An Analysis on Emissions from Ocean Going Vessel: Effective and Efficient Methods to Reduce Ship Emission

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Abstract:

Shipping sector is a key contributor to emission, as more than 85% of global trade is transported by around 90,000 ships of various types viz., tankers, container ships, bulk carriers etc., which uses category-3 marine compression ignition (CI) engine (Power output: 2500 to 70000 kW) that contributes significantly to air pollution. One of the most significant air pollution sources are ship-generated emissions. Ship emission results in acidifying the ocean and fundamentally changing its remarkably delicate geochemical balance. The average pH at the ocean surface was increased from 8.1 to 8.2.Emission control technologies available for category-3 engines are limited. Highly dense and viscous residual fuel oil (RFO) emits high ash, SOx, NOx (20-50%) and PM (750-1250%) as compared to distillate fuel.Statistical analysis on emission is donefor various ships that usedifferent fuels.The purpose of this paper is study various emission control techniques to reduce NOx, SOxand other pollutants. Emission data onboard SagarManjusha was collected to analyze the concentration of each pollutant and to arrive at suitable remedial measure to mitigate.

Keywords:CI Engines, Distillate Fuel, Emissions,Global Warming, NOx, SOx.

I. INTRODUCTION

Marine transportation is a key component of world economy. Ships transfer about85% of worldwide trading goods. About 75% of maritime routes are within exclusive economic zone (EEZ) limit, which influences air quality in coastlines. CI engines are widely used in marine vessels ranging from yatch to huge cargo vessel.Compared to automobiles, the quality of fuel used in ships is inferior, highly viscous and contains higher Sulphur.Ship CI engines that uses RFO contributes considerably to marine pollution.Rise in global temperature and melting of glacier and polar ice resulting damage to ecosystems and contribute to ocean acidification. Efforts are taken by Engineers and Scientists to minimize the emission of pollutants viz., Carbon dioxide (CO_2), Carbon monoxide (CO), Hydrocarbons (HC), Oxides of Nitrogen (NO_x), Sulphur dioxide (SO_2) and Particulate matter (PM) to the environment during incomplete combustion of an Internal Combustion engine. International Maritime Organization (IMO) is also introduced specific regulations to control the concentrations of these pollutants in exhaust gases and thereby limiting the presence of such pollutants in the environment. Various ways to reduce emission from ship are discussed here. Fig.1 shows CO_2 emission for dry bulk carriers.

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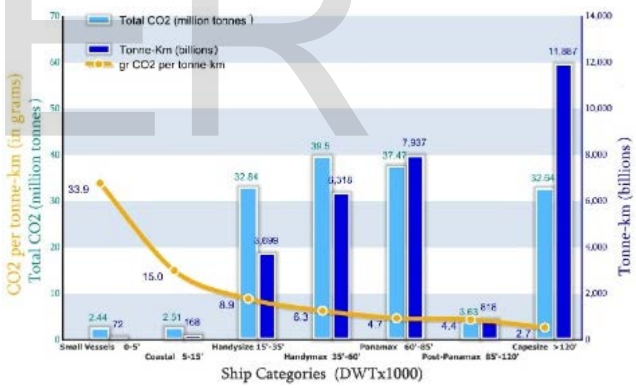

Fig.1: Ship Emissions Data

1.1 Objectives

This study has the followingobjectives:

- To study factors affecting emission for various vessels and for different fuels.
- To analyze the methodologies to minimize emission.

1.2 Emissions Influencing Factors

1.2.1 Engine Types*:* Ship main engines are designed to provide necessary power for propulsion while onboard electricity is generated by auxiliary engines. Main and auxiliary CI engines are classifiedinto high, medium and slow speed, based on engine speed available at the crankshaft. Since engine type will affect the

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prevailing combustion conditions, level of emissions of pollutants will also be influenced.

