A method to identify an optimum speed of ships for ship efficient operation

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Abstract: An efficient operation of ships is essential task required to all shipping companies in over the world. The concept of ship efficient operation is very different; however the minimum consumption of fuel for a voyage is a good explanation of the ship efficient operation. To use a minimum fuel for a voyage can be achieved by optimum speed of a ship, but the ship optimum speed is depending on some factors such as sea condition, ship condition, mode of ship charter and so on. In this paper, there presents a method to calculate an optimum speed of a ship within actual operation conditions in order to help operators following well Ship Energy Efficiency Management Plan-SEEMP).

Keywords: ship operation, optimum ship speed, SEEMP.

1. Introduction

The expenditure of fuel in shipping is normally taken about 35% to 40% of the total operation cost of a ship. Although, shipping companies are aware about this problem, but almost companies do nothings to minimize the fuel consumption even at the period in which the fuel price was as highest. Recently, in Vietnam, we carried out some surveys about what method a shipping company usually uses to minimize the fuel consumptions during ship operation. The answers from almost shipping companies are to set a package of fuel for a voyage or to set an operation speed for a ship and on a base of the ship speed, an amount of fuel per hour is supplied for a ship. So, it is clear that shipping companies do not have appropriate methods to control usage of fuel on board ships. Therefore, there results in increasing operation cost of a ship and also there may create a good condition for crews to do cheating in using fuel oil.

At present time, the shipping is highly competitive worldwide. Although, the fuel price sometimes is decreased from last year. But, the pressure of the environment protection is higher due to the requirements on control of NOx emission from marine diesel engines in Annex VI, MARPOL 73/78. According to those requirements, marine diesel engines must be equipped with special exhaust gas emission treated apertures and shipping companies also must be required to minimize the fuel consumption in order to meet the EEOI.

For complying with the dual purposes such as minimizing fuel consumption and environment protection, International Maritime Organization has already proposed so called the Ship Energy Efficiency Management Plan (SEEMP). In this Plan, there are many recommended items which should be implemented in order to help shipping companies and ships to meet safe and efficient operation of ships. However, among those recommended items, how to reach optimum operation speed of a ship rather is most important.

2. Proposed concept of optimum operation speed of ships

In practical, a concept of optimum operation speed of ships is very different in connection with boundary conditions. In some cases, the optimum speed is depending on a minimum fuel oil consumption of a main engine. It means that the optimum speed will be calculated on base of function between ship speed and minimum fuel usage per hour. But in other case, the optimum operation speed of ships will be determined by using an objective function between ship speed and operation expenditure for one voyage. However, the above explanation about optimum operation speed of ships can achieve only limited operation conditions and does not concern anything with a contribution into the environment protection which is mentioned by the Index of Energy Efficient Operation (EEOI).
2.1 Procedure to determine an optimum operation speed of ships

The requirements of IMO covering multi-purposes which include both effective operation of a ship and engine exhaust gas emission control make shipping companies in difficult situation of implementation. An appropriate solution for this objective is to raise a suitable function which can estimate an optimum operation speed of ships on a base of boundary conditions such as actual loading conditions, sea state, and mode of ship chattering, fuel price and some others. Therefore, an appropriate concept of an optimum operation speed of ships is presented by a function (1) as follow:

\[ V_{opt} = f(R_s, D, P_f, M_{charter}, S_{con}) \]  

In which: \(R_s\) - basic ship resistance; \(D\) - ship draft; \(P_f\) - actual fuel price; \(M_{charter}\) - mode of ship charter (voyage charter or time charter); \(S_{con}\) - sea state.

A new ship was designed and built with specific technical features such as total length, width, draft speed, propulsive power and displacement. With that, the resistance of ship can be determined and defined as a basic resistance (total resistance). The basic resistance of a ship will be changed dramatically during operation depending on load conditions, sea state and technical state of hull, propulsion system.

The basic resistance of a ship consists of many source resistances that can be classified into three main groups: frictional resistance, residual resistance and air resistance. In fact, during ship sailing on open sea, the basic resistance of a ship is influenced by sea wave, air, hull fouling and wind direction to ship. Therefore, the basic resistance of a ship is normally increased. The phenomenon of ship resistance increase makes a reduction of ship speed and increase of main engine fuel consumption. So, if shipping companies want to operate ships with high efficiency, the companies must find out an optimum speed of ships. To solve this problem, a calculation procedure of an operation optimum speed of a ship is proposed to be carried out into five stages.

