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The Experimental Research of Additional Energy Consumption and Exhaust Gas Emissions from Use of Marine Litter Collecting Nets

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Abstract

The problem of marine litter is one of the most important ecological problems in many countries. Lack of ecological consciousness and disregard for environmental regulations for marine pollution, results in increasing and sometimes even dangerous amounts of floating litter that either pollutes coastal areas or end up degrading into ever smaller particles and poisoning marine fauna. To solve this problem one of innovative marine litter collection nets – a light weight, easy to assemble was created. However marine litter collection would create additional trawling work which results in additional air pollutant emissions. It is there for necessary to evaluate the air pollutant emissions that occur during trawling of nets and aim to provide tools for ecological optimization of trawling work so that the least amounts of air pollution would be created while gathering the greatest amount marine litter. The special raft was designed and constructed for such nets test. The test was performed in Curonian lagoon. Marine litter collection requires additional energy consumption, because of increase of thug's engines power to overcome increase of nets resistance, that also leads to additional fuel consumptions and higher exhaust gas emissions. The article is based on experimental research of a light weight marine litter collection nets resistance measurement. Evaluation of additional energy consumption and increased exhaust gas emissions during trawling.

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Keywords: marine litter; resistance determination; energy consumption; exhausts gas emissions.

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1. Introduction

Marine litter is an environmental, economic, human health and aesthetic problem. It poses a complex and multi-dimensional challenge with significant implications for the marine and coastal environment and human activities all over the world (UNEP 2009). Over 180 species are known to ingest plastic debris. Ingestion can impair digestion and cause internal injuries or even death (EU Commision 2012). It is suggested that as much as 10% of all plastic litter end up in the sea (Thompson 2006). This would mean that presently 5.7 million tons of plastics produced in Europe per year would eventually find their way to the seas or oceans (Cauwenberghe et al. 2013). It was found that in the Baltic Sea up to 70.8% of marine litter that land on the beaches of Lithuania was polystyrene that is very dangerous for marine fauna (Balčiūnas, Blažauskas 2014).

To solve this problem one of innovations were prepared in the Marine Clean project that was the marine litter collection nets – a light weight, easy to assemble nets for collections of marine litter. And although effectiveness and need of these nets is beyond doubt an additional evaluation with regard to pollution was found to be of interest. Problem of air pollution from shipping is most harmful in the locations where shipping is intensive and the greatest number of ships is concentrated in port cities, known to be zones of increased emission amounts, which in turn also influences air quality in towns located nearby (Balčiūnas, Blažauskas 2014). The collection of marine litter was bound to be performed by small ships that would troll the net in different locations that most commonly will be coastal areas. These ships would consume a significant amounts of fuel and emit air pollutant emissions that are toxic (Nitrogen oxides (NO_x), Sulfur oxides (SO_x) Carbon monoxide (CO)) and carbon dioxide that is known to be one of the main reasons of global warming. It is there for necessary to evaluate the air pollutant emissions that occur during trawling of nets and aim to provide tools for ecological optimization of trawling work so that the least amounts of air pollution would be created while gathering the greatest amount marine litter. Klaipeda university Air pollution from ships research laboratory is specialized in research of air pollution from transportation with a special interest for marine transportation is a partner in Marine Clean project. Measurements were performed in Lithuania, in Curonian lagoon that is joined with Baltic Sea. A specialized raft was and methodology was developed to perform accurate measurements of emissions that occur during trawling tests.

The aim of the study is to address the following key tasks:

To evaluate additional energy consumption in ship during trawling work with marine litter collection nets.

To evaluate additional emissions that occurs during trawling work.

2. Methodology

2.1. Evaluation of additional energy consumption

Net submitted for the experiments is a new and original product, whose hydrodynamic characteristics are unknown. Therefore to answer the raised questions only by theoretical calculation methods is inadequate. Net's tests must ensure correct answers to these questions.

1. What additional force is needed for towing the net under different towing speeds?
2. How much additional fuel is going to be used?
3. How much additional pollutants are going to be released?
4. What could be the optimal velocity for towing the net and water area cleaning efficiency?

It is necessary to do experimental tests by towing the net with a tug boat. To get comprehensive answers to raised questions this data should be obtained:

- a) Net's resistance.
- b) Engine power, fuel consumption and emission of pollutants by the tugboat with and without the net.