1.2.2 Types of Fuel:A variety of fuels ranging from marine distillatesto heavier residual oils, which are classed based on their viscosity are used in marine engines. Marine gas oil is light and clean distillate oil containing no residual fuel oil. Marine diesel oil is a heavier distillate and may contain some residual fuel oil. Marine distillate fuels are largely used by fishing vessels, whereas bigger vessels user heavy oils that requires preheating. Some pollutant emissions viz., CO_2, SO_2 and metal emissions are predetermined solely by their fuel content irrespective of the engine combustion conditions.TABLE-I shows percentage share of marine fuel oils.

Table-I: Market Share of Marine Fuel

Fuel Type	Market Percent	Consumption per Year (MMT)
Heavy fuel 500 CSt	10	33
Heavy fuel 380 CSt	60	200
Heavy fuel 180 CSt	6	20
Distillate fuels	23	77
Others	1	3
Total	**100**	**333**

1.2.3 Ship Operational Mode:Some emission factors are dependent engine operations. Idling and rapid load changes give rise to more pollutants associated with incomplete combustion.At sea and maneuveringmain engine emissions dominatesover auxiliary engine emission where as in port generator emission only exists. Fig. 2 represents emission for various vessel types.

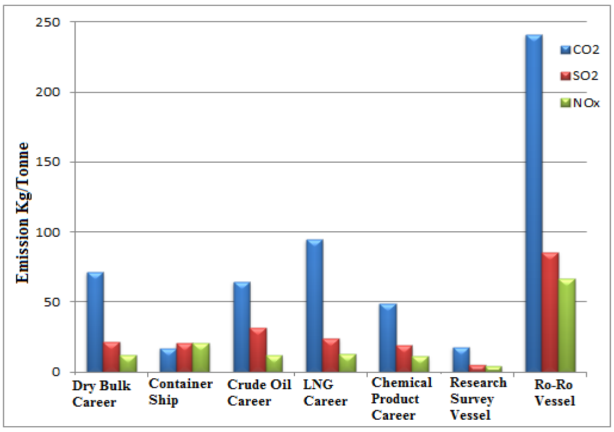

Fig. 2: Emissions vs. Vessel types

1.3Major Emissions from Ship Engines

Exhaust fumes from ship engines contain various materials which have negative environmental effects. Sulfur dioxide (SO_2) is a well-known acidic material; however nitrous oxides (NOx) also contribute to acidification.

1.3.1 Nitrogen Oxides (NOx):Nitrogen dioxide (NO_2), nitric oxide (NO) and other oxides of nitrogen together called as NOx. Combustion processes release mostly NO and NO_2. Exhaust NOx from marine diesel engines combines with hydro carbons in the atmosphere forming ozone which produces smog. Nitrous oxide is considered to be the most important ozone depleting substance.Excess atmospheric NOx contribute to acid rain. Equation (1) represents formation of Hydrochloric acid, when nitric acid from acid rain mixes with sea water. Up to 55% of original sodium chloride in aerosols may be replaced by sodium nitrate.TABLE-II represents major sea watercomposition. Apart from this many trace elements viz., Manganese (Mn), Lead (Pb), Gold (Au), Iron (Fe) and Iodine (I) exist in sea water which occur as parts ppm or ppb.

Table-II: Average Sea water Compositions

Composition	Mg/L	Percentage
Sodium (Na^+)	10800	30.72
Potassium (K^+)	400	1.14
Magnesium (Mg^{2+})	1300	3.70
Calcium (Ca^{2+})	410	1.17
Chloride (Cl^-)	19400	55.19
Bicarbonate (HCO_3^-)	140	0.40
Sulphate (SO_4^{2-})	2700	7.68
Silica (SiO_2)	2	0.01

$$NaCl + HNO_3 \rightarrow NaNO_3 + HCl \text{ ---- (1)}$$

Two sources of NOx are Fuel NOx related to nitrogen content of fuel and Thermal NOx related to chemical formation of NOx from N_2 and O_2 at 1400°C.

