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Development of an Energy Efficient Stern Flap for Improved EEDI of a Typical High-speed Displacement Vessel

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ABSTRACT

The surge in maritime trade is leading to large scale deployment of high-speed displacement ships by all nations. Cargo vessels are designed for a voyage in pre-determined routes at consistent speeds. On the other hand, high-speed displacement vessel engines designed with a capability to cater for top speeds are under-utilised during their normal course of operation. This sub-optimal utilisation impacts efficiency and increases emissions. In this study, a most favourable stern flap is designed for reducing the energy efficiency design index of a typical high-speed displacement vessel with a slender hull. CFD simulations and experimental model testing were conducted for 12 different stern flap configurations for determining most favourable flap design in the Froude no of 0.17-0.48. Performance of the most favourable stern flap was established by calculating, energy efficiency design index (EEDI) and fuel consumption based on typical operating profile. NO_x, VOC and PM emissions were estimated in with and without flap condition. Studies demonstrated that the stern flap reduced effective power demand, average fuel consumption and emissions by about 8 per cent, which when considered for the ship's operating life cycle, are significant. The most favourable stern flap reduced EEDI by 3.74 units and 1.98 units as compared to the bare hull condition and the required EEDI respectively, thereby demonstrating that EEDI could be used as an index to indicate stern flap efficiency.

Keywords: Energy efficiency design index; Energy saving device; Exhaust emissions; Stern flap

NOMENCLATURE

L	Length overall
B	Breadth
T	Draft
Fn	Froude number
R_T	Total resistance (KN)
P_E	Effective power (kW)
P_B	Engine brake power (kW)
V_{ref}	Ship velocity (knots)
MARPOL	Marine pollution
CO_2	Carbon dioxide
ODS	Ozone depleting substance
NOx	Nitrous oxide
SOx	Sulphur oxide
PM	Particulate matter
VOC	Volatile organic compound
GHG	Greenhouse gases
IMO	International maritime organisation
CFC	Chloro-Fluoro carbons
UV	Ultraviolet
EEDI	Energy efficiency design index
SEEMP	Ship energy efficient management plan
EEOI	Energy efficient operational Indicator
GloMEEP	Global maritime energy efficient partnerships
ITTC	International towing tank conference
SFC	Specific fuel consumption
QPC	Quasi propulsive coefficient

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1. INTRODUCTION

With maritime navigation taking the center stage of International trade and billions of dollars' worth cargo at stake, deployments of high-speed displacement ships have seen a surge worldwide. IMO, a specialised agency of United Nations in 1973 adopted the international convention for the prevention of pollution from Ships, which is now universally known as MARPOL regulations. Various resolutions adopted by IMO emphasise the need for research and development for the improvement of the energy efficiency of ships. One of the important landmarks of IMO was the adoption of the Energy Efficiency Design Index (EEDI) to control ship borne greenhouse gases (GHG) emissions. However, this index was not directly applicable to the surface combatants.

Unlike cargo vessels which generally voyage at the designed engine operating envelope, surface combatants operate in the sub-optimal regime, especially in loitering and cruise conditions. This is primarily because the surface combatant engines are selected to provide enough power for the top speed operations which are generally above 30 knot for a high-speed displacement surface combatant with slender hull. However, during the normal course surface combatants operate at lower to intermediate speeds ranging from 12-24 knot leading to increased fuel consumption and higher emissions. Even marginal reduction in energy consumption could lead to significant reductions in fuel consumption and exhaust emissions, increase in the speed and range, reduction in time between refueling and reduction in fuel-related infrastructure.

Of the many technologies that are available for energy saving, the stern flap has proved to be beneficial on high-speed displacement vessels, especially. Stern flap is known to improve the vessel's performance by recovering energy from the flow surrounding the ship. It was first developed by Cusanelli and was extensively used in US Surface combatants as reported by Karafiath[3],*et.al*. In this study, a stern flap is designed for reducing the energy efficiency design index of a typical high-speed displacement vessel with a slender hull. CFD simulations and experimental model testing were conducted for different stern flap configurations for determining the most favourable flap. Performance of the most favourable stern flap was established by calculating, EEDI proposed by Michalchuk[1], *et al.* & Stapersma[2] and fuel consumption. NO_x, VOC and PM emissions were estimated in with and without flap condition. Studies demonstrated that the stern flap reduced effective power demand, average fuel consumption and emissions. It was also thereby demonstrated that EEDI could be used as an index to indicate stern flap efficiency.