To evaluate the resistance of net, it should be towed when it is fully submersed (during this stage the used area of net should be noted). Net's plane should be maintained perpendicular to the direction of towing. For this purpose net was fixed in a special frame that was then attached to a specially developed raft that was made in Klaipeda University Air pollution from ships research laboratory.

In tugboat's power plant, if there is no specially prepared equipment, the engine's speed (rpm) and tugboat's speed in relation to sea bottom (from GPS) were recorded.

Engine power and fuel consumption cannot be recorded at a specified time without additional equipment because such possibilities are not provided in ship's design.

Engine's power can be found by using the measured torque and rotation speed.

$$P_e = M_t \cdot \omega, \text{kW}, \tag{1}$$

here: M_t – torque, Nm; ω – rotation speed, rad/s (s^{-1}).

Rotation speed can be determined by engine's throttle

$$\omega = \frac{\pi n}{30}, \text{ s}^{-1}. \tag{2}$$

To determine torque, engine and ship's shaft should be provided with special equipment which ship's do not have, therefore measuring of this parameter and engine's power directly is not possible. Because of this non-direct methods are used. Synchronised data on ship's engine hourly fuel consumption and speed provide such option, other data is also used, such as engine's fuel consumption depending on torque, propulsion complex characteristics (transmission and screw etc.) (Smailys 2013).

When this data is achieved, engine power in fixed load mode is determined by

$$P_e = \frac{G_f}{b_e}, \text{ kW}, \tag{3}$$

here: G_f – engine's hourly fuel consumption, kg/h; b_e – engine's specific fuel consumption, kg/kWh.

Engine's power depends on power used by ship's screw, P_e, which depends on ship's (with trawling equipment or without) resistance power P_R.

$$P_R = Rv, \tag{4}$$

$$R = C_R v^2, \tag{5}$$

$$P_T = \frac{P_R}{\eta_{tr}}, \tag{6}$$

$$P_{epr} = \frac{P_T}{\eta_{tr}}. \tag{7}$$

By combining these equations, results are obtained

$$P_{epr} = \frac{Rv}{\eta_{pr} \cdot \eta_{tr}}, \text{ kW}, \tag{8}$$

here: P_{epr} – engine power, obtained by propulsion power; R – ship's (with or without trawling equipment) resistance, N; v – ship's speed in relevance to water m/s; η_{tr}, η_{pr} – ship's transmission and screw efficiency coefficients.

It is obvious that engine power, obtained by (3) and (8) formulae should be equal

$$P_e = P_{epr} \,. \tag{9}$$

And can differ only because of used parameters indeterminacy.

When comparing power in (3) and (8) dependencies, it is obvious that power is more reliable, when defined by (3) dependency, because when reliable measurements are obtained, error can be related only with specific fuel consumption assessment, of which data can be obtained from engine‘s technical characteristics.

When using (8) dependency, result depends on two unknown parameters – η_{pr} and η_{tr}, which can have larger uncertainty.

2.2. Calculation of the resistance of net, fuel consumption and power

1. The resistance of net

$$R_{net} = R_{Raft,net} - R_{Raft}, \; N, \tag{10}$$

R – the resistance determined with dynamometer. Indexes: *Raft*, *net* – raft with net; *Raft* – raft without a net.

2. Ship’s speed in relation to water

$$v_w = \frac{v_{upstream} + v_{downstream}}{2}, \text{ m/s}, \tag{11}$$

here: $v_{upstream}$, $v_{downstream}$ – ship’s speed by GPS during its movement upstream and downstream; v_w – ship’s speed in relation to water[†].

3. Ship’s power required for trawling of the net

$$P_{ME,net} = \frac{R_{net} \cdot v_w}{\eta_{sr}\eta_{tr}}, \text{ kW}, \tag{12}$$

here: R_{net} – the resistance of net determined with dynamometer; v_w – trawling speed, with and without net, m/s; η_{sr} – screw efficiency; η_{tr} – transmission efficiency.

4) Hourly fuel consumption

$$G_{fnet} = G_{fRaft,net} - G_{fRaft}, \text{kg/h}, \tag{13}$$

G_f – hourly fuel consumption, measured during the experiment, kg/h.