$$\text{Emission} = \sum \Phi_{ijk} \times C_{ijk} \text{ ----- (2)}$$

whereΦ: Emission Factor (g/GJ),

C: Energy consumption (GJ),

i: Fuel type, j: Sector or activity, k: Technology type

1.3.2 Oxides of Sulphur (SOx):Un-burnt fuel in CI engine produces small particles of sulfur and carbon that combines with oxygen to form SOx. Percentage of Sulphur in fuel decides the quantity of SOx which when combined with water vapor, results in acid rain. Fig. 3 shows the level of sulphuric acid in pH of sea water. Equation-3 represents SOx emission factor

$$\Phi = (1-r) \times S/H \text{ ----- (3)}$$

where S = Sulphur content, H = thermal content,

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r = mass fraction of sulfur retained in the ash

1.3.3 Chloroflorocarbons (CFC's):CFCs are extremely poisonous and main reason for ozone depletion. Global shipping fleet emits approximately 3,000-6,000 tons of CFCs. Fig. 4 and 5 shows the CO_2, CH_4, N_2O levels from Marine distillates and Residual Oil.

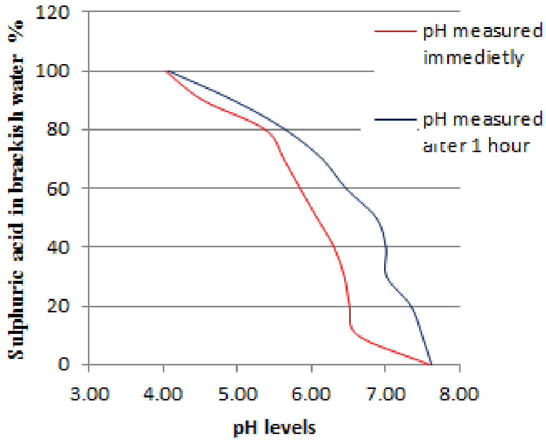

Fig. 3: Sulphuric Acid vs. pH of Sea Water

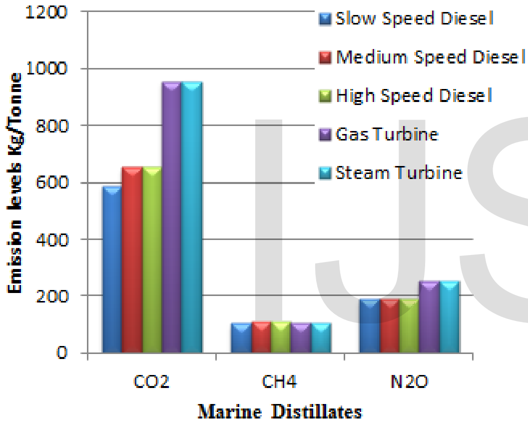

Fig. 4: CO_2, CH_4, N_2O from Marine Distillates

1.3.4Particulate Matter:PM consists of tiny solid particles and liquid droplets which consist of soot, dust, salt, acid and metals that are less than 10 microns in diameter appear as a cloud or fog. Fig. 6 shows the PM emission from Marine Distillates and Residual oil. TABLE – III represent the Nitric acid to acidity.