1.1 Ship Borne Emissions

Ships produce a variety of exhaust emissions that adversely affect both human health and the environment. Shipborne emissions primarily constitute, carbon dioxide (CO_2), nitrous oxide (NO_x), Sulphur oxides (SO_x), particulate matter (PM), ozone-depleting substances (ODSs) and volatile organic compounds (VOCs). GIoMEEP[4] report gives a detailed account of the adverse impact the shipborne exhaust emissions have on health and environment. As per the report, carbon dioxide, which is the primary ship borne GHG emitted from shipping amounted to 796 million ton of CO_2 in the year 2012 alone, which is forecast to grow exponentially in the period up to 2050.

1.2 Energy Efficient Technologies

Several energy efficient technology interventions are available to address the shipborne emissions discussed in the previous section and reduce the onboard fuel consumption. GloMEEP[5] categorised these energy efficient technologies into five principal group. i.e. machinery, propulsion and hull improvements, energy consumers, energy recovery and technical solutions for optimising the operation**.** The subject of this work includes study of energy saving device for resistance reduction to mitigate ship borne emissions. Of the many available energy-saving devices, a specific type of device called stern flap has been investigated.

1.3 Stern Flap as an Energy Saving Device

The form of the ship's hull greatly influences its efficiency. Ideally, a fine hull form would have the highest efficiency in terms of propulsion power consumption. However, in ship design, many different factors often govern the evolution of ship's hull form which may or may not lead to ideal hull shape. Therefore, ship hull form, like any other engineering problem is a compromise between various conflicting factors and is meticulously designed to meet various compelling criteria. Hull mounted energy saving devices are the cheapest options available for improving the energy efficiency of the ship. A stern flap is an energy saving device that can be easily fitted to a newly built ship or retrofitted to an existing ship. The stern flap was first developed by an American researcher Cusanelli for US Surface combatants (Karafiath[3], *et al.*). Various types of U.S surface combatants were installed with stern flaps and an estimated powering reduction ranging from 4%-19% was achieved depending on the type of vessel. After the success of stern flaps on U.S Surface combatants, these were fitted on similar vessels world over as well (Hemanth & Vijayakumar)[6,7]. Karafiath[3], *et al*. conducted extensive research into the hydrodynamics of stern flaps. It was reported that the primary mechanism by which the stern flap recovers energy is by slowing down the flow coming to it from the forward of the ship. This slowing down causes an increase in the pressure under the ship. The increase in pressure generates a forward thrust component in case of high-speed displacement ships and changes the trim in case of planing ships, to reduce the resistance. The design & development of the stern flap is an intricate process and is undertaken for a particular ship. In this study, extensive CFD studies and model testing are undertaken to arrive at a most favourable stern flap configuration.

2. DESIGN OF STERN FLAP

The scope of present work included the design of a most favourable stern flap for a generic high-speed displacement ship with a slender hull using CFD and experimental model testing. Previous research has shown that at very low speeds, performance enhancement by stern flap was not very evident at very low speeds. Therefore, in the current study, speeds from 0 kn - 10 kn were not considered which are essentially non-operational speed regimes related to entering and leaving the harbor and repositioning. In order to undertake the above analysis, hull fitted with flap configurations of chord lengths 1 and 1.5% of ship length, span of 42% and 58% transom width and three flap angles 5°, 10° and 15° were considered in the Froude no range of 0.17-0.48, with 02 kn increments. EEDI and fuel consumption was thereafter estimated for the most favourable flap. Details of the hull form is as indicated in Table 1 and stern flaps are as indicated in Table 2. 3D CAD model of the ship is indicated at Fig. 1.