2.3. Specific fuel consumption

During the litter collection nets trials a thug ship with propulsion plant: four stroke diesel engine, hydrodynamic transmission and fixed pitch propeller was used (Voith Turbo GmbH & Co).

In engine technical documentation an operational range between 1400 to 2000 rpm is given (within the limits of operational speeds). However normal operational speed is too fast for the litter collection nets trials, as a result of that engine operational characteristics ere extrapolated to low rpm (800 rpm) that matches ship’s minimum speed (below 1 m/s). In the range of these speeds engine load is only 10–20% of engines maximum continues rating (MCR) and specific fuel consumption is respectively larger by 43–27% of nominal value.

[†] the influence of wind not taken in to account

Function $b_e = f(P_e)$ was used to determine engine load according to measured fuel consumption. To achieve this goal a regression equation to combine b_e and P_e was made:

$$b_e = 0.0081x^2 - 2.0829x + 353.43, \quad (14)$$

here: b_e – brake specific fuel consumption; $x = P_{ei}$.

Engine's power in load (i) is determined by measured hourly fuel consumption

$$P_{ei} = \frac{G_{fi}}{b_{ei}}, \text{ kW}. \quad (15)$$

Since b_e and P_e values are connected by functional connection P_{ei} and b_{ei} are determined by iteration, and absolute P_{ei} value is obtained by:

$$P_{ei} = 0.01 \cdot P_{ei} \cdot P_{en}, \text{ kW}. \quad (16)$$

When all factors are considered, method used in net's testing can be described by these main traits.

1. Net is fixed by it‘s perimeter on stiff rectangular form frame.
2. Frame with net is fixed on specially designed raft.
3. Frame with net are fitted on raft so that entire net would be submersed in water and it's plane would be perpendicular to movement of raft.
4. The raft is attached to the tugboat by a towing rope, which was then attached to dynamometer that measures raft‘s resistance force.
5. For the experiment, tugboat with known engine characteristics and torque speed controlling devise, GPS to measure position, direction of movement and speed was chosen
6. Engine fuel measuring system was modified in order to precisely measure fuel consumption during the experiment.
7. For experiment water area is chosen, which would allow controlled experiment distance no less than 1.5 km. Considering that chosen route could have water currents, each experiment is done by same route to and from starting point, thus eliminating effect of current on ship's speed.
8. Experiments are done under these ship's and trawling equipment's assemblies:

- ship without raft,
- ship with raft and without net,
- ship with raft and fitted net.

9. Each variant of equipment, experiments are done in no less than three speed modes in range from minimum, which allows ship's propulsion complex to 2–3 m/s depending on equipment.
10. In each mode these parameters are measured and registered:

- Controlled ship movement route moments at beginning and end;
- Ship's speed by GPS data;
- Dynamometer measurements (except when ship is without raft);
- Operational engine rotation speed;
- Operational engine fuel consumption during controlled time frame;
- Operational engine exhaust gas composition (concentration).

Samples of fuel used on ship were taken and laboratory analysis was done, determining calorific value and elemental composition. This data is needed to correct the engine's specific fuel consumption and exhaust gas composition analysis results.

2.4. Evaluation of cleaning efficiency

Nets efficiency (without frame) of cleaning water area from litter

$$Cap_{net} = 3600 \cdot k_{sh} \cdot L \cdot v, \text{ m}^2/\text{h}, \quad (17)$$

here: L – length of net, m; k_{sh} – coverage coefficient (0.7); v – speed, m/s.

Trawling the net with ship, used in the trials, fuel consumption and air pollutant emissions would be:

$$g_{fnet} = \frac{G_{fnet}}{Cap_{net}}, \text{ kg/m}^2. \quad (18)$$

Air pollutant emissions:

$$e_{netj} = \frac{E_{netj}}{Cap_{net}}, \text{ kg/m}^2, \quad (19)$$

j – air pollutant (CO_2, CO, NO_x etc).

Calculations were done in the range of speed v = 0.2–2.0 m/s.

