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HUMAN-INDUCED VIOLATION OF IMO REGULATIONS ON EMISSION

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ABSTRACT

Marine industry had many challenges before, in 2020 one of these biggest challenges will come to the surface, (IMO) new regulations of NOx & SOx emissions substances from combustion of marine fuels will be monitored and restricted in respect of the atmosphere. The aim of this paper is to study the performance of the marine main diesel engine at various load conditions and emissions percentages at each load condition, to ensure they remain with-in environmentally safe/permissible levels, the main diesel engine variable injection timing (VIT) is set up so that there is no change in injection timing at low loads (40%MCR), this is to avoid frequent changes of pump lead during maneuvering, the start of injection advanced above 40% load. Therefore, in this study the main diesel engine parameters considered are from 40% to 84% load rating. This research study was carried out using a simulator the TRANSA Tech Sim/ERS 5000 with MAN B&W 6S50MC-C diesel engine product tanker as case study. Therefore, the operation of the ships main diesel engine performance does not take into account conditions of its operating environment in the real sea conditions. Even though the TRANSA Tech Sim/ERS 5000 could simulate some of the conditions experienced at sea due to time constraint, this research study was carried out assuming perfect sea condition conditions such as high tides, wind resistance against and along the ships sailing path, hull fouling and hull deformation resistance

KEYWORDS: *Emission, Simulator, IMO, NOx, SOx, ECA*

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INTRODUCTION

Ships, considered the major pollutions transport facility in the world. Recent studies estimate that the contribution of ships to global NOx emissions is about 15%, while 4% to 9% of the SOx emissions can be attributed to ships [1]. Asian countries issued a new low started in 2020 that punished Captains, chief engineers and owners of vessels sailing in Asian seas with ships used high sulfur content by two years in prison [2], according to the Maritime and Port Authority of Singapore, the ships must emit 85 percent less sulfur in most parts of the world than they do in most places before [3]. Singapore Port Said that ships that fail to use an approved technology such as a scrubber, low fuel Sulpher will be considered non- compliant [4]. Also, in order to operate ships in safe operation and compatible with new emissions rules, a number of parameters has been proposed and used. These include the new electronic injection models of marine diesel engines. In which the engine settings (fuel injection and exhaust valve opening/closing timings) can be controlled and thus the engine can operate in various modes with high efficiency and low emission throughout the entire operating envelope.

This research study was carried out using a simulator the TRANSA Tech Sim/ERS 5000 with MAN B&W 6S50MC-C diesel engine product tanker as case study. The benefit of the simulator software is that, it allows the instructor to introduce a large number of faults in order to training the trainee to the expectations of engines behaviors during operations in different critical circumstance.

IMO EMISSION REGULATIONS

MARPOL Annex VI sets limits on NOx and SOx emissions from ship exhausts, and prohibits emissions effect to Ozone layer. [5] Annex VI entered into force on 19 May 2005 and a revised Annex VI with restricted requirements was adopted in October 2008, which entered into force on 1 July 2010, the last requirements already started in 2020.

Sulfur Content of Fuel

MARPOL Annex VI Regulation 14.1 states that the sulphur content of any fuel oil used on board ships shall not exceed 0.05% m/m on and after 1 January 2020 (for ships operating outside an emission control area1). [6] This is commonly referred to as the IMO 2020 fuel oil sulphur limit. The sulfur limits and implementation dates are listed in Table 1 and illustrated in Figure 1. Alternative measures are also allowed (in the SOx ECAs and globally) to reduce sulfur emissions, such as through the use exhaust gas cleaning systems (EGCS) and aka scrubbers. [7] For example, instead of using the 0.05% S fuel (2020), ships can fit an exhaust gas cleaning system or use any other technological method to limit SOx emissions to ≤ 6 g/kWh (as SO2) [8]. As shown in Fig.1, a new phase of reduced sulfur oxide emission has begun where the allowable amount of fuel Sulphur was reduced to 1% in July 2010 and was further lowered to 0.1 in Jan 2015.Outside of the ECA’s, the current global limits of Sulphur is 1.5% and start reduced to 0.05% in March 2020.