Table 1. Details of hull form

Parameters	Value
L/B ratio	8.4
B/T ratio	3.9
Prototype displacement (tonnes)	4881.32

Table 2. Details of Stern flap

Parameters	Value
Chord length	1 and 1.5% ship length
Span	42% and 58% transom width
Angle	5° 10° and 15°

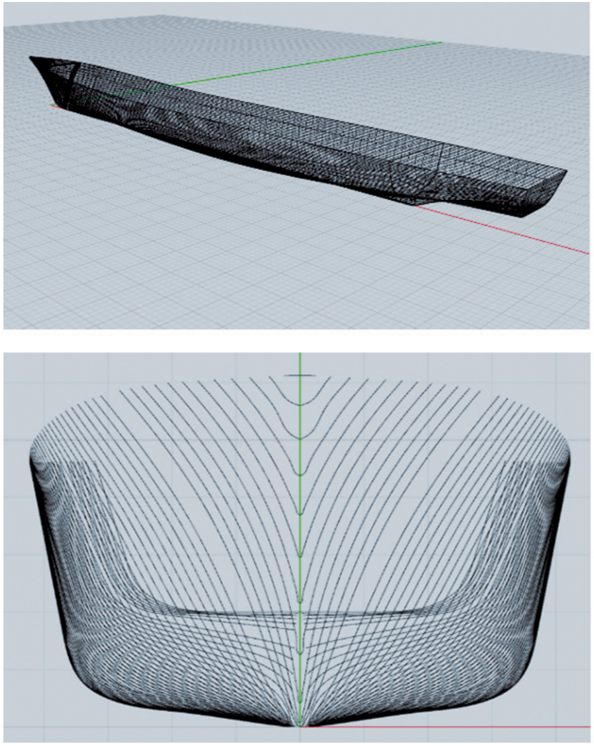


Figure 1. 3D CAD model of the ship.

2.1 Methodology

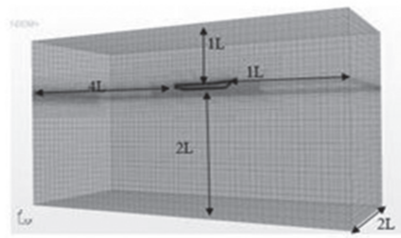
The methodology adopted for the study was firstly to estimate the resistance values of the hull from CFD simulations and towing tank tests on a bare hull model and validate the accuracy of CFD modelling. After ascertaining the accuracy of the results, simulations of the model hull form with various stern flap configurations were to be undertaken and the resistance values compared for drag reduction. Post-CFD simulations, stern flaps are fitted on to the hull model and analysed by experimental testing in a towing tank.

2.2 CFD Modelling and Validation

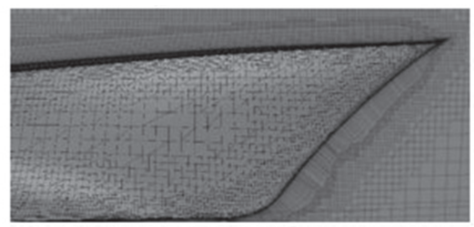
In order to accomplish the above strategy, a bare hull model (scale of 1:35) was first generated in CAD software (Rhino) which was then modelled in commercial CFD software Star CCM+. In this package, RANS equations are solved for solution to the governing equations. For the purpose of closure of Reynolds stress terms, k– ε turbulence model was used. Volume of fluid (VOF) method was used to capture the wave free surface effects. Dynamic fluid body Interaction (DFBI) method was used to couple fluid-body motions.

2.2.1 Setup of Computational Domain

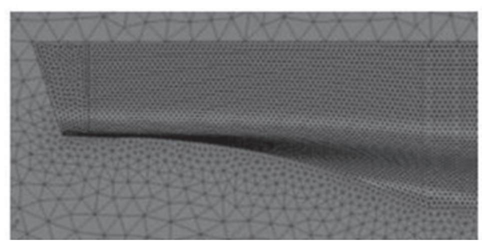
Modelling of the computational domain was undertaken as per ITTC Guidelines[8]. For the purpose of the present investigations, a rectangular domain was utilised. The velocity inlet exterior boundary is placed at 1L distance from the hull, whereas the pressure outlet boundary is located at 4L distance from the hull. Velocity inlet top and bottom boundaries are at 1L and 2L distances, respectively from the hull. Distance between velocity inlet side boundary and symmetry plane was taken as 2L.Since the hull model is symmetric about the centerline and in order to reduce the computational time, half hull model with wall condition was used for the numerical simulations. In order to improve the quality of the solution, a combination of structured and unstructured grids have been used. The Finite volume computational solver for the domain was discretised using hexahedral cells. Trimmer was utilised to trim these hexahedral cells to form polyhedral cells in the vicinity of the hull surfaces to accurately capture the surface curvatures. In the areas around the hull, near field transom stern region and kelvin wave region, volume grids were generated in order to capture the free-surface effects and flow pattern. In order to capture high flow gradients inside the boundary layer close to the ship hull, prism layer meshing was used. Details of the domain and mesh are as indicated in Fig. 2.