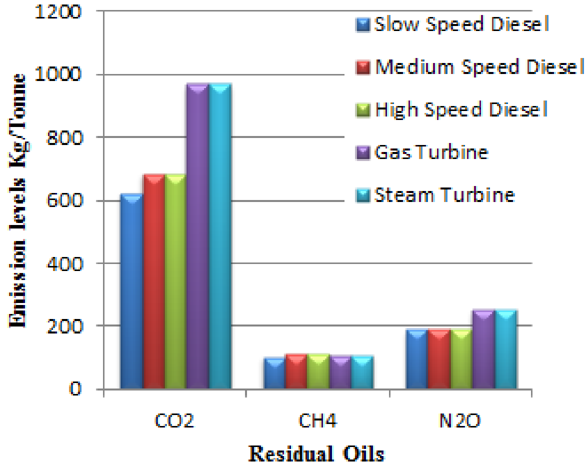

Fig. 5: CO_2, CH_4, N_2O emission from Residual Oil

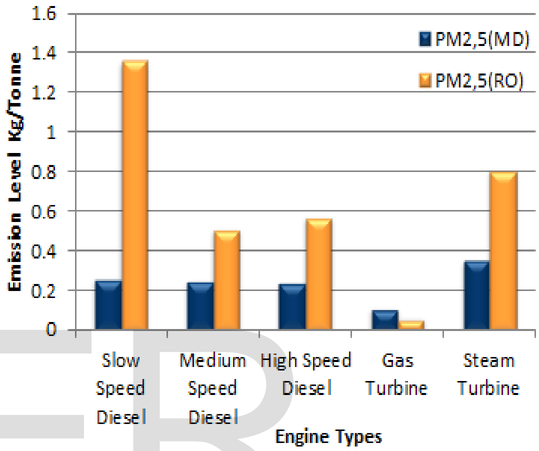

Fig. 6: PM from Marine Distillates & Residual Oil

Table-III: Contribution of Nitric acid to the Acidity

Parameter	Quantity		
Sulphur content in fuel (%)	3.5	1.5	0.5
Specific NOx emissions (g/kWh)	20	20	20
SO_2 removed (%)	30	95	95
NOx removed (%)	20	20	20
Discharged cooling water (t/h)	30	30	50
H_2SO_4 (mg/L)	631	270	90
NO_2contribution to acidity (%)	20.34	37.34	64.13

*4 Main and 2 Auxiliary Engines at 85% MCR

1.4 Emission Measurement Techniques

Gas concentration method is one of the main techniques used to measure emission. It is categorized into two types.

1.4.1 Non Separation Methods: Here candidate gas is not isolated from the mixture.Following are the three main types of Non separation methods.

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- Non Dispersive Infrared Analysed (NDIR)

- Differential Absorption LIDAR (DIAL)

- Chemiluminescence NOx detection

1.4.2 Separation Methods: In this method gas is separated from the mixture is being measured.Two main types of separation methods are

- Gas Chromatography

- Orsat Gas Analyser

II. EMISSIONCONTROL TECHNOLOGIES

Ocean absorbs 25 to 30% of CO_2 emissions. About 89% of the CO_2 dissolved takes the form of bicarbonate ion, about 10% as carbonate ion, and 1% as dissolved gas. Skeletons of snails, clams, crabs and lobsters are formed using carbonate. CO levels influence the physiology of water breathing organisms of all kinds. Acidification of seawater affecting the marine life that ultimately affects land based animals including humans.

Research is underway for developing new emission control technologies as IMO urged for reducing marine pollutions. AnnuallyMarine vessels consumes 300 million tons of fuel, estimated to emit 1.2-1.6 MMT of particulate matter, 12-14 MMT SOx emissions and 22-24 MMT NOx emissions. Marine pollution act 73/78 Annexure VI sets limits on ozone depleting substances viz., global Sulphur emission to 3.5%, then progressively to 0.5%, effective from 1stJanuary 2020. Two broad classification of emission control technologies are in cylinder control solution and post treatment.

2.1 NOx Reduction Techniques:

Following are few NOx reduction techniques used.

2.1.1 Homogeneous Charge Compression Ignition (HCCI):

It is a process in which the charge is premixed before being compression ignited and it can be used for the fuel other than diesel. In real HCCI engines there are always some thermal or mixture in homogeneities and it is sometimes desirable to introduce additional stratification. HCCI is having advantage of allowing good control over the mixture distribution, since fuel/charge distribution are established prior to the final compression to autoignition. It is suitable for high load application since it allows for good air utilization.

2.1.2 Low Temperature Combustion (LTC):

It is suitable for diesel engines in which the auto ignition is closely coupled to the fuel-injection event to provide control over ignition timing. LTC depends EGR and 10-150 CA injection time shifting, which results in lower temperature that delays ignition and provides more time for premixing. Though it is a main advantage, but it is difficult to implement in practical engines.

