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Influence of Hull Condition on Ship Emission: Study Case of a Panamax Vessel

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Abstract. *This paper analyzes the case of an oil tanker vessel, class Panamax, belonging to Petrobras Transporte S.A. fleet, observing the fuel oil consumption of the main engine, before and after hull treatment. Investigations were conducted based on main engine performance, daily report of fuel oil consumption and energy efficiency regulations and guidance, in order to calculate the ship emission. The main results show that the treatment of the hull provides a significant reduction on the consumption of fuel oil, thus reducing the ship emission. The research also identifies the financial savings resulting from cleaning and painting of the hull.*

Keywords: *ship, hull, fuel, emission, EEOI*

1. INTRODUCTION

The shipping industry presents less contribution to emissions when compared to others modes of transport. Studies have shown that sea transportation can lead to less CO₂ emission for certain regions (Chang, 2017), which can be globally expected. Additionally, ships have also reduce their participation on atmospheric pollution, mostly due to several improvements on ship design, including cargo carrying capacity, alternative type of fuel being used and engine performance (Zurawski, 2017; Turbo, 2004). However, greenhouse gas (GHG) emission and particles matter are still a major concern for environmental impacts (IMO, 2009a) and thus need to be addressed.

International Maritime Organization (IMO) has been playing a significant role on the control and reduction of environmental impact consequence of ship emissions, setting challenging goals and limits for the following years. Furthermore, the Marine Environment Protection Committee (MEPC) released documents providing ways to achieve the limitation and reduction of GHG coming from ship in operation (IMO, 2009a).

The oil consumption is the largest merchant operating expense. Fuel economy is the key to make transport more competitive. The experiments results discussed in this paper provide valuable knowledge aiming at the energy efficiency.

Estimated the cost with combustion to generate sufficient energy to overcome the resistance acting on the hull and move the ship represent between 50% to 70% of the total cost of operation (Rehmatulla and Smith, 2015). For this reason, maritime transportation aims to reduce the effects of friction resistance on the surface of the hull, hence representing a lower operational cost and providing less GHG emission.

Petrobras Transporte S.A. (Transpetro) is a big logistic company from Brazil, acting on the transportation of oil and gas by pipeline and over the oceans and seas. Transpetro has an important maritime department, possessing several vessels to transport oil and gas to and from the Brazilian coast, as well as worldwide.

For this research, a Panamax oil tanker performed an international route going from and to Brazil, passing by the Canary Islands. In between voyages, the vessel was subjected to hull cleaning and painting during a small period dry-docking. Considering that the vessel did the departure voyage in adverse hull condition with a significant extra resistance due friction and went back to Brazil after hull treatment, it is possible to compare: the fuel savings; the GHG emission; and the costs between departure and return voyage.

Before the departure voyage, the main engine of the Panamax ship was already running overloaded for the load diagram. Then, an underwater inspection was requested and carried out to verify the hull condition. It was observed that

the hull condition was requiring cleaning and painting, in order to reduce the frictional resistance.

2. METHODOLOGY

In order to arrive at a solution that is as optimal as possible, some general knowledge is essential, such as hull design of a ship, main diesel engine parameters and total resistance that influence the propulsion system. The engine parameter was evaluated through a home made main engine software made and owned by Transpetro, which will be explained in details on the full paper; all operational indicators were collected and used to support the maintenance. The data used for the calculations and considerations in this work was based on noon logbook reports performed by crew.

Some assumptions can be cited, such as: it was not considered the weather and sea influences.

2.1 Basic Theory of Ship Resistance

To move a ship, it is first necessary to overcome resistance, *i.e.* the force working against its propulsion. The calculation of this resistance R_T presents a important role in selection of correct propeller and the subsequent main engine choice. Resistance of a ship is highly influenced by its speed, displacement and hull form. The total resistance R_T , consists of many source-resistances R which can be divided into three main groups (Turbo, 2004), viz:

1. Frictional resistance - R_f
2. Residual resistance - $R_w + R_e$
3. Air resistance - R_a

Wave resistance refers to energy loss caused by waves created by vessel during its propulsion through the water, while eddy resistance refers to the loss caused by flow separation that creates eddies, particularly at the aft end of the ship. The residual resistance normally represents 8-25% of total resistance for low-speed ships. In calm weather, air resistance is, in principle, proportional to the square of vessel speed, and proportional to cross-sectional area of ship above waterline (Turbo, 2004).