Computational domain



Surface mash of the hull form



Prism layer and volume mesh in the vicinity of the hull

Figure 2. Details of computational domain and mesh.

2.2.2 Grid Independence Study

Grid independence study was undertaken to minimise the discretisation errors due to the discretisation of the computational domain in to control volumes. Simulations were started initially with coarse meshing and thereafter was progressively refined to finer mesh. In this study, total resistance of the model hull was used as the criteria for monitoring the grid independency. Using each mesh formation, the simulation was undertaken for hull model fitted with flap of chord length 1% model length, 58% model transom width and turning angle of 5° for the Froude number of 0.25. The results of grid independence study are as indicated at Table 3 and Fig. 3. Based on the grid independence study, the grid independent solution was arrived at a grid configuration with 1.46 million cells. This configuration was used for further study

Table 3. Grid convergence

No of cells (millions)	Model resistance (N)
0.7	8.76
1	8.72
1.46	8.60
1.8	8.60

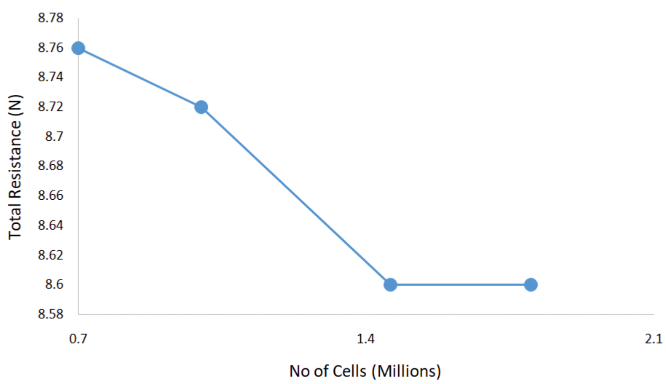


Figure 3. Grid independence study.

2.2.3 Validation

The CFD model used in this study was validated with the experimental resistance results obtained in towing tank tests. Resistance trends obtained computationally for w/o flap condition match fairly well with experimental data. The results are as plotted in Fig. 4.

The comparison between CFD and experiment shows good agreement at lower Froude numbers. Marginal divergence starts to appear above Froude numbers 0.31. The divergence was of the order of 10% which is considered reasonably accurate and can be used for carrying out further investigations. At this Froude number, the transom moves from wet condition (portion of transom is immersed) to dry condition (no transom is immersed) and there is an abrupt dip in the free surface just behind transom with a clean flow separation from the transom edge. From this Froude number onwards generation of lift under the transom stern, wave formation and spray at the bow region are significant. This coupled with usage of single grid method in CFD are attributable for marginal divergence at intermediate and higher speeds. Mesh refinement has been undertaken to limit the divergence to about 10%.

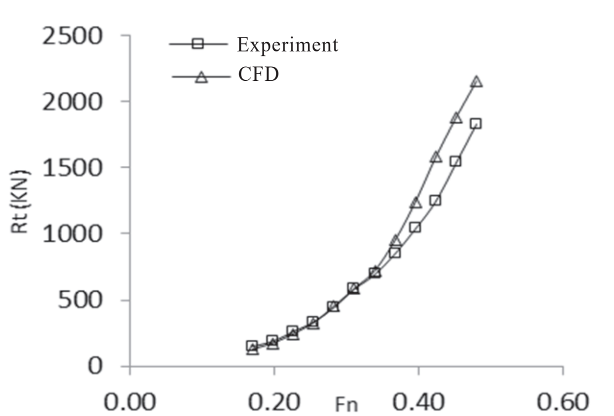


Figure 4. Experimental vs. Numerical resistance values.

