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SHORT INTRODUCTION ON PRESENT DESIGN AND TRENDS REGARDING ENERGY EFFICIENCY IMPROVEMENT ON LARGE CRUDE OIL TANKERS

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Abstract: This paper covers some aspects regarding present technology used in large crude oil carriers design and operation, as well as requirements regarding energy management on board. Obviously, due to complexity of such subject, there cannot be an exhaustive presentation. It is intended as a mere starting point for further discussion and research regarding possibilities to improve vessel's general energy efficiency, including ways of using non-conventional and renewable energy, with due regard to specific trading routes involving large oil tankers. Some practical figures achieved typically on a Very Large Crude Oil Carriers engaged in international voyages are presented. A brief explanation on Energy Efficiency Index (EEI) and Carbon Conversion Factors (CF), as accepted by IMO, is also included. Work may be continued with further theoretical research in energy efficiency improvement on board such vessels. The article is structured in five parts: Introduction, Main Particulars of Large Tankers, Oil Tankers Outfitting, Energy Management Plan and Conclusion.

Key words: Carbon, Efficiency, Energy, Management, Oil Tanker, VLCC

1. INTRODUCTION

Some maritime disasters resulting in large oil spills and public outrage, like Torrey Canyon (1967), Amoco Cadiz (1978), Exxon Valdez (1989), Prestige (2002), have triggered significant changes as of building, maintenance, inspection and operation of oil tankers, especially the larger ones.
New regulatory requirements have been introduced as follows: [9]; [10]:

- Double skin in the way of cargo oil and bunker oil tanks.
- Limitation of each individual cargo oil tank volume with the aim of reducing most probable discharge in case of a marine casualty involving bulkhead(s) rupture and loss of hull integrity.
- Requirements in regard of corrosion protection of the ship's structure, especially in the cargo oil tanks and water ballast tanks area.
- New rules for structural design and material certification.
- Requirements for structural inspection during vessel's operational lifetime in order to verify its hull and structural integrity.
- Promoting best practices in regard of vessel's operation.
- Requirements for thermal engines fitted and fuels used in order to reduce release to atmosphere / environment of carbon monoxide, carbon dioxide, nitrogen and sulphur oxides, etc.
- Improved equipment and installations with the aim of avoiding release to atmosphere of volatile organic compounds, hydrogen sulphide and ozone depleting substances.
- Ballast Water Treatment in order to avoid transfer of marine invasive species.

In line with above, Industry is encouraged to explore new methods and research directions in regard of fossil fuels reduction, usage of alternative technologies and power sources, as well as improvement of ships general energy efficiency in order to reduce overall environmental footprint.

With reference to energy efficiency improvement, following topics are taken into account:

- Hull optimization in order to reduce drag.
- Energy economy by use of miscellaneous devices designed to increase propeller efficiency, reduce of hull drag, etc.
- Usage of renewable energy (wave, wind, solar).
- Structural optimisation and overall lightweight reduction by using modern design and new materials.
- New design of the entire outfit on board in order to increase energy efficiency (main and auxiliary engines, residual heat economisers,

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cargo and ballast handling systems, refrigeration, air conditioning, hydraulic power packs, etc.
- Energy Efficiency Management during operation.
- Route Management and Optimization.

2. MAIN PARTICULARS OF LARGE CRUDE OIL CARRIERS (SUEZMAX AND VLCC)

Design and outfitting of oil tankers are based on regulatory, technical and commercial requirements. Regulatory and technical requirements are established by IMO, Maritime Government Administrations, Classification Societies, etc. Commercial requirements may vary with the needs of actors involved such as Ship-owners, Oil Majors, Traders, Shipyards, etc.

Most common large tankers engaged in oil transportation on medium and long distances are typically named Suezmax and VLCC.

Suezmax

Suezmaxes are designed to comply with Suez Canal restrictions in regard of maximum transit draft in fully laden condition. They are generally used for medium and long haul of crude oil, less often residual fuel oil and very occasionally refined petroleum products. Their typical carrying capacity is about 1,000,000 barrels. Usual dimensions: Length Over All = 270 meters; Beam = 48 meters, Summer DWT = 150,000 – 180,000 MT

Figure 1 Suezmax vessel at Kakinada Anchorage, India. (*Source: Author's personal archive*).