The influence of frictional and residual resistances depends on how much hull is below the waterline, while the influence of air resistance depends on how much of the ship is above the waterline. The analysis took care to maintain the same volume of draft submerged in the outward and return journey, in order to improve the same resistances.

It can be observed that for this study case, the frictional resistance represents the largest influence on the ship's displacement. For this reason, the effects of residual resistances and air will be disregarded and we will take into account only effects of friction in the analysis of engine performance and atmospheric emissions. Climatic effects, trim and other factors will also be disregarded.

2.2 Ship Emission Measurement during Operation

The determination of efficiency was made by calculation using the EEOI (Energy Efficiency Operational Indicator). This indicator was created by MEPC (Marine Environment Protection Committee), an independent commission created by IMO to create actions useful in combating environment pollution. This indicator will be used in present work to compare emissions before and after hull treatment, relating the atmospheric pollution emitted by vessels and noting the vessel maintenance state. EEOI is given by the following expression (IMO, 2009b):

$$EEOI = \frac{\sum_j FC_j * Cf_j}{m_{cargo} * D}$$

Where:

- j is the fuel type
- FC_j is the mass of consumed fuel j
- m cargo is cargo carried (tonnes)
- D is the distance in nautical miles corresponding to the cargo carried.
- $C_f = 3.114400$, as detailed below on Tab. 1:

Table 1. Fuel Coefficient (C_f) for each type of fuel in marine transport (IMO, 2009b)

Type of Fuel	Reference	Carbon Content	Cf (t-CO ₂ /t-Fuel)
1. Diesel/Gas Oil	ISO 8217 Grades DMX through DMC	0.875	3.206000
2. Light Fuel Oil (LFO)	ISO 8217 Grades RMA through RMD	0.86	3.151040
3. Heavy Fuel Oil (HFO)	ISO 8217 Grades RME through RMK	0.85	3.114400
4. Liquefied Petroleum Gas (LPG)	Propane	0.819	3.000000
	Butane	0.827	3.030000
5. Liquefied Natural Gas (LNG)		0.75	2.750000

The determination of the specific fuel oil consumption (SFOC) was calculated by using the parameters of the engine in operation. It takes in consideration the mass of fuel consumed, the consumption per hour, the engine revolution, engine power, ambient pressure, blower inlet temperature, low-temperature air cooler inlet temperature and de LCV of the fuel oil. Some of the parameters have to be recalculated for correction in the ISO 3046 standard. Figure 1 below shows the method:

Fuel Oil Consumption									
Description	Unit	25%	50%	75%	100%	100%(2)	110%	Remark	
Measured Value	Start Value	kg							
	Stop Value	kg							
	Time	min							
	Drain	kg							
	Difference	kg							(Z)=(Start Value - Stop Value)
	Consumption per 1 Hour	kg/h							
Loaded Condition	Engine Revolution	rpm							
	Engine Power	kW							(B)
Measured Spec.fuel Computation		g/kWh							(C)=(A)/(B)x1000
ISO CORRECTION									
Description	Unit	Load	25%	50%	75%	100%	100%(2)	110%	
Amb. Pressure (Pa)	mbar	Actual							(D)=0.07 x(1000-Pa)/1000
Blower inlet Temp (Ta)	°C	Actual							(E)=(Ta-25)x0,0006
		Factor							
LT Air Cooler Inlet Temp (Tw)	°C	Actual							(F)=(Tw-25)x0,0007
		Factor							
LCV	kcal/kg	Actual							(G)=LCV/10200
		Factor							
S.F.O.C (ISSO correction)		g/kWh							(H)=[(C)x(G)] x [3-{(D)+(E)+(F)}]

Figure 1. SFOC Table

One of the most important parameters to calculate the specific fuel oil consumption is the effective power of the engine. Once there are three principal resistances over the hull of the vessel, the engine needs to generate a sufficient power to guarantee the propulsion of the ship. The electronic main engine has a computadorised system within the ship owner is able to evaluate the parameters of the engine, including an interface to show the PV diagram. Figure 2 shows the PV diagram obtained by the electronic system.