2.2.4 Model Experiments

Post completion of CFD analysis, physical FRP hull model was fabricated. The model scale (1:35) was selected based on hydrodynamic considerations. FRP hull was manufactured to the geometric scale according to ITTC recommended procedures[9]. The manufactured hull model is as shown (Fig. 5).

Towing tests were conducted at the IITM towing tank facility where extensive research was previously undertaken on wedge flap design by Lijo[10], *et al*. The tests were conducted in even keel condition. After the conclusion of the model tests for bare hull and 12 configurations of the stern flaps indicated, resistance values are obtained for the best performing candidate from among the 12 different configurations tested, with constant chord length 1.5% L, span 42% B and angles 5°, 10° and 15°. In Tables 4, 5 and Fig. 6, the Froude number is a non-dimensional number given by $Fn = \frac{V}{\sqrt{gL}}$ Froude no 0.17 corresponds to lowest speed and 0.48 corresponds to the maximum speed. It can be seen that the introduction of the most favourable stern flap reduced the resistance values of the ship as compared to the without flap condition (bare hull). The highest reduction

Figure 5. FRP ship model (1:35 Scale).

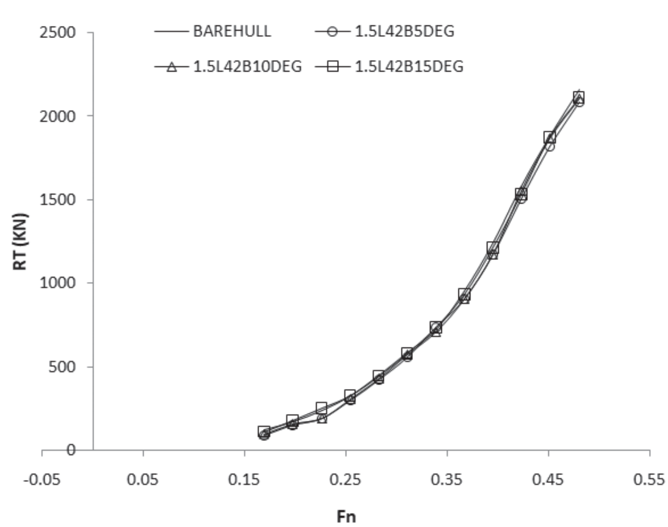


Figure 6. Resistance curve (entire Froude no range).

Table 4. Model test resistance value

Froude No (Fn)	Bare Hull	5D-1.5L42%	% Reduction in Resistance	10D-1.5L42%	% Reduction in Resistance	15D-1.5L42%	% Reduction in Resistance
0.17	4.28	3.53	17.59	3.76	12.24	4.05	5.32
0.2	5.83	5.46	6.38	5.55	4.76	6.04	3.65
0.23	7.88	6.81	13.54	6.87	12.83	8.13	3.23
0.25	10.42	9.89	5.12	10.05	3.52	10.45	0.29
0.28	13.81	13.15	4.78	13.33	3.48	13.71	-0.75
0.31	17.4	16.83	3.29	17.22	1.06	17.37	-0.20
0.34	21.24	21.74	-2.34	21.01	1.06	21.65	1.92
0.37	27.12	26.16	3.55	26.10	3.76	26.79	-1.23
0.4	34.34	32.81	4.47	32.85	4.33	33.75	-1.71
0.42	43.03	41.39	3.81	42.44	1.36	41.91	-2.61
0.45	50.51	49.12	2.76	50.22	0.58	50.34	-0.33
0.48	57.83	56.31	2.62	56.77	1.84	56.90	-1.61

