or secondary measures to reduce the level of harmful substances into the atmosphere. Therefore, the financial factor constitutes a drawback since most shipowners are looking only to obtain good revenues rather than being concerned about the environmental issues. However, it is now time to change the mentality of people.

The outstanding idea would perhaps be a co-operative alliance between the oil industry and the engine and boiler manufactures in order to optimise the quality of fuel and equipment including the operational procedures onboard ships. On the contrary, the fuel treatment designers should develop equipment with improved cleaning efficiencies or the engine designers will have to make engines with higher capacity to stand up to the bad quality of fuel.

Finally, experiments and research should be continuously exercised for better performance and economic operations of the engines and other related equipment for fuel consumers. This should be the most valuable tool in developing successful achievements in solving fuel oil problems in our beloved society for the present and the future.

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