The influence of ship operational parameters on fuel consumption

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Abstract

The paper discusses the influence of the main vessel operational parameters on fuel consumption. These parameters are the speed trough the water, mean draft and trim. The focus is set to the flow phenomena around certain elements of hull geometry as they are sensitive on the selection of discussed parameters. Therefore, the understanding of the flow properties and their impact on ship resistance thus the fuel consumption and emission is crucial taking into account legislative changes imposed by IMO with respect to carbon dioxide emissions from ships.

Introduction

Maritime transport is changing under the influence of external conditions related to the development of maritime technology, relocation of distribution centers and the quantity of cargo flow or the capacity of waterways and coastal infrastructure. An important factor in this transition is the growing awareness of the impact of transport on the environment, as reflected in legislative changes. Of particular importance in this regard is the reinforcement of the IMO provisions to limit carbon dioxide emissions from ships. The carbon dioxide emission quantity may be, assuming constant operational conditions, expressed as:

$$E_{CO2} = ZP \cdot C_F \qquad (1)$$

where:

E_{CO2} – quantity of emmited carbon dioxide expressed in t;
ZP – fuel consumption expressed in t;
C_F – non-dimensional fuel to CO_2 conversion coefficient.

Therefore, the fuel consumption optimisation results in lowering the carbon dioxide emissions.

Optimization of the ship's structure and systems for energy efficiency is important, but not the only factor limiting the negative impact on the environment. The use of appropriate solutions in the operation of the ship provides equal potential for reducing greenhouse gas emissions [1]. Among the elements influencing emissions reduction to the greatest extent is the selection of the favourable operating parameters (i.e. speed, draft and trim of the ship), both at the level of the fleet (fleet management and logistics) and individual ships (the route selection, optimization of load and water ballast) [2]. The solution of these tasks is based on the use of reliable, easy-to-application and universal models for prediction of fuel consumption and hence, emissions. An attempt to build such models must be based on sound understanding of the ship operational parameters' influence on fuel consumption. The present paper discusses the influence of most important parameters with respect to efficient ship operation.

Main ship parameters influencing fuel consumption and emission from ships

There are many factors influencing the energy efficiency of a ship (usually understood as amount of fuel consumed during the certain voyage with specific amount of cargo). Some of them are defined on ship design phase (e.g. hull form, propeller or main engine type) and can be hardly modified in

operation. Some others, although may change during ship operation, cannot be easily influenced by ship crew (e.g. hull and propeller fouling) or are totally beyond the crew control (weather conditions, presence of current or water depth). As far as the energy efficient ship operation is concerned there are few important parameters which, if properly adjusted, may benefit both in decrease of fuel consumption and low emissions. These ship's parameters are:

– speed trough the water;
– mean draft;
– trim.

Influence of ship speed

Vessel speed is the parameter mostly influencing the level of fuel consumption. This relation can be illustrated by Adirality Coefficient commonly used in shipbuilding. The formula originally was used to determine the relation between power, speed and the displacement of the ship. But can be also used to compare values correlated with the power, e.g. hull resistance or fuel consumption. Hence, the formula described in the literature as the fuel coefficient [3] can be written:

$$ZP_C = \frac{\Delta^{2/3} \cdot V^3}{ZP} \qquad (2)$$

where:
ZP_C – fuel coefficient,
Δ – ship displacement,
V – ship speed,
ZP – main engine fuel consumption.

As indicated by analysis of the above formula, the speed of the ship, appearing in a third power, is the dominant factor. This conclusion is consistent with the experience derived from an analysis of both the ship model testing and measurement of fuel consumption during the operation of the vessels. Hence the speed reduction is the most common way to reduce fuel consumption. To a considerable simplification, one can assume that the speed decrease by 1% results in a decrease in fuel consumption by 2%. Nevertheless, it is worth noting

that, according to recently published studies [4], speed reduction can lead to a number of adverse effects, often neglected when ship speed decrease is decided. Among these undesirable effects are:

– an increase of the rate of hull and propeller fouling;
– a decrease on the propeller efficiency due to operation under different conditions than assumed for the optimization of its design;
– prolongation of the voyage, i.e. the time the main systems of the ship are engaged;
– reduction of the efficiency of waste heat recovery systems and consequently higher fuel consumption by auxiliary engines.

So, the decision to reduce the speed may result in lower than expected fuel savings and also cause an increase in other operating costs of the ship (e.g.: cost of maintenance and repair of systems, the cost of maintaining the good condition of the hull and propeller).