Table 1: MARPOL Annex VI Fuel Sulfur Limits

Date	Sulfur Limit in Fuel (% m/m)	
	Sox ECA	Global
2000	1.5%	4.5%
2010.07	1.0%	
2012		3.5%
2015	0.1%	
2020		0.5%

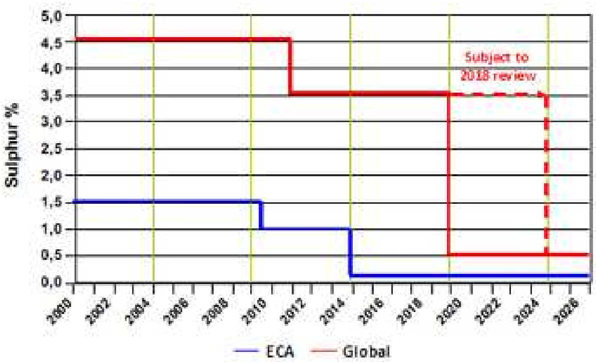

Figure 1: MARPOL Annex VI Fuel Sulfur Limits.

NOx Emission Standards

Marpol Convention Annex VI was determined to control NOx emitted from ships. The first tier started in 2000 year, the second in 2011, and the third is issued from 2016 and it will be a necessity to comply those last requirements. [9] In case of NOx between the first and second tier the emission was limited 20%, while the next step will be limited 80% of the first as shown in Fig.2 & Table 2. Marine industry has many challenges to reduce NOx emission because of high temperature emitted from exhaust. Anew technology started to reduce maximum exhaust temperatures by using early inlet valve closing (Miller timing), redesign combustion chamber and controlled fuel injection timing. The new designed diesel engine used a new technology reduced NOx emissions about 20-40%, but this not enough to total comply with tier three. [10]

Table 2: MARPOL Annex VI NOx Emission Limits

Tier	Date	NOx Limit, g/k wh		
		n < 130	130 < n < 2000	n > 2000
Tier I	2000	17.0	45 n-0.2	9.8
Tier II	2011	14.4	44 n-0.23	7.7
Tier III	2016†	3.4	9 n-0.2	1.96
† In NOx Emission Control Areas (Tier II standards apply outside ECAs).				

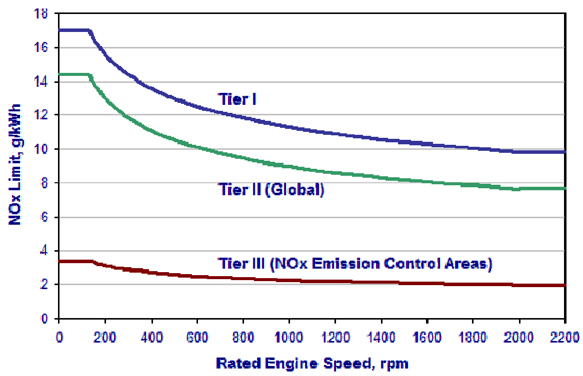

Figure 2: MARPOL Annex VI NOx Emission Limits.

EMISSION CONTROL METHODS AVAILABLE TODAY

Many researches and studies have been published about reducing exhaust gas emissions from marine diesel engines, with attention being on either controlling the emissions generation inside engine cylinders or removing the exhaust gas emission by after-treatment as SCR (selective catalytic reduction) for NOx emission reduction in MAN B&W two-stroke diesel engines for marine[11], SAM (scavenge air moisturizing) system in the MAN B&W 8S60MC engine,[12] EGR (exhaust gas recirculation) in MAN Diesel two-stroke engine and Cleaning the exhaust gas with scrubber but recently in 2019 some accidents happened by using exhaust emission treatment because of bad operation and leak of monitoring engines during sailing time by engine crew.