Table 5. Ship resistance values

Froude No (Fn)	Bare Hull	5D-1.5L42%	% Reduction in resistance	10D-1.5L42%	% Reduction in resistance	15D-1.5L42%	% Reduction in resistance
0.17	124.28	90.35	27.30	100.51	26.31	113.64	8.57
0.2	170.80	153.78	9.97	157.92	8.37	179.43	-5.05
0.23	241.10	193.11	19.90	195.58	23.57	251.46	-4.30
0.25	326.15	301.70	7.50	309.01	5.68	326.41	-0.08
0.28	452.02	421.70	6.71	429.58	5.32	446.17	1.29
0.31	585.69	558.90	4.57	576.06	1.72	582.67	0.52
0.34	720.77	740.87	-2.79	709.14	1.57	736.94	-2.24
0.37	952.37	907.95	4.66	905.44	5.17	935.63	1.76
0.4	1242.69	1172.56	5.64	1174.67	5.80	1214.48	2.27
0.42	1583.73	1509.06	4.72	1555.39	1.88	1531.72	3.28
0.45	1883.21	1818.80	3.42	1867.41	0.87	1872.97	0.54
0.48	2158.34	2088.55	3.23	2108.40	2.39	2114.25	2.04

of resistance was exhibited by 5° flap i.e. 8%. These model resistance values were extrapolated to obtain the full-scale ship resistance values using Froude's method[11].

Similar to the trend obtained in the model tests, all three stern flaps (5°, 10° and 15°) decreased the resistance, while 5° stern flap produced a maximum reduction in the total ship resistance (R_T). Resistance trends for the ship with and without flaps are as indicated in Fig. 6.

In order to have a better appreciation of resistance reduction accrued by the stern flap, resistance trends in lower Froude number range have been separately indicated in Fig. 7. It can be seen clearly seen that the 5° flap in addition to high speed performance i.e. above Fn 0.31, performed better as compared to the 10° and 15° flaps, especially in lower/ intermediate regime which is significant considering the profile of the vessel, where the vessel spends most of its voyage time. The performance observed for flap substantiates the conclusions of an integrated wedge flap design reported recently by Lijo[10] *et.al*. especially with regard to advantage accured in resistance due to the usage of larger chord length and enhanced performance above a critical Froude number of around 0.31.

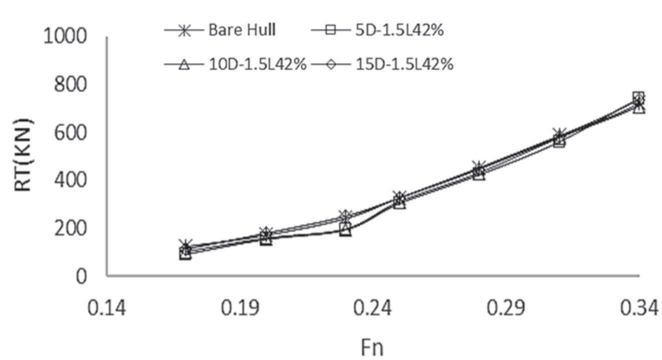


Figure 7. Resistance curve (low Froude number range).

3. ESTIMATION OF ENERGY EFFICIENCY DESIGN INDEX

After establishing the efficacy of stern flap in reducing the resistance, estimation of fuel efficiency was calculated based on typical time profile of a high-speed displacement vessel (Fraser [12]). For the subject high-speed displacement vessel with slender hull form, the Froude no range of 0.17-0.48 was considered which accounts for 100% of its operational time, corresponding to 50% of total voyage time in a typical 71-day at-sea deployment. In these calculations, it can be reasonably assumed that resistance variation can be considered as a good indication of propulsive power and thereby relative fuel usage. Table 6 indicates the resistance values for the full-scale ship in bare hull condition and ship fitted with 5^o flap.

In order to calculate the fuel consumption, the engine brake power was calculated. For this purpose, quasi propulsive coefficient (QPC) was considered as 0.62, shaft transmission efficiency was considered as 0.97and 15% engine derating was considered. Specific fuel consumption (SFC) was taken as 216 g/kWh. The vessel was estimated to spend a total of 1704 h at sea.