Reduction in cruising speed resulting in main engine operation under low loading also affects the increase in NOx emissions. According to data published by Germanischer Lloyd [4], in the case of a large container ship with a capacity of 13,000 TEU and main engine power ~70 MW, reducing the speed of ~10% (assuming a 10,000 NM cruise), will cause an increase of NOx emissions by ~35 mt. Simplified calculations of fuel consumption and NOx emissions for the above case is shown in table 1.

As indicated by the above data, sailing at reduced speed allows for a significant reduction in fuel consumption. This implies, however, the consequences which, to some extent, reduce the expected benefits. For this reason, the shipbuilding industry, the trend to increase the main dimensions of the vessel. This procedure allows to keep a similar capacity (in terms of quantity of cargo per unit of time) while minimizing the crusing speed.

The examples of this concept are VLCC and ULCC vessels of more than 400 m length for the transport of crude oil. In addition to tankers, the use of which is controversial because of the significant threats to the environment (tanker accidents have

Table 1. Influence of engine load on ship speed, fuel consumption and emissions – 13,000 TEU container vessel on 10,000 NM voyage (own study based on [4])

Main engine load	Main engine power	Ship speed	Voyage duration	Fuel cons.	Fuel cons. reduction	NOx emission		Increase/decrease of NOx emission	
%MCR	kW	kn	days	t/voyage	%	t/day	t/voyage	t/voyage	%
100%	70000	25.0	16.6	5030	–	20.8	345.8	–	–
75%	52500	22.7	18.3	3930	22%	20.8	380.5	34.6	10%
50%	35000	19.8	21.0	3030	40%	16.8	352.8	7.0	2%
25%	17500	15.7	26.5	1990	60%	9.1	240.4	–105.4	–31%

caused major environmental disasters [5] e.g.: Tasman Spirit [2003, more than 12,000 t cargo], Prestige [2002 63,000 t cargo], Erika [1999 over 15,000 t cargo]), container ships with a capacity of several thousand TEUs gain increasing owners interest.

The flagship project of this type is a Triple E Class containership. Danish owner Maersk has ordered at the Korean group Daewoo 10 ships (with the option to build the further 10) of this type. Triple E class container ships have a capacity 18,000 TEU and a design speed 19 knots (about 24% lower than the typical ocean container vessel). Ships are designed to serve the Asia-Europe route. The first unit of this type entered service in July 2013.

Fig. 1. Visualisation of Ultra Large Container Vessel – Triple-E Class

Ships of this type are characterized by 50% reduction of CO_2 emissions per unit of transported cargo (TEUs). Despite the benefits of economies of scale there is still an ongoing discussion about the impact of a massive flow of cargo on the functioning of the logistics chain. Service of such large vessels requires infrastructure changes in the ports with respect to e.g.: quays' preparation, installation of lifting equipment capable of handling 25 rows of containers, and setting up efficient transport channels to allow for the distribution of a large amount of cargo inland.

The industry magazines forecast that the increase in the size of container ships will cause marginalization or even elimination of the smaller ports which are unable to handle the largest ships.

In parallel to the changes in the infrastructure the change of the fleet structure takes place. The smallest container feeders will no longer work and their functions are taken over by container ships with a capacity of several thousand TEUs. Another important issue that remains poorly understood is the growing disparity between the performance of marine and land transport channels.

Oversupply of cargo in the ports may cause the traditional land transport channels (railway) reach their maximum capabilities, due to the conditions of infrastructure. This will force the launch of other transport channels whose environmental impact is greater (road transport). Thus, reduction of harmful emissions at sea achieved by employment of ultra large vessels may cause a significant increase of environmental pollution on land.

Influence of ship draft

Changing the draft is not effective in terms of fuel consumption control. Although the resistance of the ship hull and therefore fuel consumption decreases with decreasing draft as indicated by fuel coefficient formula, the same is not true in case of fuel consumption related to the transported cargo. Both, the design analysis and in-service experience, show that reduction of draft causes the ship capacity to decrease faster than fuel consumption. This is due to the geometric characteristics of the hull. Along with reduction of draft the block coefficient decreases due to slender fore and aft ends and bilge radius. Furthermore, usually the residual resistance coefficient increases at reduced draft due to non-optimum submergence of the bulbous bow. In addition, with the decrease of draft the share of deadweight in the displacements reduces.