LOSS OF PROPULSION DUE TO SCRUBBER SAFETY SYSTEM FAILURE

A fully laden Capesize bulk carrier fitted with an in-line open-loop scrubber was departing Singapore and entering the Traffic Separation Scheme, when several critical alarms were activated in the engine room. The alarms included that, the exhaust gas high temperature alarm for the auxiliary engine and exhaust gas deviation alarm for the main engine. Within a few minutes of the alarms, the vessel’s main engine shut down and the vessel were no longer under command. The Master immediately reported the incident to Singapore’s Port Operations Control Centre and requested for tug assistance. Fortunately, there was no other ship close enough within the vicinity of the stricken vessel to pose an immediate collision hazard. Tug assistance was rendered and the stricken vessel was towed back to Singapore port waters where she anchored for repairs, the suspected causal factors for the incident and sequence of failure were as follows: It was suspected that the volume of water spray did not adjust accordingly and automatically when the main engine load changes during maneuvering. This may have led to water accumulation in the scrubber, also suspected that the drain valves were not completely opened and/or that drain lines were choked. This could have restricted the flow of wash water overboard. The overboard valve could have been closed. The high-water level sensors that were part of the scrubber safety system and supposed to automatically stop the wash water pumps, did not activate when the high-water level was reached. The seawater pumps continued to supply seawater to the scrubber unit causing wash water to overflow from the scrubber space into the main and auxiliary engines through the exhaust piping. The incident caused severe damages to the main and auxiliary engine components as shown in fig 3, affecting the turbochargers, cylinder heads, pistons and liners. The crankshaft bearings were also removed for inspection. The vessel stayed in port to complete the repairs and subsequently departed around three weeks later. This incident highlighted the importance of maintaining the automation and safety system of the scrubber in good working order and is frequently tested, as failure may result in serious consequences. [13]

Figure 3: Ship Scrubber System Failure Causes Flooding of Engine Room.

FULL MISSION ENGINE ROOM SIMULATOR (ERS)

The simulator designed and compatible with: - STCW Code: Section A-1/12 and Section B-1/12. - ISM Code: Section 6 and Section 8. This simulator has hardware consoles and panels to operate and control main engines, auxiliary machinery, gears, propulsion system and electric systems. This Simulator is consisting of three main parts:

- Engine Control Room (ECR) with main engine control console and main electric switchboard
- Engine Room which has two PC projectors and control console for 3D vision
- Instructor's Room.

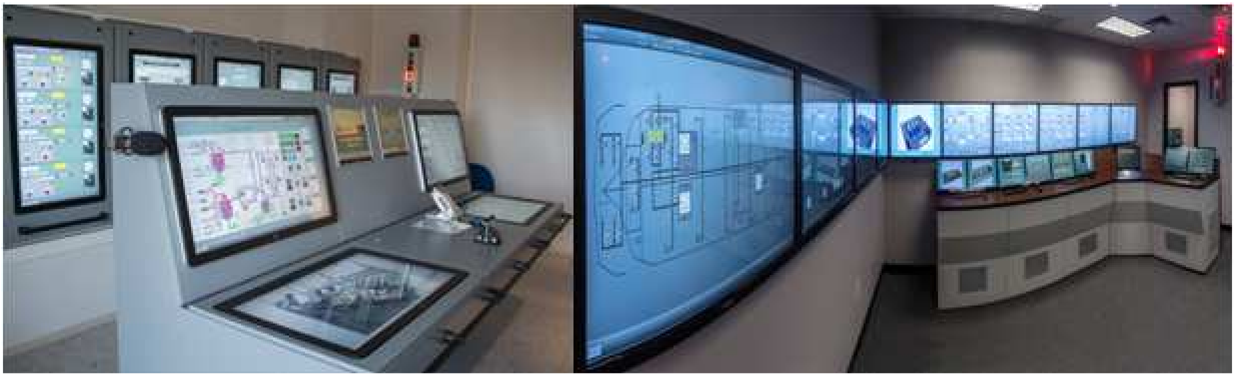

Figure 4: Lay-Out Computer Based Training (CBT) Engine Room Simulator.

As shown in fig. 4, there are six CBT type ERS and one Full mission type ERS. ERS is also called Work Station (WS). The trainee is able to study the operation of the engine plant alone or in a group. The various simulated systems on the monitor can be viewed by trainee in mimic panel. These graphic mimic panel can be controlled and readjusted to study different types of tasks and by used full mission type ERS, the trainee is able to practice more realistic operations.

SIMULATOR CASE STUDY& ENGINE PERFORMANCE CALCULATIONS

The main engine was selected in case study, MAN B&W model 6S60 MC-Two stroke, slow speed, MCR 18420 BHP at 105 RPM, reversible 6 cylinders, 2 stroke, 400 mm, bore 600 mm, as shown in figure 5.