- Ship basic resistance will be determined on a base of specific technical features of an actual ship;
- A change of ship basic resistance will be estimated on a base of actual operation conditions such as loading condition (ship draft), sea state, wind direction and some other more if it is necessary;
- Based on a mode of ship charter and calculated results from first two stages mentioned above, a ship optimum operation speed will be determined;
- To verify the determined optimum operation speed of a ship (stage 3), let check a time of ship arrival to a port based on criteria “Just on time”;
- To determine the index of energy efficient operation of ship (EEOI) in certain period of ship operation in orders to verify a ship operation in compliance with requirements of the environment protection.

2.2 Formulas needed in determination of ship optimum speed

In practice, to determine an optimum operation speed of ships is complicated. There is no concert mathematical model for this purpose due to many boundary conditions influencing on the optimum speed of ships. Therefore, helping to come to final result of optimum speed calculation, there needs to use several formulas concerning with ship resistance, gross profit of shipping and some others. Our idea
in order to create a method to determine an optimum operation speed of ships is to divide needed formulas into four groups:

a- Formulas to calculate basic resistance of ships

b- Formulas to calculate changes of ship resistance such as:

- Wave resistance:

\[ \Delta R_w = dR_0 [0.667 + 0.333 \cos \alpha], \quad \Delta R_0 = 0.64H_w^2 \frac{C_b}{L} \frac{B}{g \rho} \]

(2)

In which: \( \alpha \) - angle of wave to ship (0° is head sea) [°]; \( H_w \) - height of wave [m]; \( C_b \) - block coefficient of ship; \( B \) - width of ship [m]; \( L \) - length between perpendiculars [m]; \( \rho \) - density of sea water [kg/m³].

- Air and wind resistance:

\[ \Delta R_A = 0.28 \times 0.5B^2 \times V_w^2, \quad V_w = 5.53H_w - 0.093H_w^2 \]

(3)

In which: \( V_w \) - wind velocity [m/s] and wind velocity is calculated on base of height of sea wave.

- Resistance due to hull roughness:

\[ \Delta R_{Fou} = \frac{140d}{630+d} \% \text{ or } \Delta R_r = K \times S \times V^n \]

(4)

In which: \( d \) - days out of dock; \( K \) - coefficient; \( n \) - coefficient [1.9 to 2.1]; \( S \) - wet surface of ship and \( S = 2.56(W \times L)^{0.5} \) [m²].

- Resistance due to draft:

\[ \Delta R_D = 0.65R_f \left( \frac{\nabla 0}{\nabla} - 1 \right), \quad R_f = 0.5 \times \rho \times V_0^2 \times S \times C_T \]

(5)

In which: \( R_T \) - basic resistance of ship; \( \nabla \) - actual displacement of ship; \( \nabla 0 \) - design displacement of ship; \( S \) - wet surface of ship; \( V_0 \) - design speed of ship; \( C_T \) - coefficient.

c- Formulas to determine an optimum operation speed of ships:

As it is well known, the fuel consumption of a marine diesel engine is so much depending on an operation speed of a ship. Therefore, there must identify an optimum speed during a ship operation. To do so, it is necessary to create an objective function in order to find the optimum speed in conjunction with ship chartering mode (time charter or voyage charter). In fact, there are some objective functions, but an objective function which is chosen is a function determining a gross profit per day of a ship as mentioned in (6);

\[ GS(d) = P \times W \times V \left[ d - c_r - pF(d) \right] \]

(6)
In which: \( P \) - freight rate per ton of good; \( W \) - ship displacement (DWT); \( d \) - ship sailing distance including ballast ship [nautical mile]; \( V \) - ship speed [knot/h]; \( C_R \) - expenditure of ship per day [USD/day]; \( p \) - fuel price [USD/ton]; \( F(d) \) - fuel consumption depending on ship speed \( V \).