On the other hand, one should be aware of the critical constraints on the maximum draft of the ship. Among them, the most important are the parameters of shipping routes which in areas close to ports, tight passages or channels, impose the maximum allowable draft. Draft is also an important parameter in view of the ship structure load. Along with the draft increase the hydrostatic pressure exposed on vessel plating increases. Therefore, the increase of draft above the level adopted for the dimensioning of the ship's structure can cause damage.

Influence of ship trim

Trim of the ship is a parameter that can significantly affect the level of fuel consumption in operation. Results of the onboard registrations presented in figure 2 indicate that for a fixed displacement and constant ship speed change of trim cause the differences in fuel consumption ranging from 3 to 7 percent. This change is important from the point of view of the operating costs. Unfortunately, the impact of trim can not be easily determined at the ship design stage.

The effect of trim on the fuel consumption varies significantly from both, the speed change and

the draft of the vessel. Qualitative determination of these relations requires multivariate numerical calculations.

Obtaining quantitative data requires the execution of resistance and propulsion tests for wide range of speeds, drafts and trims. Due to the costs and time constraints such tests are rearly performed. It is worth noting that the effect of trim on the fuel consumption is important for the operator, owner or charterer, who do not usually take an active role in the ship design cycle, in which the hydromechanics analyzes are carried out.

Fuel consumption *ZP* [t/24 h]
PCTC 2130 cars – Draft *T* = 7.2 m
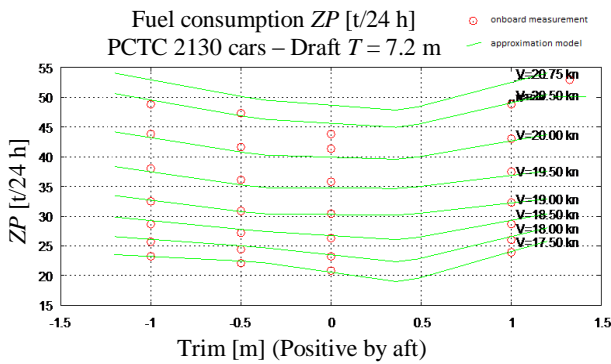
○ onboard measurement
— approximation model

Fig. 2. Fuel consumption at different trim settings [own study based on data provided by CTO SA]

The difficulty in determining the trim effect on the fuel consumption is mainly due to the complexity of the hull geometry. Design practice shows that the hull form designed and optimized for parameters (speed and draft) defined in the contract retains its beneficial properties in a small range of variation of these parameters. Significant changes in navigational parameters (reduced draft or speed) cause that the hull optimized to ensure minimum losses in flow and thus resulting in low fuel consumption do not function properly.

Inflence of the bulbous bow immersion

A prime example of the above-mentioned phenomenon is the flow around a bulbous bow of the ship. Such bow is a typical element of the hull geometry of most cargo vessels operating at relative speeds (in terms of Froude number) above 0.2.

The main purpose of the application of bulb is a reduction of wave making component of the resistance by generating a high-pressure area in front of the stem and, consequently, an additional wave at the bow, which through favorable interference with the wave generated by a moving body, lowers the bow wave height.

Key parameters for the quality of fixed geometry bulb are its immersion below the free surface of the water and the speed of flow around it (the same as the speed of the ship). Bulb immersion must be adjusted to the actual speed of the vessel in order to ensure its proper functioning. Furthermore, it is necessary to take into account the phenomenon of dynamic trim and sinkage associated with the generation of the pressure field on the surface of the hull in motion. Changing ship trim allows customizing the bulb immersion to current speed.
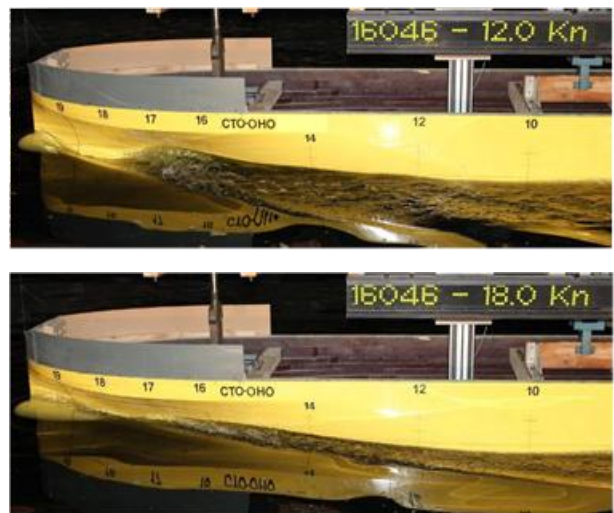