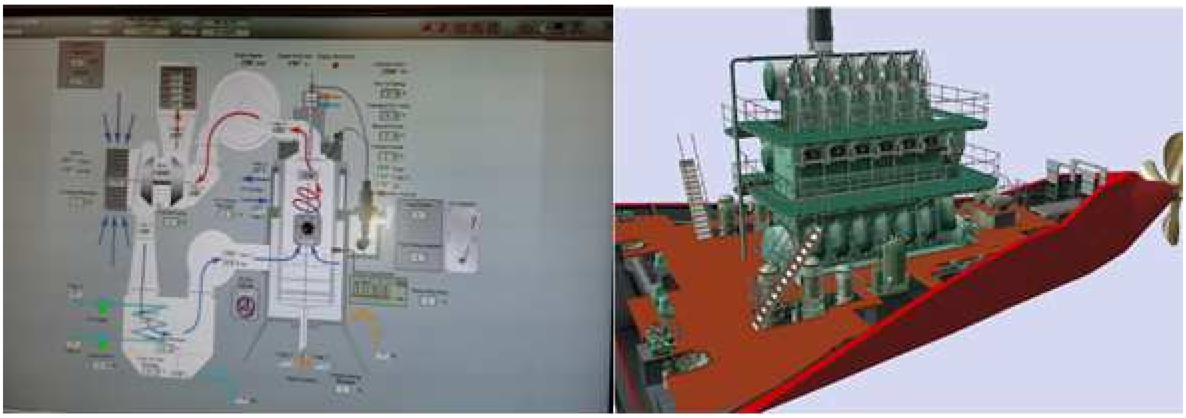

Figure 5: Engine Room Layout.

This chapter contains results obtained from the ERS simulator was collated and calculations for engine fuel specific fuel consumption (SFC) at various fuel loads. These results were used to plots evaluation graphs which shall be used for further discussions. Specific fuel consumptions and efficiencies at different fuel load calculated, also Sox, NOx, CO & CO2 measured, mechanical & thermal efficiencies also calculated. During simulation test engine rpm kept constant, load kept constant in NCR about 81% load, fuel oil used wad heavy fuel oil Density 989 @ 15C kg/m, Viscosity 290.8 @ 50C m^2/s, Sulfur 1.5%m/m.

Equations used in Calculations

- IP = Σ cylinder powers
- $FE = \dot{m} * HCV$
- $\rho T = \rho^{15} - \Delta T * 0.00063$
- Specific fuel consumption (SFC) = $\frac{C * \rho * 10^6}{h * BP} * \frac{LCV}{HCV}$
- $\eta m = \frac{BP}{IP}$
- $\eta th = \frac{BP}{FE}$

Where,

m = Mass flow rate of fuel (kg/s)

c = flow rate of fuel (m3/hr)

HCV = Higher Calorific Value = 41.83 MJ/kg

LCV = Lower Calorific Value = 39.57 MJ/kg

ρ15 = Specific gravity at 15 °C = 0.97

ρT = Specific gravity at given temperature

BP = Brake Power

IP = Indicated Power

FE = Fuel Energy

ηm = Mechanical Efficiency

ηth = Thermal Efficiency

v = Rate of fuel consumption

h = Time

Performance Analysis Based on Fuel Load and Emission at 40% Engine Load

T = 121 °C v. = 748 l/hr BP = 3945 kW

- IP = (741 + 731 + 736 + 745 + 750 + 739) kW = 4442 kW
- FE = $\dot{m} * HCV = \frac{0.97 * 10^3 * 748 * 10^{-3}}{3600} * 41.83 * 10^3$ = 8449.66 kW
- $\eta m = \frac{BP}{IP} = \frac{3945}{4442} * 100$ = 88.8%
- $\eta th = \frac{BP}{FE} = \frac{3945}{8449.66} * 100$ = 46.67%
- $\rho 121 = \rho^{15} - \Delta T * 0.00063 = 0.97 - (121 - 15) * 0.00063 = 0.903$
- SFC = $\frac{C * \rho^{121} * 10^6}{h * BP} * \frac{LCV}{HCV} = \frac{0.748 * 0.903 * 10^6}{1 * 3945} * \frac{39.57 * 10^3}{41.83 * 10^3}$ = 161.97 g/kW.hr