Very large crude carrier (VLCC)

VLCC's are large tankers typically engaged on long and very long distances transportation of crude oil, very occasionally fuel oil. Their typical carrying capacity is about 2,000,000 barrels. Usual dimensions: Length Over All = 340 meters; Beam = 58-60 meters, Summer DWT = 300,000 MT (approximately). Normally this kind of vessel cannot access most majority of the world ports, except certain Oil Terminals specially designed for this size.

Figure 2 VLCC during Ship To Ship crude oil transfer operation to a Panamax size vessel in the Gulf of Tonkin (*Source: Author's personal archive*).

General layout of an Oil Tanker.

An Oil Tanker typical compartmentation consists of:
- Cargo Oil Tanks Compartment
- Water Ballast Tanks Compartment
- Cargo & Ballast Pumps Compartment (Pump Room)
- Engine Room
- Steering Gear Room
- Navigational Bridge
- Cargo & Ballast Control Compartment (Cargo Control Room)
- Living and Social Spaces Compartment.

As an example, below are given main particulars of a VLCC. Worth to mention that other larger or smaller size Oil Tankers fitted with centrifugal Cargo and Ballast Pumps (Panamax, Aframax, Suezmax, ULCC) have a similar design and outfitting.

Ship's Particulars:
- IMO No.: 9312511
- LOA: 332,848M
- LBP: 320,00M
- Beam: 58,00M
- Design Height: 31,00M
- Draught (summer): 22,70M
- DWT (summer): 307284
- ME Power: 29400KW@76rpm
- Max Speed: 16.58 Kts
- Building Shipyard: Dalian, China
- Year of Build: 2007

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3. BRIEF PRESENTATION ON OIL TANKERS OUTFITTING

In terms of their role in the operation of the ship, installations on board an oil tanker may be classified as main propulsion, steering, power generating installations, support installations and specific operating installations (cargo, ballast, inert gas systems).

3.1 Propulsion plant

The propulsion installation is intended to provide mechanical energy to the movement of the ship in a longitudinal direction. In modern oil tankers, it consists of the main slow diesel engine, shaft and propeller. The propeller force depends on a series of parameters: diameter – D, number of blades – Z, tilt of the propeller axis, step – p, propeller speed – n, etc.
Propulsion force in the direction of the axle [6]:

$$F = \rho n^2 D^4 (1 - t) K_F \left(J, \frac{p}{D}\right), \tag{1}$$

where:

t - push reduction fraction due to the influence of the hull;
J - thruster advance (v – axial speed, w – scale factor).

$$J = \frac{v(1-w)}{nD} \quad , \tag{2}$$

p/D – pitch coefficient.
During operation, a lateral force and a moment of torsion occur:

$$M = \rho n^2 D^5 K_M \left(J, \frac{p}{D}\right). \tag{3}$$

3.2 Steering system

Steering gear is designed to keep the ship in the direction of travel, as well as to ensure the necessary course changes by means of a rudder driven by an electro-hydraulic system. The rudder behaves like a small wing that generates a force and a moment of yaw that allows the ship to steer. On large oil tankers it is used normally a hydraulic actuated, semi-balanced rudder.
The approximate expressions of the steering force and the moment are [6]:

$$F_y = C_y \frac{\rho v^2}{2} S; \tag{4}$$

$$M_Z = C_y \frac{\rho v^2}{2} S \frac{L}{2}, \tag{5}$$

where: S – rudder area, L – ship's length, C_y – the lift coefficient.

3.3 Support installations

- *The power-generating facility* has the role of providing the necessary energy for the operation of all the electrical equipment on board.
- *The electricity distribution installation* has the role of ensuring the transmission of electricity to consumers through distribution panels, command/control panels and electrical circuits. Electrical circuits can be force circuits for three-phase current that supply large consumers (electric motors), remote control circuits or domestic circuits (lighting, single-phase current sockets, etc.).
- *The steam production plant* has the role of providing the necessary steam to heat and maintain the heavy fuel at the temperatures necessary for transfer, purification and combustion, to operate the steam turbines, to heat the cargo compartments, to heat the social and residential compartments, to protect some installations exposed to frost in winter. On board large tankers this plant is oversized due to main pumps fitted on cargo and ballast systems are normally high capacity centrifugal pumps driven by steam turbines.
- *The installation for the generation of inert gas and ventilation of cargo tanks* is designed to ensure that an atmosphere that does not allow combustion is maintained inside tanks and cargo piping, due to its too low oxygen content (less than 8%), as well as an atmosphere slightly positive from the atmospheric one (approximately 200-1400 mm water column), in order to prevent the infiltration of atmospheric air into the inert atmosphere in the event of possible leaks of the installation.