A fuel consumption of a ship can be expressed by \( F(d)= k.V^3 \); \( k \) - coefficient depending on operation conditions. Based on the mentioned relation of \( F(d) \), there can find a formula to identify an optimum operation speed of a ship as (7):

\[
V_{opt} = \left( \frac{PW}{3pkd} \right)^{1/2}
\]  

The formula (7) can be used to determine an optimum operation speed of a ship if a calculated speed is higher than operation speed which is already set in a charter contract. This formula can also be developed to calculate an optimum operation speed of a ship in more complicated operation conditions which include a time in port, delay time due to bad weather and sailing time in canal of a ship. However, the mode of ship charter is a real factor influencing on a mathematical model to determine an optimum operation speed of ships and the mathematical model can be expressed as follows:

- In case of ship time charter:

\[
V_{opt} = V_{max} \left[ \frac{C_s + F_{Aux}}{(k-1)F_{ME}} \right]^{1/k}
\]  

where: \( C_s \) - ship charter price per day [USD/day]; \( F_{Aux} \) - Fuel expenditure of auxiliary engines per day [USA/day]; \( F_{ME} \) - Fuel expenditure of main engines per day [USA/day]; \( k \) - coefficient depending on technical conditions of propulsion system; \( V_{max} \) - highest speed that can be generated by a ship [knot/h].

- In case of ship voyage charter:

As it is known that a goal of ship voyage charter is to reach maximum profit for every day. So, a mathematical model to determine an optimum operation speed of a ship will be expressed in other form as mentioned in (9)

\[
24V_{opt} + \left[ \frac{k \times S / RT \left( 24V_{opt} \right)^{k-1}}{(k-1)P_{time} / RT} \right] = \frac{C_i \left( 24V_{max} \right)^k}{(k+1) \times F_{ME} \times P_{time} / RT}
\]  

Where: \( k \) - coefficient for both formulas and \( k = 3 \) for diesel propulsive system, \( k = 2.5 \) for steam turbine propulsive system; \( C_i \) - freight income and is equal to gross a value minus expenditure such as port fee, loading and unloading fee and some others; \( S \) - sailing distance for one round trip; \( RT \) - round trip of ship. Then the formula (9) can be realized by using trial and error method and final mathematical model as follow:

\[
V_{opt} = \left[ \frac{24 \times C_i \times \left( V_{max} \right)^k}{k \times F_{ME,Vmax} \times S / RT} \right]^{1/k-1}
\]  

Where: \( F_{ME}, V_{max} \) - fuel consumption per day at maximum operation speed of a ship.

**d- Formula to determine EEOI**

An index to ensure whether a ship, which is complied with requirement of environment protection is an Index of Energy Efficiency Operation mentioned in Annex VI, MARPOL 73/78. The index is expressing
a ratio between CO2 volume [M] discharged by a ship per unit of ship transportation. The index is modelled to express an energy efficiency operation of a ship for one voyage and for a period of ship operation. For a voyage, the index is expressed as follow:

\[
EEOI = \frac{\sum_j FC_j \times C_{Fj}}{m_{cargo} \times D} \quad \text{[MCO2/voyage]} \quad (11)
\]

and for a period of ship operation:

\[
\text{Average } EEOI = \frac{\sum_i \sum_j (FC_{ij} \times C_{Fj})}{\sum_i (m_{cargo,i} \times D_i)} \quad (12)
\]

In which: FC- total fuel consumption of ship on open sea and in port for a voyage or a period of operation; j - a kind of fuel (DO or FO); i - voyage number; FC_{ij}- the mass of consumed fuel j at voyage i; CF_{ij} is the fuel mass to CO2 mass conversion factor for fuel j; m_{cargo} is cargo carried (tonnes) or work done (number of TEU or passengers) or gross tonnes for passenger ships; and D is the distance in nautical miles corresponding to the cargo carried or work done.

2.3 Determination algorithm of ship optimum speed operation

Based on the procedure to determine an optimum speed operation of ships and to ensure a ship in compliance with the environment protection, the above mentioned formulas are used to create an algorithm to determine an optimum speed operation of ships. The algorithm is expressed in figure 1 and then there can use MATLAB package software to solve the mentioned mathematical model to get unknown variables such as an optimum operation speed of concert ship, the EEOI and some other needed parameters.

3. Application on board ships

The mentioned method to determine an optimum operation speed of ships has been applied on board of two ships belonging to Khaihoan Ship marine Corp. Khaihoan Ship Marine is an Oil Tanker Company which has a Head Quarter in Ho Chi Minh City.
Figure 1 Algorithm to determine an optimum operation speed of a ship

START

GIVEN PARAMETERS
- L
wl, L
pp, B, DA, DF, \( \bar{V} \), \( d \); \( V \);
- Engine: Ne\(_{max}\), Ne\(_{m}\), Ne\(_{f}\), \( n_\ldots \)
- \( \alpha \), \( \eta_H \), \( \eta_R \), \( \eta_O \), \( \eta_D \), \( \eta_S \)...
- Propellers: D, H/D, S, J, t,

CALCULATE NECESSARY COEFFICIENTS
- CB; Cwp, t, w...