Specific Fuel Consumptions and Efficiency at 50% Engine Load

T = 121 °C v. = 1141 l/hr BP = 6205 kW

- IP = (1129 +1120 +1124 +1135 +1132 +1126) kW = 6766 kW
- SFC = $\frac{C * \rho^{121} * 10^6}{h * BP} * \frac{LCV}{HCV} = \frac{1.141 * 0.903 * 10^6}{1 * 6205} * \frac{39.57 * 10^3}{41.83 * 10^3}$ = 198.38 g/kW.hr

Specific Fuel Consumptions and Efficiency at 59% Engine Load

T = 121 °C v. = 1485 l/hr BP = 8165 kW

- IP = (1467 +1460 +1470 +1465 +1471 +1460) kW = 8793 kW
- SFC = $\frac{C * \rho^{121} * 10^6}{h * BP} * \frac{LCV}{HCV} = \frac{1.485 * 0.903 * 10^6}{1 * 8165} * \frac{39.57 * 10^3}{41.83 * 10^3}$ = 155.36 g/kW.hr

Specific Fuel Consumptions and Efficiency at 69% Engine Load

T = 121 °C v. = 1908 l/hr BP = 10560 kW

- IP = (1881 +1890 +1885 +1887 +1876 +1879) kW = 11298 kW
- SFC = $\frac{C * \rho^{121} * 10^6}{h * BP} * \frac{LCV}{HCV} = \frac{1.908 * 0.903 * 10^6}{1 * 10560} * \frac{39.57 * 10^3}{41.83 * 10^3}$ = 154.34 g/kW.hr

Specific Fuel Consumptions and Efficiency at 75% Engine Load

T = 120 °C v. = 2158 l/hr BP = 12074 kW

- IP = (2136 +2126 +2116 +2120 +2133 +2123) kW = 12754 kW
- SFC = $\frac{C * \rho^{121} * 10^6}{h * BP} * \frac{LCV}{HCV} = \frac{2.158 * 0.904 * 10^6}{1 * 12074} * \frac{39.57 * 10^3}{41.83 * 10^3}$ = 152.84 g/kW.hr

Specific Fuel Consumptions and Efficiency at 81% Engine Load

T = 120 cc v. = 2421 l/hr BP = 13696 kW

- IP = (2400 +2390 +2403 +2398 +2401 +2395) kW = 14387 kW
- SFC = $\frac{C * \rho^{121} * 10^6}{h * BP} * \frac{LCV}{HCV} = \frac{2.421 * 0.904 * 10^6}{1 * 13696} * \frac{39.57 * 10^3}{41.83 * 10^3}$ = 151.15 g/kW.hr

RESULTS AND DISCUSSIONS

Engine Operation Parameters in Normal Conditions

Results from previous formulas was tabled as shown in table 3, all these parameters used to compare separately by exhaust emissions during the same load to indicate the performance of load to exhaust emissions.

Table 3: Fuel Load & Efficiencies in Normal Operation

Fuel Load (%)	Indicated Power (Kw)	Brake Power (Kw)	Fuel Energy (Kw)	Mechanical Efficiency (%)	Thermal Efficiency (%)	Specific Fuel Consumption (G/Kw.Hr)
40	4442	3945	8449.66	88.8	46.67	161.97
50	6766	6205	15895.4	91.7	39.04	198.38
59	8793	8163	16737.23	92.8	48.78	155.36
69	11298	10560	21333.3	93.5	49.5	154.34
75	12755	12074	24261.4	94.67	49.77	152.84
81	14387	13696	27189.5	95.2	50.37	151.15

As shown in figure 5 & table 4 in normal operations engine when fuel load increased SOx decreased but CO & NOx increased, this regarding to incomplete combustion& low exhaust temperature in low loads and high exhaust temperature in high load.

Table 4: Fuel Load & Exhaust Emissions in Normal Operation

Fuel Load %	SOx (PPM)	CO (PPM)	NOx (PPM)
40	78	31	664
50	84	42	739
59	83	51	819
69	78	62	896
75	76	68	939
81	72	76	994