3.4 Cargo and ballast systems

On board oil tankers these systems have the role of handling liquid oil cargo and water ballast, respectively. They generally consist of single stage centrifugal pumps, piston pumps and ejectors. Typically, cargo system on a VLCC is fitted with 3 cargo oil pumps with a capacity of about 5500 cubic meters / hr each, 2 cargo stripping ejectors of about 500 cu meters / hr each and 1 steam driven reciprocating piston pump with a capacity of about 150 cubic meters / hour, while ballast system has 2 water ballast pumps with a capacity in the range of 3000 cubic meters / hr each and 2 ballast stripping ejectors of about 300 cu m/hr each. It is a common practice that such centrifugal pumps are lined up to work in parallel.

4. SHIP'S ENERGY EFFICIENCY PLAN

In July 2011, IMO adopted the concept of The Energy Efficiency Index of Ships (EEDI), which regulates the minimum energy efficiency criteria of new ships built after 2013. It is determined according to

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carbon dioxide emissions per ton-mile of cargo transported. Through the global adoption of EEDI, it was

aimed at increasing the energy efficiency of ships by 10-30% between 2013 and 2025. The improvement of the Energy Efficiency Index of Ships has induced the need to develop a Management Plan regarding the energy efficiency of the ship.

The Energy Efficiency Management Plan is prepared in accordance with MARPOL Annex VI, Regulation 22.2[10] and IMO MEPC Resolution. 282(70) / 2016 – Guide for the elaboration of the Ship's Energy Efficiency Management Plan [10].

The plan consists of two parts:

- Part I – Establishing a mechanism to improve the energy efficiency during the operation of the ship.

- Part II – Collecting fuel consumption data.

Methods to improve energy efficiency - IMO MEPC. 282(70) are [10]:
- Optimal voyage planning - IMO Resolution A.893 (21) [10]
- Hydro meteorological assistance of navigation
- Speed optimization for timely arrival in the destination port
- Optimization of the power used for propulsion
- Optimization of the ship's manoeuvre.
- Optimization of the amount of ballast used
- Maintenance of the hull
- Maintenance of the main propulsion system
- Recovery of waste heat
- Improving fleet management
- Improvement of operational procedures for cargo handling.
- Energy management on board the ship
- Optimization of the type of fuel used to reduce CO_2 emissions
- Optimization of computer-aided consumption
- Use of renewable energy sources (wind, solar, photovoltaic).
- Use of wind-assisted propulsion.

The Ship Energy Efficiency Management Plan (SEEMP) is a measure which establishes a mechanism of energy efficiency improvement on board ships at acceptable costs. It is designed to assist ship's operators in monitoring energetic performance of every individual ship and of entire fleet as a whole, over a certain period, introducing the concept of Energy Efficiency Operational Indicator, (EEOI). EEOI is intended to assist operators in monitoring energy efficiency and encourage improvement of energetic performance due to better conditions in vessel's operation such as: better voyage planning, hull cleaning & propeller polishing, fitting of improved residual heat recovery equipment, etc.

Such SEEMP do encourage owners and operators to consider new technologies and practices for overall energy performance improvement on ships.

According to the IMO MEPC Resolution. 282(70) / 2016 [10], the calculation of the Energy Efficiency Index (EEI) is conceptually based on the formula:

$$EEI = ECO2 / (M \times D). \tag{6}$$

where CO_2 emissions (ECO_2) are expressed in grams, M is the transported mass expressed in metric tonnes and D is the transport distance expressed in Nautical Miles.

CO_2 emissions (ECO_2) over an hour (h) may also be expressed as the product of the amount of fuel consumed in an hour (FCH) and the carbon dioxide (CF) conversion factor, i.e. the amount of CO_2 resulting from the combustion of a unit of fuel

$$ECO_2 \times h = FCH \times CF. \tag{7}$$

Fuel consumption per hour (FCH) can also be expressed as Machine Power (MP) multiplied by the specific fuel consumption (SC) expressed in grams per kilowatt hour

$$FCH = MP \times SC. \tag{8}$$

Replacing fuel consumption per hour (FCH) in (9) results in:

$$ECO2 = MP \times SC \times CF. \tag{9}$$

Replacing CO_2 emissions (ECO_2) in (8) results in:

$$EEI= (MP \times SC \times CF \times h) / (M \times D). \tag{10}$$

In other words:

$$EEI = (MP \times SC \times CF) / (M \times V) \quad [g\ CO_2 / (Tone \times Mm)], \tag{11}$$

where V is the speed of the vessel expressed in knots.