Table 6. Comparison of extrapolated full-scale ship resistance values in w/o flap and with flap condition

Froude No (Fn)	Bare hull resistance (KN)	5D-1.5L42 % (KN)
0.17	124.28	90.35
0.2	170.80	153.78
0.23	241.10	193.11
0.25	326.15	301.70
0.28	452.02	421.70
0.31	585.69	558.90
0.34	720.77	740.87
0.37	952.37	907.95
0.4	1242.69	1172.56
0.42	1583.73	1509.06
0.45	1883.21	1818.80
0.48	2158.34	2088.55

From Table 7 above, it is clear that stern flap attached to the transom of a high-speed displacement vessel reduced the average fuel consumption by 16% in low Froude nos and 3% in the intermediate Froude nos and 5% in high-Froude no regimes w.r.t the bare hull condition and time profile of the ship, which translates into significant cost savings and emissions reduction over the lifetime of the ship. The average reduction in fuel consumption achieved across all the Froude numbers is 8.8%. The variation in fuel saving is attributed to the fact that in higher Froude no regimes, with the increase in Froude number the power requirement increases exponentially. EEDI calculations were performed for the vessel in with and without flap condition in order to investigate the efficacy of the stern flap in reducing the CO_2 emissions, which is the primary GHG. IMO as a part of its technical measures to reduce GHG's from ships, established Energy efficiency design index (EEDI) for ships in 2011. The aim was to make all the new ships 10% more efficient by the start of 2015, 20% more efficient by 2020 and 30% more efficient by 2025. The EEDI is essentially a measure of the ship's energy efficiency in terms of the CO_2 emissions per ton-mile of goods transported relative to a reference value. The equation for the calculation of EEDI for commercial vessels with conventional propulsion was given as: -

$$EEDI = \frac{\left(\prod_{j=1}^{n} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)}.C_{FME(i)}.SFC_{ME(i)}\right) + (P_{AE}.C_{FAE}.SFC_{AE}) + \left(\left(\prod_{j=1}^{n} f_j.\sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)}.P_{AEeff(i)}\right)C_{FAE}.SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)}.P_{eff(i)}.C_{FME}.SFC_{ME}\right)}{f_i.f_c.f_l.Capacity.f_w.V_{ref}}$$

Table 7. Fuel consumption in with and w/o flap condition

Speed (kn)	Brake Power (KW) - W/o Flap	Brake Power (KW) -Flap	% time	Fuel Consumption (t) - W/o Flap	Fuel Consumption (t) -Flap	% Reduction in fuel consumption
0.17	1500.76	1091.01	0.21	116.00	84.33	27.3
0.2	2406.24	2166.44	0.11	97.42	87.71	10
0.23	3881.84	3109.17	0.02	28.58	22.89	19.9
0.25	5907.61	5464.74	0.03	65.23	60.34	7.5
0.28	9097.15	8486.90	0.03	100.45	93.71	6.7
0.31	12966.03	12373.01	0.03	143.17	136.62	4.6
0.34	17407.12	17892.62	0.01	64.07	65.86	-2.8
0.37	24917.19	23754.83	0.03	275.13	262.30	4.7
0.4	35013.90	33037.98	0.01	128.87	121.60	5.6
0.42	47810.26	45555.96	0.01	175.97	167.68	4.7
0.45	60641.01	58567.02	0	0.00	0.00	NA
0.48	73844.42	71456.44	0	0.00	0.00	NA

$P_{ME/AE}$ 75% of rated installed power of main and auxiliary engines at V_{ref}

Capacity Deadweight

C_f Carbon factor

V_{ref} Ship speed (knots)

f_j Factor to account for ship-specific design elements

fw Non-dimensional coefficient indicating a decrease in ship speed due to sea conditions

f_c Cubic capacity correlation factor

f_i Factor for general cargo ships.

However, the above formula could not be directly applied to surface combatants. Hence in 2014, EEDI equation for surface combatants was given by Michakchuk[1], *et al*. as:

$$WEEDI = \frac{C_F \cdot \left(\sum_{i=1}^{nME} P_{ME(i)}.SFC_{ME(i)} + P_{AE(i)}.SFC_{AE(i)} \right)}{\Delta_{deep}.V_{ref}}$$

where,

P_{ME} Power of engines at cruise speed

Δ_{deep} Deep displacement (tonnes)

V_{ref} Cruise speed (knots)