Fig. 3. Bulbous bow performance at non-optimum (upper) and optimum (lower) speed [CTO SA]

Figure 3 shows a view of the bow wave system generated by the hull moving at two speeds and the same initial draft. Despite significantly reduced speed the bow wave system is significantly more complex. In particular, for a speed of 12 knots with a short wave with a deep hollow appears in the area of theoretical frame 18 ½.

| 12 kn | 17 kn | 35 kn |

Fig. 4. Transom wave system evolution – high speed displacement vessel [CTO SA]

This patern is typical for the flow around a bulb located too close to the free surface. In this case, change of the trim resulting in increased bulb immersion would result in less developed wave system and consequently lower total resistance of the hull and fuel consumption.

The choice of ship's trim with respect to proper immersion of bulbous bow does not automatically guarantee a reduction of fuel consumption. Beside the bulb there are other elements of the hull geometry around which the flow changes significantly with the trim and thus affects the hull resistance and fuel consumption.

Inflence of the transom immersion

Other key components with this respect are stern and transom. Resistence of the flow around the stern part of the ship depends, as in the case of bulb, both on the speed and the immersion. In the worst case, when the velocity of flow around submerged part of the transom is too low an area of strong turbulent flow, combined with a significant drop in pressure can be observed. Since the normal to the surface of the transom is approximately perpendicular to the direction of vessel motion, the pressure drop in this area greatly increases the resistance of the hull.

Phenomena associated with the flows around the transom observed in model tests are illustrated in figure 4. Initially, at low speeds, highly disturbed flow can be noted behind the transom, which, after reaching a sufficiently high speed, separates. Simulation using computational fluid dynamics tools allows for more precise understanding of this phenomenon.

Figure 5 shows the pressure field and streamlines for highly disturbed (top row) and detached (bottom row) flow behind the ship transom. Calculations were done at CTO SA with use of CFD code ANSYS STAR-CCM+ taking into account free surface deformation and dynamic trim and sinkage of the hull. Presented results are a part of the standard hull form optimisation process.

The occurrence of disturbed flow behind the transom causes a significant increase in resistance due to the presence of the vortex and resulting pressure drop. A reduced pressure acts on the wetted surface of the transom resulting in a force directed opposite to the direction of flow.

On the other hand, taking into account the horizontal run of the buttock in the stern area, a significant rise of the transom can cause a significant reduction of waterline and thus increase the Froude number characterizing flow around around the hull and the consequent increase in wave resistance.

Adjustment of the trim also affects, although to a lesser extent, other factors leading to the change of resistance of the hull and thus the change in fuel consumption. Although the following factors usually do not have a decisive impact in specific cases may affect the level of fuel consumption.

Due to the complex, asymmetric with respect to midship, shape of the hull, trim change, in spite of having the same displacement (i.e. realized by moving mass inside the hull of the ship), casues change of the wetted area. Since the frictional resistance is a linear function of the wetted surface, its significant changes affect the resistance and consequently the level of fuel consumption. In practice, as illustrated in figure 6, where the changes of the wetted surface for a bulk carrier in few operational conditions are presented, these changes are not significant.

In the case of a significant bow trim of the ship not only the loss of the positive impact of bulb on the wave system due to its deep immersion but also
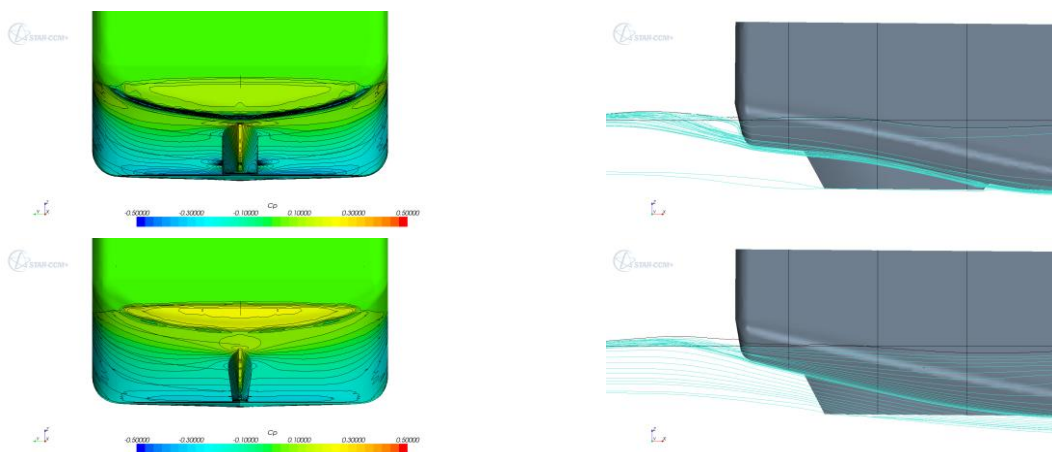