If it is conventionally considered that the useful mass carried in tonnes M is equal to the nominal deadweight of the vessel, then it can be written in the following form:

$$EEI = (MP \times SC \times CF) / (DWT \times V)\ [g\ CO_2 / (TDW \times Nm)]. \tag{12}$$

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As can be seen from eq.(11) and (12), a ship is overall the more energy efficient as the Energy Efficiency Indicator (Index) is lower.

Another approach of leading international experts (Rightship Organisation, Carbon War Room) is to calculate the energy efficiency of an existing vessel using the existing data on the consumptions of a particular vessel.

The EEOI (Energy Efficiency Operational Index) is based on the IMO's methodology for calculating the EEDI (Energy Efficiency Design Index). The main difference between EEDI and EEOI relates to the way of collecting consumption data. While EEDI data is made available by classification societies and refers to a new vessel at the time of commissioning, the data for the calculation of the EEOI are calculated retroactively for existing vessels using the data available from ship-owners, charterers, shipyards, etc.

However, the actual formula for calculating the EEOI for an existing vessel has not been made public by the initiators. The differences refer to the calculation of the fuel consumption (theoretical or real) and to the transport capacity (constructive or actually used DWT of the vessels).

In conclusion, the above approaches lead to the calculation of carbon emissions in grams per tonne and nautical mile (g/TNm) and are related to the transport distance and the quantity of cargo transported.

For reference, the carbon dioxide conversion factors (CF) for different types of fuels are given in below Table 1:

Table 1. The CF (t-CO_2/t-Fuel) certain value at each type of fuels.[10]

Fuel Type	Reference	Carbon content	CF (MT CO2/MT Fuel
Diesel Oil	ISO 8217	0.8744	3.206
Light Fuel Oil	ISO 8217	0.8594	3.151
Heavy Fuel Oil	ISO 8217	0.8493	3.114
LPG	Propane	0.8182	3.000
LPG	Butane	0.8264	3.030
LNG		0.7500	2.750
Methanol		0.3750	1.375
Ethanol		0.5217	1.913

Source: IMO, Ship Energy Efficiency Regulations and Related Guidelines, Module 2

Proceeding on sea voyages

- The sea passage of the ship is carried out at an economic speed, consistent with the planned operation date.
- The navigation route is chosen by the Master, based on the available hydro-meteorological information, usually in consultation with a specialized shore based meteorological office appointed by the shipping company.
- It is decided whether some maintenance and repair operations are required, as well as supply of fuels and materials.
- Cargo tanks preparation is made for the next cargo, depending on the cargo previously transported.

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Table 2. Fuel Oil consumption in MT/24 Hrs on a VLCC (307284 TDW), build in 2007, in laden condition with a mean draft of 21.0 M, in good weather ≤ BF 5. Total daily consumption figures rounded to the nearest MT, for more clarity.

Speed (Kts)	ME Power (Kw)	Rpm	Load % MCR	Specific Consumption FO for ME (g/kwh)	ME FO Consumption (MT / 24 hrs)	AE FO Consumption (MT / 24 hrs)	Total Cons. (MT / 24 hrs)
8	7391	49,4	25,1%	200,0	35,5	5,5	41
8,5	8015	50,8	27,2%	199,5	38,4	5,5	44
9	8684	52,2	29,5%	198,9	41,5	5,0	46
9,5	9405	53,6	32,0%	198,4	44,8	5,0	50
10	10183	55,1	34,6%	197,8	48,3	4,5	53
10,5	11023	56,6	37,5%	197,2	52,2	4,5	57
11	11934	58,2	40,6%	196,6	56,3	3,5	60
11,5	12921	59,8	43,9%	196,1	60,8	3,5	64
12	13993	61,4	47,6%	195,5	65,7	3,5	69
12,5	15160	63,1	51,5%	195,0	70,9	3,5	74
13	16431	64,9	55,8%	194,5	76,7	3,5	80
13,5	17817	66,7	60,6%	194,1	83,0	3,5	86
14	19331	68,6	65,7%	193,8	89,9	3,5	93
14,5	20986	70,5	71,3%	193,6	97,5	3,5	101
15	22797	72,5	77,5%	193,6	105,9	3,5	109
15,5	24781	74,6	84,2%	193,8	115,2	3,5	119
16	26957	76,8	91,6%	194,3	125,7	3,5	129

Table 3. Fuel Oil consumption in MT/24 Hrs on VLCC (307284 TDW), build in 2007, in ballast condition with a mean draft of 9.5 M, in good weather ≤ BF 5. Total daily consumption figures rounded to the nearest MT, for more clarity.