If another ship is used for the trawling, for example with lower engine power, fuel consumption and emissions will be lower, because of greater relative engine power used for trawling and as a result that – reduction in emissions and fuel consumption

$$k_{net/ship} = \frac{C_{Rship} + C_{Rnet}}{C_{Rnet}} = 1 + \frac{C_{Rship}}{C_{Rnet}} \quad (20)$$

We can see that if the resistance factor for the ship decreases so does the amounts of emissions and fuel consumption. It is there for necessary to use low power ships for trawling operations that would ensure satisfactory efficiency of cleaning the marine litter and maximum performance of the tug boat.

3. Description of the experiment process

3.1. Test object

The test object was marine litter collection net, developed during the Marine Clean project. Net was, made very light and easy to handle. The length and width of the litter collection nets are given in (see Fig. 1 and Table 1).

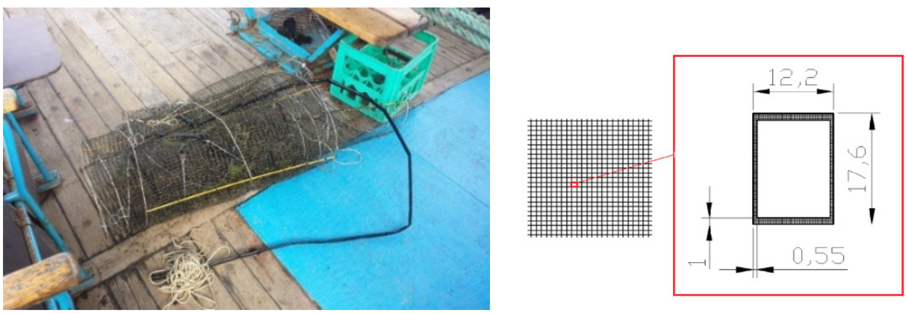

Fig. 1. Marine litter collection nets.

Table 1. Parameters of the litter collection nets.

Parameter of the net	Value
Length	6000 mm
Width	800 mm

Litter collection net was made from plastic, with horizontal float running along the upper part of the net. Net is made to collecting for floating litter in depth no more than 1 m.

To perform evaluation of the marine litter collection nets correctly keeping uncertainties to a minimum a special raft was designed and constructed to test the marine litter collecting net (see Fig. 2). To maintain rafts stability and flexibility in the windy weather conditions it designed to be fully adjustable and easily dismountable. It was built from relatively light materials and its total weights did not exceed more than 250 kg. The main dimensions of the raft in working operation are $L \times D \times H$ (6.0 × 6.0 × 1.5 m). In the middle of the raft the frame for net's mounting was designed, which purpose to keep the net completely outstretched and stably fixed on the raft during marine litter collecting operation, frames main dimensions are L × D × H (6.0 × 0.3 × 1.0 m).

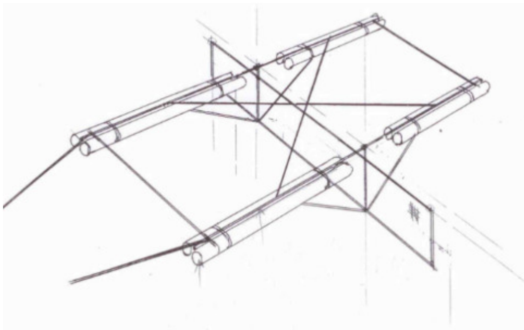

Fig. 2. Sketch of designed and constructed raft.

The preparation for the experiment done by: assembling of the raft, testing it's behaviour on water (stability and floating characteristics), preparing ship's fuel supply system for fuel consumption measurements. A gravimetric fuel consumption measurement system was installed on ship (see Fig. 3).

Fig. 3. The fuel measurement system, for fuel weight lost determination.

The test of net was performed at Curonian lagoon, that is joint with the Baltic Sea, near "Kiaulės nugara" island. The ship "Lagūna" (see Fig. 4) was used for trawling operations (raft with net) in different ship's engine speeds, each speed were kept constant during the trawling operation when ship was moving upstream and downstream. The testing principal was to maintain parameters constant while data was recorded.

Depending of the mode the engine's rotating speed where set. In the first and second mode's the engine speeds where 900, 1200, 1600 rpm. Higher speeds were avoided, because of the risks to lose or shred the net.

Ship's basic working parameters were determined in 6 speeds 800, 1000, 1300, 1600, 1800, 2000 rpm.