Fig. 5. Numerical flow analyses at stern area: left column – pressure field, right collumn – streamlines, upper row – disturbed flow, causing increase of resistance [CTO SA]

an additional resistance generated by the flow around the wider upper part of the stem should be expected.
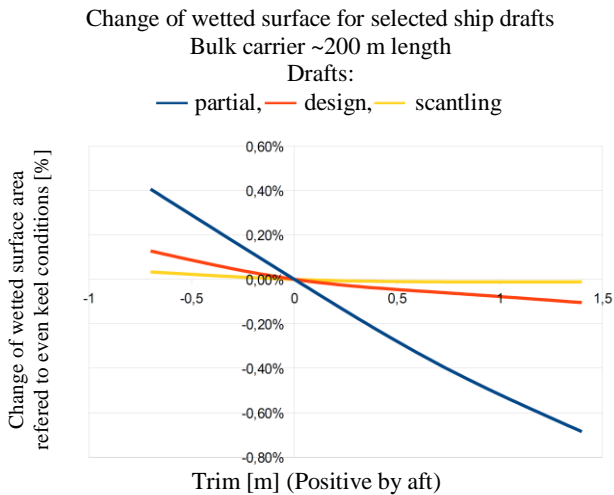

Fig. 6. Trim influence on ship wetted surface

The wave generated in such condition is shown in figure 7. Practice shows, however, that significant bow trim is not used, especially in bad weather conditions due to the reduction of freeboard and the risk of significant foredeck flooding.
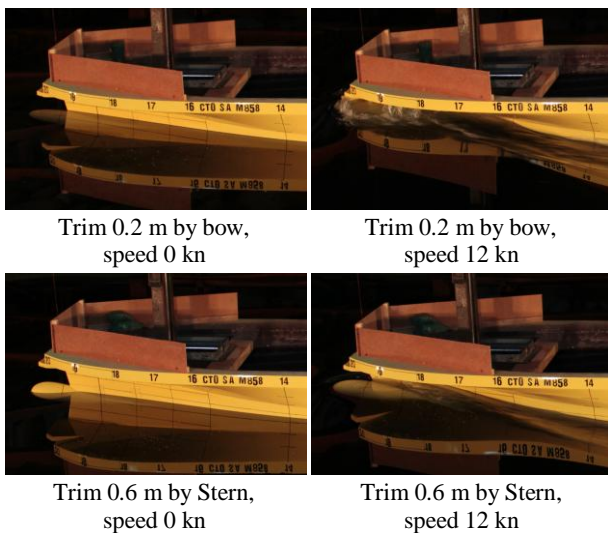

Fig. 7. Bow wave system for bow trim (upper) and aft trim (lower) [CTO SA]

Other trim dependent factors

Among the trim dependent factors which affect the ship resistance and thus fuel consumption, the flow around appendages should be considered. These elements are small compared to the size of the main hull and placed on the surface. Examples

of common appendages are bilge keels, rudder consoles or shaft brackets. These elements are oriented in such a way that their position aligns with streamlines of the flow around the ship hull.

In this way, the pressure resistance is minimized and the total resistance of the appendage is approximately equal to the frictional resistance of the flat plate of the same area. In case of elements with small span in the flow direction, so called form factor, must be also taken into account. However, in the case the ship is operated in the conditions far different from those for which the position and alignment of the appendages have been designed, an increase in resistance can be expected.

Significant changes of the trim also affect, although slightly, the efficiency of the propeller. With the increase of trim the direction of water flow to the propeller changes causing an increase in the transverse velocity components of the flow. It may cause increased risk of cavitation. In addition, the direction of the force generated by the propeller is not parallel to the direction of ship motion and hence the effective thrust force is reduced.

Conclusions

The analysis of the examples presented above indicates that the effects of the ship operational parameters on fuel consumption can not be described by simple relations. Effects of trim change depend on the vessel speed and the mean draft. The most important factor with this regard is the hull form, especially in case of the presence of bulbous bow or stern transom. The determination of the conditions resulting in the reduction of fuel consumption requires the application of a computational model which properly reassembles these complex relationships and interactions of the various components of flow around the hull.

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