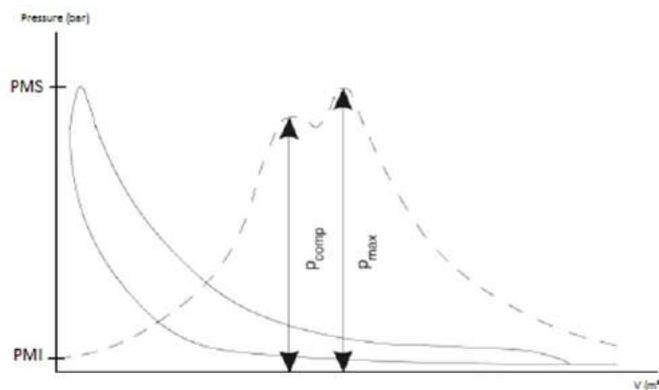


Figure 2. PV diagram

To know the effective power of the engine, it is important to follow some steps and use the information obtained by the system of the electronic engine. The steps are mentioned below.

- Effective power (P_e) is given by the following expression:

$$P_e = (k_2) * n * (p_e)$$

Where:

- k_2 is a cylinder constant;
- n is the engine speed (rpm);
- p_e is the mean effective pressure.

- Cylinder constant (k_2) is determined by the dimensions of the engine by the following expression:

$$k_2 = 1.309 * S * D^2$$

Where:

- D is the cylinder diameter (0,7 m);
- S is the piston stroke (2,8 m);
- p_e is the mean effective pressure.
- For this engine type, S70ME-C, $k_2=1.7959$

- Mean effective power (p_e) is given by the following expression:

$$p_e = (p_i) - (k_1)$$

Where:

- p_i is the mean indicated pressure (bar);
- k_1 is the mean friction loss (bar);

k_1 has proved to be practically independent of the engine load. By experience, has been found to be approx. 1 bar

- Mean indicated power (p_i) is given by the following expression:

$$p_i = A/L * C_s$$

Where:

- A is the area of the indicator diagram (mm^2);
- L is the length of the indicator diagram (mm);
- C_s is the spring Constant (mm/bar).

Due to the friction in the thrust bearing, the shaft power is up to 1 percent less than the effective engine power, depending on speed and load conditions and plant type (FPP/PPP)

3. RESULTS AND DISCUSSION

The results presented in this section were calculated through internal company software and tools and its inputs obtained from the noon reports of the ship during the voyage. The information disclosed in this article is extremely reliable and would back that up of studies in this area.

3.1 Operational Condition

The departure route was held in a path of 2834 miles, with an average speed of 10.7 knots in 11 days. The vessel was in ballast, whereas it was used the same volume of cargo from the return voyage, only for comparison propose a load equal. Already on the return, the vessel has developed an average speed of 14 knots, retracing the 4381 miles in 13 days, as summerized on Tab. 2. The routes can be checked in Figure 3 and Figure 4. The cargo transported on lap was 52,000 tonnes, the same as outward.

Table 2. Comparing data from each voyage

Voyage	Distance (nm)	Time (days)	Average Speed (knots)	Cargo (ton)
Recife x Tenerife	2.834	11	10.7	52.000
Tenerife x Rio Grande	4.381	13	14	52.000



Figure 3. Departure route



Figure 4. Return route

In operations, the erosion of paint film will begin and the marine plants and barnacles will grow on hull. The hull was overthrown and will no longer have a smooth surface, which means that friction resistance will be higher. The total resistance, caused by fouling, may increase by 25-50% throughout the vessel lifetime (Turbo, 2004).

In the literature, the impact of hull status on fuel consumption is typically derived from "resistance modeling" as developed in (Telfer, 1964) and (Todd, 1967). This involves estimating ship's total resistance and then removing or correcting factors such as wind or waves, leaving only the effects of the hull (Aas-Hansen, 2011). (Gundermann, 2016) work explicitly studies the impact of hull cleaning. Specifically, its analysis the level of resistance added before and after dry docking shows reduction of pre-dock resistance level.

To solve this problem, two repairs were made:

1. Removal of the marine plants, barnacles and paint;
2. Anti-fouling paint.

There are several methods for cleaning hull of vessels. The method used in this study was the hydroblasting in a dry place, which provides hull cleaning by means of a water jet on high pressure. This is a modern and practical procedure, performed with own equipment for this purpose and by professionals specialized. Figure 5 shows the condition of hull before the treatment and Figure 6 shows after the maintainance.