All testing modes (rafts with net installed, raft with net removed, ship without the raft) were performed in almost calm weather conditions. To maintain accuracy ships speed and other parameters were recorded after their stabilisation. When the ship reached the required speed the test started. At the same time the fuel consumption, exhaust gas concentration, dynamometer values, and data from ship's bridge (speed, engine rotation speed and weather conditions etc.) were recorded. All testing modes were performed in the same manner (see Fig. 5), only when ship was working without the raft; no dynamometer values have been monitored.

Fig. 4. Thug ship used during experiment (Rafta picture).

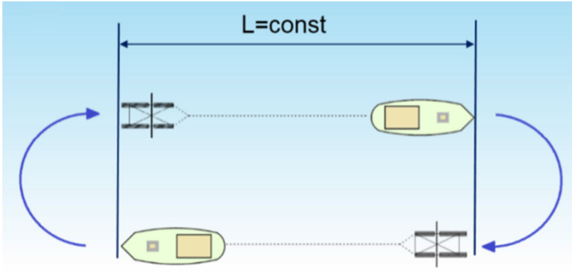

Fig. 5. The experiment execution scheme.

Weather conditions and water current speed was received from port's dispatcher.

Fuel consumption measurement where performed by capturing the change of fuel's weight during the given working mode. For the measurement we used the laboratory scale Precisa XB 10200G, and a glass bottle with 1 inlet and 1 outlet. The basic fuel system was changed without any complications, fuel supply hose was inserted in the glass bottle and the hose leading to the engines fuel pump was fixed in the lower end of the bottle. This measuring system simply extended ship's own fuel supply system. The returning from the engine fuel was connected to the bottle crating close loop system. The procedure required high concentration, because it was necessary to avoid air being sucked into the engine.

The ship's exhaust gas pollutant's concentrations were measured as well, for the determination of air pollutants we used portable gas analyser "Testo 350 MARITIME" which measure (CO_2, NO_x, SO_2 and CO) in accuracy from 5.0 to 0.2% depending on measured component and measurement mode.

The trawling resistance of the test system was measured too, for this we used the electronic dynamometer KERN HTS – max weight 10 t, it accuracy ± 0.1%.

To reduce the ships propeller's tabulated water influence on the dynamometers indication, the raft was dragged by 30 m long rope that have should provide enough distance to avoid turbulence from ships screw effecting net's resistance.

4. Results

Results of calculation of brake specific fuel consumption (b_e, g/kWh) are given in Fig. 6.

Results of nets resistance evaluation. The experiment data, for evaluation of the net's resistance were determined by measuring the increase of net's weight during the different trawling speeds. To get the specific resistance for tested net, the determined resistance of raft subtracted from the measured resistance of raft with installed net. The additional increase of power usage, fuel consumption and increase of air pollutants only for net were determined. The main experiment date is given in Table 2.

The theoretical calculation of the resistance for given speed range were done for the tested net, from two different sources in three equations: $R_{net}^{th}(1)$, $R_{net}^{th}(2)$, $R_{net}^{th}(3)$ (Naumov 2012; Revin 1959). To compare the test results and theoretical calculations of net's resistance the estimation in the speed range from 0.2 to 2 m/s were done, the results are given in graphical interpretation (see Fig. 7). The results shows that calculating of any net's resistance the results are very inconclusive, this is because different experiments gives values which mostly depends from accuracy assessing ambient conditions, and mostly from the specific net's parameters as material properties and geometrical characteristics.

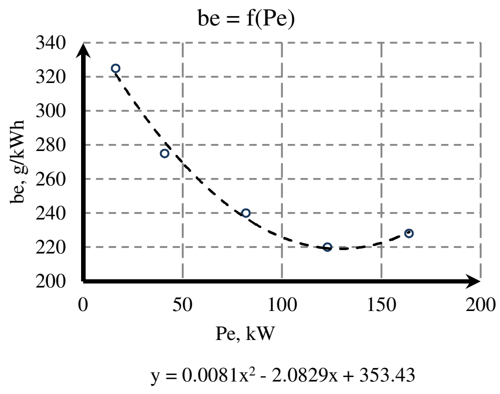

Fig. 6. Calculated brake specific fuel consumption of ship's "Lagūna" engine.