The above formula estimates the EEDI for a particular cruise speed but does not account for the time profile. The formula was later modified by Stapersma[2] to capture the effects of ship's time profile:

$$IWEEDI = C_F.(\sum_{i=1}^{nME} P_{PROP(i)}.SFC_{MAIN(i)} + \frac{(P_{AE(i)} + P_{MISC(i)}).SFC_{AUX(i)}).W_{f,i}}{\Delta_{deep}.\sum_i V_{ref,i}.W_{f,i}}$$

$$P_{prop} = \eta_{trm}.P_D \text{ [13]}$$

η_{trm} Transmission efficiency (0.97)

P_D Delivered power

Δ_{deep} Deep displacement (tones)

V_{ref} Ship speed (knots)

I Operating point (in the present study, every speed in the operating profile was considered as an operating point)

$W_{f,i}$ Weight factor of the operating point (fraction of time spent by the vessel)

Required EEDI is calculated using the equation (Stapersma[2]):-

$$EEDI_{req} = \frac{a}{b^c}$$

a = 1040.1, b = displacement (4748t), c = 0.381

Akin to any typical modern-day high-speed displacement vessel, hybrid propulsion with a combination of diesel engines as cruise engines and gas turbines as boost engines were considered. Warship EEDI calculation was undertaken for all flaps and values indicating CO_2 emissions thus obtained in with flap and bare hull condition are as indicated in Table 8.

From the above-attained EEDI values, it can be clearly established that stern flap with chord length 1.5% L, span 42%, angle 5° has reduced EEDI (indicative of CO_2 emissions) by 3.74 units as compared to bare hull condition and 1.98 units when compared to the baseline required EEDI value. In addition to the CO_2 emissions, stern flap performance regarding reduction in emissions of other pollutants such as NOx, VOC, and PM were calculated based on estimated fuel consumptions at each speed for a 71-day trip as per the equation (Trozzi[14]):

Table 8. EEDI value comparison in w/o flap and with flap conditions

Condition	Attained IWEEDI	Bare hull IWEEDI	Required IWEEDI
1.5L42B5DEG	44.93	48.67	46.91
1.5L42B9DEG	45.71	48.67	46.91
1.5L42B10DEG	45.80	48.67	46.91
1.5L42B15DEG	47.95	48.67	46.91
1.5L58B5DEG	47.06	48.67	46.91
1.5L58B9DEG	46.16	48.67	46.91
1.5L58B10DEG	47.52	48.67	46.91
1.5L58B15DEG	46.04	48.67	46.91
1L42B5DEG	46.59	48.67	46.91
1L42B9DEG	47.27	48.67	46.91
1L42B10DEG	47.64	48.67	46.91
1L42B15DEG	47.57	48.67	46.91
1L58B5DEG	46.28	48.67	46.91
1L58B9DEG	47.06	48.67	46.91
1L58B10DEG	47.88	48.67	46.91
1L58B15DEG	48.06	48.67	46.91

$$E_{Trip,i,j,m} = \sum_p \left(FC_{j,mp} + EF_{i,j,mp} \right)$$

E_{Trip} Emission over the complete trip (tonnes)

FC Fuel consumption (tonnes)

EF Emission factor (kg/tonne)

P Phase (loitering, cruising, etc.)

i Pollutant

j Engine type

m Fuel type

The NOx, VOC and PM emissions reduced by about 8.8% by the usage of stern flap. In summary, it has been established that usage of the stern flap on high-speed displacement vessel as an efficient energy saving device contributes to reducing the EEDI and other emissions.

4. CONCLUSIONS

This paper evaluated the effectiveness of stern flap most favourable for fitment on a high-speed displacement vessel with a slender hull form and its response to operations at various speeds. It also investigated the potential of the stern flap as an energy saving device. Inspite of challenging engine operating envelope and operating profile of a high speed displacement vessel, it has been shown that a suitably designed stern flap reduced the EEDI by 3.74 units w.r.t bare hull condition and fuel consumption, NOx, VOC, PM emissions by about 8.8%. The study has also demonstrated the EEDI could be used as a performance indicator for the stern flap. Similarly, EEDI could be used as a performance index for other energy saving devices as well.

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Current research was entirely undertaken under his guidance.