2.1.3 Timing Retard:

Retarded fuel injection timing is the simplest way to minimize NOx from a ship diesel engine. About 6-8 g/kWh of NOx reduction is possible at a cost of an increased fuel consumptionof 5-7 g/kWh. Increased fuel consumption increases the specific CO_2.

2.1.4 Humid Air Motor (HAM):

HAM technique can result in up to 60% reduction of NOx emission level. Rearrangement of air supply system and additional space required are the main limitations to install HAM equipment in existing ship engine. Fig .7 shows the pictorial representation of a HAM system.

2.1.5 Miller Cycle:

Lower compression ratio, high pressure turbo-charging, variable air inlet valve timing and charge air cooling are the changed features from conventional engine. This results in lower combustion chamber temperature with same power output.

2.1.6 Selective Catalytic Reduction (SCR):

SCR is a technique of controlling NOx emissions from lean-burn IC engines which are characterized by an oxygen-rich exhaust. Over 90% of NOx emission can be reduced in this technique. In presence of reducing agent (Urea or NH_3), the catalyst selectively targets NOx, this technology is named as SCR. Schematic representation of SCR system is shown in Fig.8. Urea/ ammonia is dosed ahead of catalyst bed, based on the measured NOx level or by its predicted concentration knowing the engine's operating parameters. Equation 8 shows the chemical reaction in SCR system.

$$NO + NO_2 + 2NH_3 \rightarrow 2N_2 + 3H_2O \text{ ----- (4)}$$

A solution of urea or ammonia is injected on the exhaust gas at a temperature of 290-350°C. The catalyst promotes a reaction between ammonia and NOx to form nitrogen and water vapor when this mixture is passing on it. Major demerits of SCR system includes complexity of system, high operating and capital costs and disposal of spent catalyst. 5-7% of reducing agent is consumed as compared to fuel burnt. Electronic control system is used to calculate precise quantity of reducing agent to ensure more than 90% of NOx reduction. High combustion temperatures lead to economical fuel consumption and low particulate levels but increases NOx.

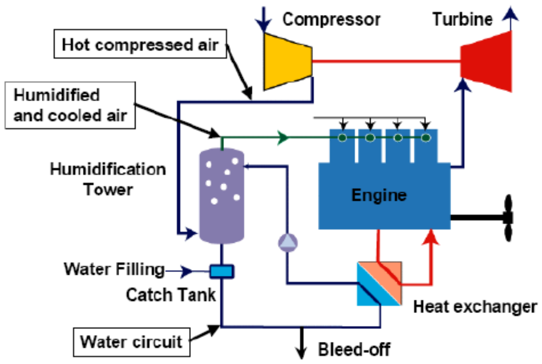

Fig. 7: Scheme of HAM System

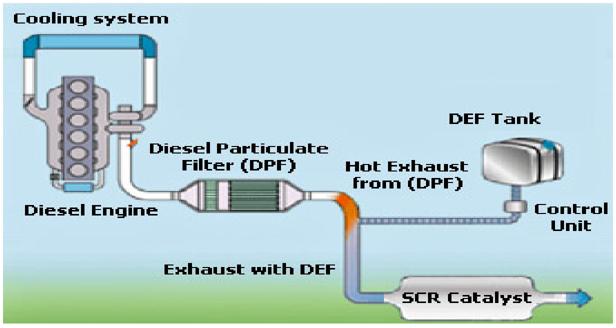

Fig. 8: Scheme of SCR System

2.2 SOx Reduction Methods:

Few SOx reduction methods are discussed below.

2.2.1 Flue Gas Desulphurisation (FGD):

FGD is removal of SO_2 from exhaust. Apart from SO_2, FGD also removes NOx and particulate matter, which have impacts on acidification. Few FGD technologies are discussed here.

Limestone/Gypsum System:A solution of powdered limestone dissolved in water is injected into exhaust. SO_2 reacts with calcium ions forms calcium sulphite slurry which when passed through compressed air forms calcium sulphate. Around 90% of SO_2 will be removed. Main limitations are limestone has to be stored and gypsum waste in large quantities is produced.