CALCULATE CHANGES OF RESISTANCE
- Resistance due to wave;
- Resistance due to wind;
- Resistance due to roughness;
- Resistance due to cargo

TOTAL RESISTANCE CHANGE
\[ \Delta R_T = \Delta R_w + \Delta R_s + \Delta R_{vow} + \Delta R_D \]

CHANGES OF “V” or “PE”
- \( \Delta P_E = P_{fr} - P_E \) or \( \Delta P_E = \Delta R \times V \)
- \( V_1 = \sqrt{\frac{R + \Delta R}{c}} \) and \( V = V - V1 \)

RESULT DISPLAY

Yes

CALCULATE OPTIMUM SPEED “Vopt”
- \( V_{opt} = V_{max} \left[ \frac{C_{gyr} + F_{max}}{(k-1) \times F_{MF}} \right]^{1/k} \)
- \( V_{opt} = \left[ \frac{24 \times C_j \times (V_{max})^2}{k \times F_{MF} \times \frac{S}{RT}} \right]^{1/2-1} \)

CALCULATE INDEX OF ENERGY OPERATION
\[ EEOI = \sum FC_j \times C_{\eta_j} / m_{cargo} \times D \]

END
3.1 Technical features of M/S “Glory Ocean”

The Glory Ocean is oil/chemical tanker and she is under Bureau VERITAS classification. Her main technical features are mentioned in table 1.

Table 1 Main technical features of M/S Glory Ocean

<table>
<thead>
<tr>
<th>No</th>
<th>parameters</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hull</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Dead weight [DWT]</td>
<td>12.806</td>
</tr>
<tr>
<td>2</td>
<td>Total length [m]</td>
<td>134.85</td>
</tr>
<tr>
<td>3</td>
<td>Length between perpendiculars [m]</td>
<td>126.8</td>
</tr>
<tr>
<td>4</td>
<td>Register width [m]</td>
<td>22.0</td>
</tr>
<tr>
<td>5</td>
<td>Register draft [m]</td>
<td>10.6</td>
</tr>
<tr>
<td>6</td>
<td>Design draft [m]</td>
<td>7.78</td>
</tr>
<tr>
<td>7</td>
<td>Operation speed [knot]</td>
<td>13.2</td>
</tr>
<tr>
<td>8</td>
<td>Maximum operation speed [knot]</td>
<td>14.0</td>
</tr>
<tr>
<td>Main engine</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Engine Name</td>
<td>8PC2-6/2L, 4 strokes</td>
</tr>
<tr>
<td>2</td>
<td>Number of cylinders</td>
<td>8</td>
</tr>
<tr>
<td>3</td>
<td>MCR [kW]</td>
<td>4400</td>
</tr>
<tr>
<td>4</td>
<td>Nominal revolution [rpm]</td>
<td>520</td>
</tr>
<tr>
<td>5</td>
<td>Reduction gear ratio</td>
<td>3.0</td>
</tr>
</tbody>
</table>

3.2 Application results

- **Voyage**: The Glory Ocean was sailing from Vungtau City to Quinhon port and back with full load and ballast. Distance of sailing is about 356.8 [nautical miles]. We did test on board ship under two operation conditions namely: under ballast condition and full load condition. The technical features of the both conditions are mentioned in tables No.2. Meanwhile, test results are showed in table No.3 for the ballast condition and No.4 for the full load condition.

Table 2 Operation conditions of M/S Glory Ocean

<table>
<thead>
<tr>
<th>No</th>
<th>Operation conditions</th>
<th>Value</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ship under ballast</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Bow draft</td>
<td>3.2 [m]</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Stern draft</td>
<td>5.8 [m]</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Sea state</td>
<td>NE Bo 3 and 4</td>
<td></td>
</tr>
<tr>
<td>Ship under full load</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Bow draft</td>
<td>10.0 [m]</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Stern draft</td>
<td>10.0 [m]</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Sea state</td>
<td>NE Bo 3 and 4</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Mode of ship charter</td>
<td>Voyage Charter</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Operation speed and revolution of a main engine</td>
<td>500 [rpm]; 166.6 [rpm]; 13.2 [knot/h]</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Kind of fuel</td>
<td>FO</td>
<td></td>
</tr>
</tbody>
</table>