Speed (Kts)	ME Power (Kw)	Rpm	Load % MCR	Specific Consumption FO for ME (g/kwh)	ME FO Consumption (MT / 24 hrs)	AE FO Consumption (MT / 24 hrs)	Total Cons. (MT / 24 hrs)
8	4542	42,0	15,4%	202,8	22,1	7,5	30
8,5	5010	43,5	17,0%	202,3	24,3	7,0	31
9	5528	44,9	18,8%	201,8	26,8	6,5	33
9,5	6103	46,5	20,7%	201,2	29,5	6,0	35
10	6739	48,1	22,9%	200,6	32,4	5,5	38
10,5	7443	49,7	25,3%	200,0	35,7	5,0	41
11	8224	51,4	28,0%	199,3	39,3	5,0	44
11,5	9089	53,2	30,9%	198,6	43,3	4,5	48
12	10047	55,1	34,1%	197,9	47,7	4,5	52
12,5	11108	57,0	37,8%	197,2	52,6	3,5	56
13	12283	59,0	41,7%	196,4	57,9	3,5	61
13,5	13586	61,0	46,2%	195,7	63,8	3,5	67
14	15028	63,1	51,1%	195,0	70,3	3,5	74
14,5	16626	65,3	56,5%	194,4	77,6	3,5	81
15	18397	67,6	62,5%	193,9	85,6	3,5	89
15,5	20358	70,0	69,2%	193,6	94,6	3,5	98
16	22530	72,5	76,6%	193,5	104,7	3,5	108
16,5	24937	75,0	84,8%	193,8	116,0	3,5	119
17	27603	77,6	93,8%	194,5	128,8	3,5	132

Source for Tables 2 & 3: Vessel's shipyard documentation and on board records.

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5. CONCLUSION

Design, building and operation of oil tankers are based upon several decades' old technology and are subject to regulatory, technical, financial and commercial constraints. Despite ongoing technological progress which led to improved electronically controlled engines, better specific fuel consumption, stricter environmental standards, etc. a major breakthrough in regard of vessel's design, operation, materials, installations, cargo and ballast (sea water) handling has not been achieved.

Energy efficiency is a paramount characteristics of an oil tanker from the regulatory, specific equipment, operation, and commercial point of view. Most of the specific operations like loading, discharging, and cargo oil tanks preparation result in release to atmosphere of certain quantities of hydrocarbons and hydrogen sulphide, instead of same being utilised to generate additional energy on board or at shore based facilities. Moreover, the larger the tanker, the larger the quantities involved.

During ballast passages, oil tankers need to carry a quantity of sea water ballast amounting to about 30 % of their nominal transport capacity (Deadweight), which require additional energy consumption. Moreover, such ballast needs to be loaded, treated and discharged using supplementary amount of energy. Not to say that such installations needed to handle the ballast water are an added weight to the lightship.

Research regarding energy efficiency improvement cannot and should not be limited to improved propulsion and on board energy generation, as an example. A real breakthrough can be achieved only by an interdisciplinary approach in regard of design, construction, operation, maintenance and recycling of the vessels at the end of their operational lifetime. Energy efficiency question should not be limited only to how much energy would be needed to transfer this much cargo from point A to point B over these much Nautical Miles. In a larger view question may be raised on how much energy would be necessary to build, carry a certain total amount of cargo over a certain total sea distance during a certain scheduled operational life time and then recycle the vessel.

Following points may be of relevance when attempting to follow above quest:

- Using of new materials for hull, superstructures and installation building in order to reduce lightweight.
- Radical changes in ship's design which will permit substantial reduction or total elimination of sea water ballast carriage needs. This may reduce the size / eliminate ballast water handling installation, further reducing vessel's lightweight.
- Investigating the possibility of operating the vessel in non-displacement or partly displacement mode when in light condition.
- Using of renewable / non-conventional energy for main propulsion, to boost main propulsion, to generate additional energy for on board installations or as a mean of emergency propulsion / steering in extraordinary circumstances.
- Using of residual cargo vapours to generate additional power
- Using of variable geometry elements in building the hulls and superstructures.

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