Spray Dry System: Here slurry of slaked lime is injected into the flue gases in a fine spray and the flue gases are simultaneously cooled. SO_2 reacts with slurry and forms a solid reaction product.

Wellman-Lord Process: In this method hot exhaust gases are passed through a pre-scrubber where ash, hydrogen chloride, hydrogen fluoride and SO_3 are removed. SO_2 present in a cooled flue gases reacts with Sodium Sulphite solution form Sodium bisulphite.

2.2.2 Seawater Scrubbing Process (SWS):

It is a process that exploits the natural buffering capacity of seawater to absorb acidic gases. The hot exhaust gas reaches the scrubber after passing through a dust collector. In scrubber seawater flow counter-current to gases absorbs SO_2, reacts with air formssulphuric acid and NOx to nitric acid. Further seawater is added to bring the pH back to normal seawater values. The dilution is typically between 5:1 and 10:1.After removing heavy metals and chlorides, it can be discharged directly, but in sensitive areas it can be added with limestone before discharge.This system is inherently reliable with low capital and operational costs and it removes up to 99% of SO_2, 80% PM and 10-20% of NOx and HC. Further below mentioned equations represents Deposition of sulphate and sulphuric acid.

$$H_2SO_4 \rightarrow H^+ + HSO_4^- \text{------ (5)}$$

$$HSO_4^- \rightarrow H^+ + SO_4^{2-} \text{------ (6)}$$

$$NH_3 + H_2O \rightarrow NH^+ + OH^- \text{ ---- (7)}$$

$$2NH_4^+ + SO_4^{2-} \rightarrow (NH_4)_2 + OH^- SO_{4(aq)} \text{ ---- (8)}$$

Though Sulphur can be removed in refineries using catalysts (molybdenum, cobalt, nickel, zinc and copper) post treatment methods are economical. Also these catalysts have to be replaced in constant intervals and it has negative impact on environment.

Dry Scrubber:Uses hydrated lime treated granulates instead of sea water.It can be used in conjunction with SCR unitsto reduce both SOx and NOx emissions.

2.2.3 Alternative Fuels:

SO_2 emission is depends on Sulphur content of the fuel. Use of low Sulphur content fuel is the cheapest and easiest method for reducing SO_2 emission. Engine that uses low Sulphur HFO needs less lubricating oil and maintenance and also PM emissions reduces.

2.3 Other Emission Reduction Techniques:

Few emission reduction methods are discussed here.

2.3.1 Power or Speed Variation:Variations inPower or Speed during a voyage increase the fuel consumption. Steady RPM is the simplest and most economical option to implement.

2.3.2 Electric Propulsion Systems:Electric power generation and propulsion is a vital factor for reducing carbon emissions, particularly on vessels with diverse operating profiles. Variable speed operation of the propeller and more efficient electric motors may reduce fuel consumption.

2.3.3 Upgrading Core Systems:Dynamic positioning (DP) is now used in most of offshore vessels for different outcomes. DP maintains a fixed position. Apart from this DP also ensure that a vessel sails on an exact track, which is useful for underwater construction or pipe laying for instance. DP system consumes more fuel as it needs extra power to maintain the position at high sea

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states. Recent innovations on of DP systems reduce the fuel consumption. Softwaresare used to predict change in position and power requirement while in DP operation.

The other novel ways to further reduce carbon footprint are to improve the control strategy, closed ring operation, energy storage.

2.3.4 Streamlining Propeller and Hull Design: This is another measure to reduce carbon emissions, streamlining make the ships to move faster without using as much fuel. One of the routes to reduce drag is to optimize the hull. This is usually done by rearranging the equipment located in the hull.

2.3.5 Weather Routing: Varying weather, current and depth conditions while cruising affect the ship speed. Routing optimizations through a reliable weather and current forecast minimizes power requirement and reduces emission.