- **Ship under ballast**

Based on the technical features and operation conditions, selection of an optimum operation speed of m/s Glory Ocean has been determined by using the algorithm (figure1). The algorithm then was solved on MATLAB package software and all necessary results are showed in table 2.
Table 3 Selection of an optimum operation speed under ballast conditions

<table>
<thead>
<tr>
<th>Operation parameters</th>
<th>Optimum operation plans</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculation</td>
<td>PA2</td>
</tr>
<tr>
<td>Engine revolution [rpm]</td>
<td>460</td>
<td>457</td>
</tr>
<tr>
<td>Ship speed [knot/h]</td>
<td>13.02</td>
<td>12.9</td>
</tr>
<tr>
<td>Arrival time (#)</td>
<td>-1h</td>
<td>-2 h</td>
</tr>
<tr>
<td>Fuel consumption <a href="*">l/h</a></td>
<td>639.4</td>
<td>620.0</td>
</tr>
<tr>
<td>Fuel consumption per day [T/day]</td>
<td>13.5</td>
<td>12.8</td>
</tr>
</tbody>
</table>

(*) fuel consumption measured by flow meters
(#) Arrival time is indicated by (-) [late arrival] and (+) [earlier arrival]

- Ship under full load:

Using the same procedure as for the ship sailing under ballast, results of selection of an optimum operation speed are presented in table 4.

Table 4. Selection of an optimum operation speed under full load

<table>
<thead>
<tr>
<th>Operation parameters</th>
<th>Optimum operation plans</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calculation</td>
<td>P1</td>
</tr>
<tr>
<td>Engine revolution [rpm]</td>
<td>465</td>
<td>460</td>
</tr>
<tr>
<td>Ship speed [knot/h]</td>
<td>~13.0</td>
<td>12.8</td>
</tr>
<tr>
<td>Arrival time (#)</td>
<td>~20 [min]</td>
<td>~1.5 [h]</td>
</tr>
<tr>
<td>Fuel consumption <a href="*">l/h</a></td>
<td>659</td>
<td>651.43</td>
</tr>
<tr>
<td>Fuel consumption per day [T/day]</td>
<td>13.95</td>
<td>13.85</td>
</tr>
</tbody>
</table>

3.3 Discussion

To find an optimum operation speed of M/S Glory Ocean, the procedure and algorithm mentioned above have been used. For both cases, optimum operation speeds of the ship were calculated, then on a base of the calculated speeds, let the ship sailing with that in certain period of time (may be one or two hours). During this period of trial, a fuel consumption of main engines was taken by flow meters and an arrival time also should be estimated. Next stage is to make some other plans with the ship operation speeds which are lower or higher than the calculated speeds and then all the optimum plans should be taken into comparison. Best plan is a plan in which an operation speed of a ship will allow ship arrives on time with minimum fuel consumption. In case of M/S Glory Ocean, a good operation plan can be chosen as follow:

- For ship under full load: there can operate the ship with a main engine revolution of 460 rpm or 465 rpm (calculated speed) and used fuel for only main engine can be saved 0.74 T/day, although the ship will arrive to port a little bit late in comparison with plan “just on time”;

- For ship under ballast: the plan with calculated speed should be chosen and ship may arrive to port about one hour later.
4. Conclusion

At present period, the shipping is very competitive worldwide. One hand, the shipping companies must ensure their ability in carrying goods safely with reasonable freight rate and in the other hand, shipping companies also must comply with the requirements of environment protection. It means that ships have to be in good technical conditions; therefore they may or have to be equipped with further necessary equipment in order to support ships in compliance with strict standards set by IMO in Annex VI, MARPOL 73/78. However, according to our survey results, even some newly built ships cannot match the criteria of EEOI during operation. There can conclude some reasons, but mainly ship crews have a problem with understanding about ship optimum operation speed and EEOI.

The procedure and algorithm of determination of ship optimum operation speed as mentioned above is necessarily to be developed and applied on board ships. The test results in m/s Glory Ocean are very positive and are highly appreciated by the owner (Khaihoan Ship Marine Corp.). The method is being in further development under support of Vietnam Ministry of Transportation and it will be widely used to help shipping companies and ship crews in Vietnam.

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