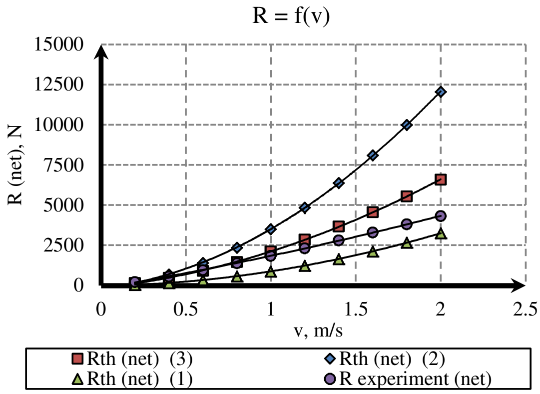

Fig. 7. Theoretical calculations of net's resistance comparison with experimental results (in speed range 0.2 to 2 m/s).

Table 2. The experiment data from net resistance measurement, the increase of trawling power, fuel consumption and specific air pollutants emission factors.

R	P_e	b_{eME}	G_f	eCO_2	eSO_2	eNO_x	eCO
N	kW	kg/kWh	kg/h	g/kg fuel	g/kg fuel	g/kg fuel	g/kg fuel
214.0	0.04	0.353	0.02				
551.2	0.22	0.353	0.08				
947.2	0.57	0.353	0.20				
1381	1.10	0.351	0.39				
1840	1.84	0.348	0.64	3112	0.02	10.9	1.9
2316	2.78	0.343	0.95				
2805	3.93	0.336	1.32				
3302	5.28	0.327	1.73				
3804	6.85	0.316	2.17				
4308	8.62	0.303	2.61				

Results of trawling capacity and air pollutants emission are given in Table 3.

Table 3. Specific net characteristics for water area, where test was performed.

v	e_{CO}^{net}	e_{NOx}^{net}	$e_{SO_2}^{net}$	$e_{CO_2}^{net}$	g_f^{net}	Cap_{net}
m/s	$kg/m^2 \times 10^{-7}$	$kg/m^2 \times 10^{-7}$	$kg/m^2 \times 10^{-9}$	$kg/m^2 \times 10^{-4}$	$kg/m^2 \times 10^{-5}$	$m^2/h \times 10^3$
0.2	0.095	0.54	0.10	0.156	0.5	3.0
0.6	0.42	2.4	0.44	0.69	2.21	9.1
1	0.80	4.6	0.85	1.32	4.23	15.1
1.4	1.2	6.8	1.2	1.94	6.23	21.2
1.8	1.5	8.7	1.6	2.48	7.96	27.2
2	1.6	9.4	1.7	2.69	8.64	30.2

One of main objects was to estimate the net's marine litter collection capability, and to calculate the extra fuel consumption and air pollutant emission during the experiment. From the experiment results, the special factors were made which could be used for earlier mentioned speed range.

5. Conclusions

1. Marine litter collection nets trials were carried out in Baltic Sea natural lagoon "Kuršių marios" (Curonian lagoon).
2. A special raft and frame have been developed for the trials of marine litter collection net. The net was fixed in frame in such way that is geometrical parameters would not change during trials. Nets plain was always perpendicular to the direction of the operation of the raft. Rafts resistance was measured using a digital dynamometer.
3. During the trials, the following parameters were measured:

- The ship's speed *v*, knot is determined by the GPS;
- Ship's fuel consumption, measured by weight;
- Composition of ships main engine exhausts gas; measured by automatic gas analyser;
- Resistance of raft with net and without net; measured with dynamometer.

4. During data analysis resistance of the net for speed range between 0.94 to 2.05 m/s were determined. The results were then extrapolated to 0.2 m/s. In this range power and fuel consumption that goes to overcoming the net's resistance were determined.
5. The tests results showed that net's resistance coefficient C_D is equal to 0.395. Comparing measurement results with theoretical evaluations using empirical formulas shows that the measurement results are within the range of estimated theoretical values.
6. Estimated corresponding fuel consumption and air pollutant emissions for ship and net, trawling and cleaning of 1 ha water area. Amounts of consumed fuel and air pollutant emissions depend not only on the net properties but also on the operational characteristic of ship's engine power and trawling speed. Optimal power of ship main engine for the trawling operations would be such that during trawling operation in different speed engine torque would always be maximum and the engine would be capable of operation in low speed.

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