III. EMISSION REDUCTION ONBOARD SHIP SAGAR MANJUSHA

Buoy tender cum research vesselSagarManjusha is a multi-disciplinary research vessel of operated and maintained by Vessel ManagementCell. It can accommodate 11scientists, 8officers and 10crews and having an endurance of 20days. Two numbers of articulated electrohydraulic cranes each having 5t safe working load (SWL) with an outreach of 8m and an A-Frame of SWL 12.5t especially serves the need of buoy deployment and retrieval operations. This vessel has many sophisticated facilities viz. A winch of 4500m capacity is used for launching/retrieval of portable scientific equipments. The vessel is also facilitated with survey equipment like single beam and multi-beam echo-sounders, used for EEZ survey at Indian exclusive economic zone. Fig.9 shows vessel SagarManjusha and TABLE- IV shows the vessel details.

Fig. 9: SagarManjusha

Table- IV: Vessel Particulars of SagarManjusha

Length Overall	60 m
Beam	11 m
Draft	3.5 m
Service Speed	11 knots
GRT	1065 T
Main Engine	2 x 578 kW
Engine Speed	1200 RPM

3.1 NOx Reduction:

Weather routing technique is used to minimize NOx emission. All cruises are well planned to minimize the use of fuel and thereby emission. Weather forecasts from Indian National Centre for Ocean Information Services (INCOIS) and M/s Fugro are used for route optimization.

Vessel SagarManjusha is having 2 main engines each of 578 kW and engine speed of 1200 RPM. TABLE-V shows permitted NOx values.

Table-V: Permitted NOx values

Tier	Ship Construction date	Total emission limit (g/kWh) n = engine speed (rpm)		
		n<130	130≥n≥1999	n ≥2000
I	01-01-2000	17	$45.n^{-0.2}$	9.8
II	01-01-2011	14.4	$44.n^{-0.23}$	7.7
III	01-01-2016	3.4	$9.n^{-0.2}$	2.0

From the table, the permitted limit of NOx emission for SagarManjusha is found to be

$NOx = 45.0 \times n^{-0.2} = 45 \times 1200^{-0.2} =$ **10.9 g/kW-h**

A test was conducted to find NOx emission from SagarManjusha. It was found that NOx levels are well within the limit and complying IMO regulations. Further it was decided to reduce NOx emission by employing Exhaust Gas Recirculation (EGR) and Diesel Particulate Filter (DPF) along with Diesel Oxidation Catalyst (DOC) as indicated in Fig.10.

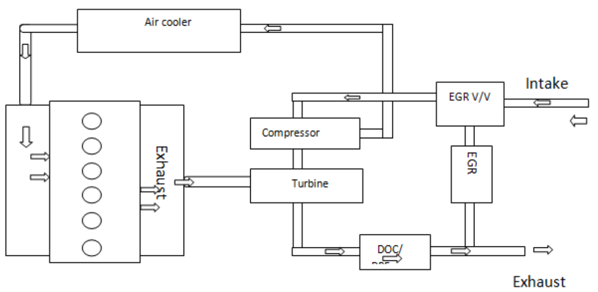

Fig. 10: Proposed NOx Reduction Technique

3.2 SOx Reduction:

One of the effective methods to minimize SOx emission is the use of low Sulphur marine fuel. TABLE-VI shows the Sulphur content of various marine fuels.

Initially, Marine Diesel Oil (DMC) was used in SagarManjusha. The Sulphur content in DMC is 2%. As a SOx reducing measure, the fuel grade was changed to Marine Diesel Oil (DMX) which has 1% Sulphur. Total SO_2emission for DMC is calculated as

For DMC: 21 x % S = 21 x 2 = 42 Kg/ Ton.

Average consumption of fuel in SagarManjusha is estimated as 3 Ton/Day.

Annual SO_2 emission is = 42 x 3 x 365 = 45990 Kg ~ **46 Ton**.

For DMX: 21 x % S = 21 x 1 = 21 Kg/ Ton.

Annual SO_2 emission is = 21 x 3 x 365 = 22995 Kg ~ **23 Ton**.