Figure 5. Hull before treatment

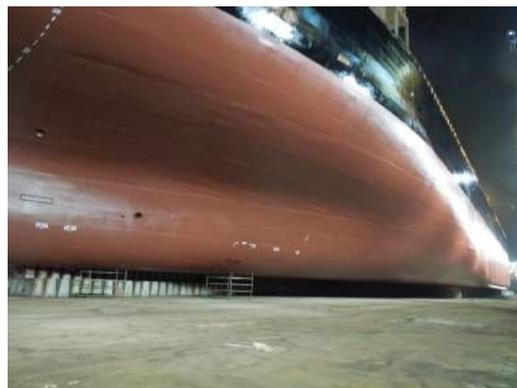


Figure 6. Hull after treatment

3.2 Emissions

During the first Voyage, the vessel was with 10.7 knots media speed and with engine’s load about to 90%. In the return voyage, the vessel developed 14 knots media speed with 75% engine’s load. For both cases, from and to Brazil, SFOC curves are shown below in Figure 7:

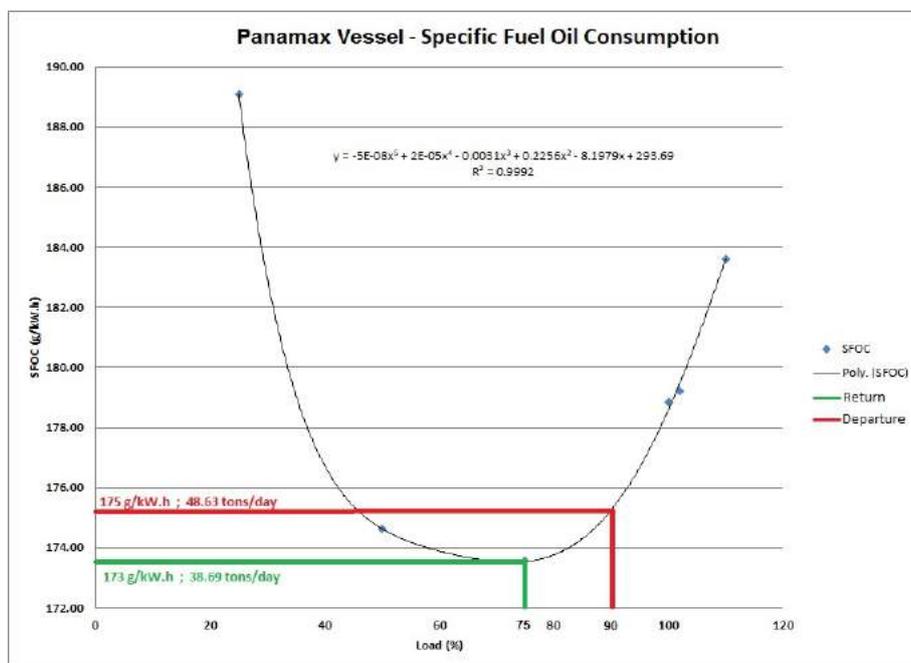


Figure 7. SFOC:Departure x Return

Observing the shown curves, the conclusion is that the consumption of the vessel in the back voyage was next to the ideal. The CO₂ emission was calculated based on EEOI methodology, already presented in this paper. Data below shown on Tab. 3 were obtained from the system of the company and used to calculate the following results on Tab. 4:

Table 3. Heavy Fuel Oil consumption for each equipment

Consumption (ton)				
Voyage	Main Engine	Auxiliary Engine	Boiler	Total
Recife x Tenerife	535	28	20	583
Tenerife x Rio Grande	503	63	33	599

Table 4. Comparing CO₂ emission in each voyage

Voyage	Distance (nm)	Cargo (ton)	Consumption (ton)	EEOI (g CO ₂ /ton nm)
Recife x Tenerife	2.834	52.000	583	12.32
Tenerife x Rio Grande	4.381	52.000	599	8.19

4. CONCLUSION

The literature indicates that hull treatment of these long-haul seafaring vessel benefits the performance of the main engine and reduces environmental impact. This research is useful for an existing publication of two important ways.

Firstly, the research proposes a practical methodology to assess the impact of hull cleaning on fuel consumption and atmospheric emissions. Second, it harnesses the availability of data from the largest Brazilian shipping company through data from the ship's daily reports, collected in the company's internal systems, to empirically evaluate the impact of good hull maintenance of a long-haul charter vessel.

Consumption is clear that periodic hull treatment can improve energy efficiency, accurately measuring its impact is challenging due to others fuel consumption types, such as speed, wind direction, wave height, use of the rudder and water temperature, among others. It was observed a reduction about 33% in the GHG emission.

As a maintenance strategy, it is necessary to routinely monitor the state of conservation of the hull through sensors and visual inspection in order to maintain the good performance of the vessel in its voyages.

5. ACKNOWLEDGEMENTS

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