Total SO_2 reduction = $[SO_{2\,(DMC)} - SO_{2\,(DMX)}] / SO_{2\,(DMC)}$= (46-23)/46 **= 50%**

Table- VI: Sulphur Content of Marine Fuel

Fuel	Viscosity (Centistokes)	Sulphur (%)
Intermediate Fuel Oil (IFO-380)	380	< 3.5
Intermediate Fuel Oil (IFO-180)	180	< 3.5
Low Sulphur Intermediate Fuel Oil (LS-380)	380	< 1.0
Low Sulphur Intermediate Fuel Oil (LS-180)	180	< 1.0
Marine Diesel Oil (DMC)	1400	2
Marine Diesel Oil (DMX)	550	1
Low Sulphur Marine Gas Oil (LSMGO)	-	< 0.1
Ultra Low Sulphur Marine Gas Oil (ULSMGO)	-	< 0.0015

3.2 CO_2 Reduction:

Variousenergy efficiency methods are discussed in Table-7. One of the easiest and cheapest methods for ship performance optimization and fuel consumption reduction is Trim optimization. It can be done by proper ballasting or choosing of proper loading plan.

Model test is conducted using computational fluid dynamics (CFD). Trim is defined as the difference between the draught at AP (T_A) and the draught at FP (T_F). Trim = $T_A - T_F$.

$$P_D = R_T.V/\eta_D \text{ ---- (9)}$$

Where P_D: Propulsive power, R_T: Hull resistance, η_D: Total propulsive efficiency, V: Ship speed

$$\text{Resistance reduction} = 0.5\ \rho.V^2.S.C_T \text{ ----(10)}$$

Where S: Wetted Surface Area, C_T: Total constant Coefficient

Increase of total propulsive efficiency

$$\eta_T = \eta_{H.}\ \eta_{O.}\eta_{rr} \text{ -----(11)}$$

Where η_H: Hull efficiency, η_O: Open water propeller efficiency, η_{rr}: Relative rotational efficiency. TABLE-VII show the energy efficiency methods and its outcome

Table- VII: Energy Efficiency Methods and its Outcome

Energy Efficiency Methods	Results
Trim/Draft	Trim and draft monitoring and optimization
Advance hull coating	Re-paint using advanced paint
Hull condition	Fouling free hull
Propeller condition	Fouling free Propeller and damage avoidance
Reduced auxiliary power	Reducing electrical load via power management

Fuel consumption at full speed (11 knots) is estimated as 4 Tons/day. Average CO_2 emission per day is 3.21 ton/ ton of fuel.

Annual CO_2 emission is = 3.21 x 4 x 365 = 4687 Ton.

By optimizing trim and vessel operating speed (9 knots), the average fuel consumption was reduced considerably (3 ton/day) thereby reducing CO_2 emission.

Annual CO_2 emission is = 3.21 x 3 x 365 = 3515 Ton

Total CO_2 reduction = $[CO_{2\,(11\ knots)} - CO_{2\,(9+trim)}] / CO_{2\,(11\ knots)}$= (4687-3515)/4687 **= 25%**

IV. CONCLUSION

Global warming gave an alarming indication to prevent our environment from pollution. Industries, Automobiles, Ships etc., are the major contributors of pollution. Various techniques to minimizemarine emission are discussed here.This study has presented an up dated and best possible estimate of ship emission factors. It provides evidence on the reductions in NOx/SOx emissions as secondary effects of carbon reduction policies. Emissions of NOx/SOx can be substantially reduced by adoption of new emission control and combustion techniques as discussed in this paper. We have analyzed the emissions levels forvarious categories of vessels including our own research ship SagarManjusha.

The following observations are made for SagarManusha:

1. Weather routing and Steady (constant) engine speed resulted in NOx reduction. Exhaust Gas Recirculation and Diesel Particulate Filter along with Diesel Oxidation Catalyst are proposed to reduce NOx further.
2. Annual reductions of 23 tons of SOx are achieved by using Marine Diesel Oil (DMX) which contains 1% of Sulphur.
3. Trim optimization resulted inreduction of 1172 tons CO_2.

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