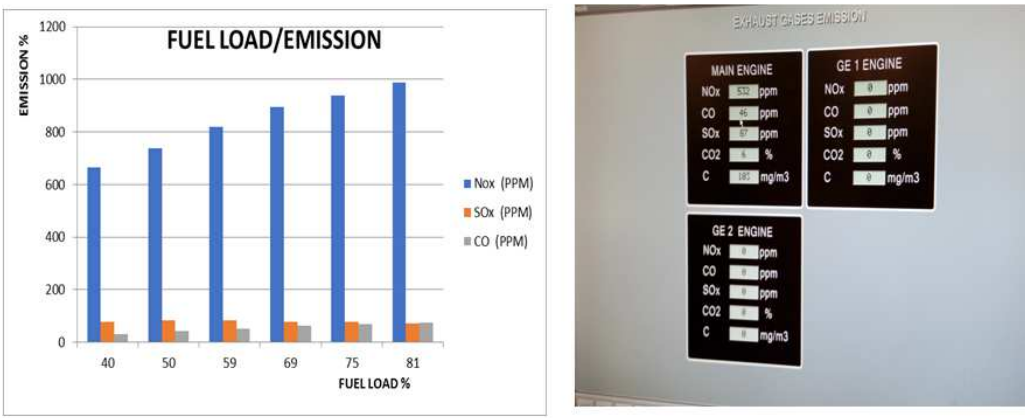

Figure 6: Fuel Load & Exhaust Emissions in Normal Operation.

Engine Operation Parameters in Bad Operation Conditions (Human Errors)

In this research, common engine troubles tested to simulate the common troubles happened during operation by human errors, this engine trouble as turbocharger fouling, fuel injector blocked, piston ring wear down and air cooler chocked, this test compared the exhaust emission during normal operation and in bad operation. All tests carried out during (NCR) normal continuous rating of engine, because this is the common speed in all engine during sailing time, also during all tests carried out all parameters and indicated power curves with common trouble tested, as shown in figure 7 was listed and analyzed to find out the exhaust emission during those tests.

Figure 7: Indicated Power Card with Defect Injector.

Turbo Charger Fouling Test Results

Compared to normal operation in the same conditions and during Turbo charger fouling test noticed that NOx increased by 33 PPM, SOx decreased by 2 PPM, CO increased by 6 PPM and CO2 increased by 0.2%.

Injector Chock Test Results

During Injector Chock test noticed that NOx increased by 45 PPM, SOx decreased by 1 PPM, CO increased by 7 PPM and CO2 increased by 0.3%.

Piston Ring Wears Down Test Results

During piston ring wear down test noticed that NOx increased by 37 PPM, no change happened to SOx, CO increased by 3 PPM and CO2 increased by 0.2%.

Air Cooler Blocked Test Results

During test noticed that NOx increased by 48 PPM, SOx decreased by 1 PPM, CO increased by 2 PPM and CO2 increased by 0.3%.

Table 5: Fuel Load & Efficiencies in Normal Operation

	NOx (PPM)	SOx (PPM)	CO (PPM)	CO2 %	C (mg/m3)
Normal Operation	994	72	76	4.7	68
T/C Fouling	1027	70	82	4.9	68
Injector Chock	1039	71	83	5	68
Piston Ring Wear Down	1031	72	79	4.9	68
Air Cooler Blocked	1042	71	78	5	68

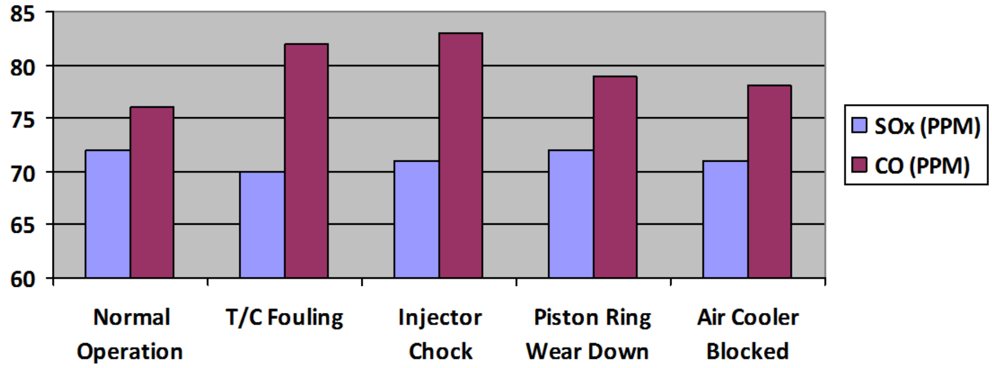

Figure 8: Sox & CO Emission in Different Engine Faults.

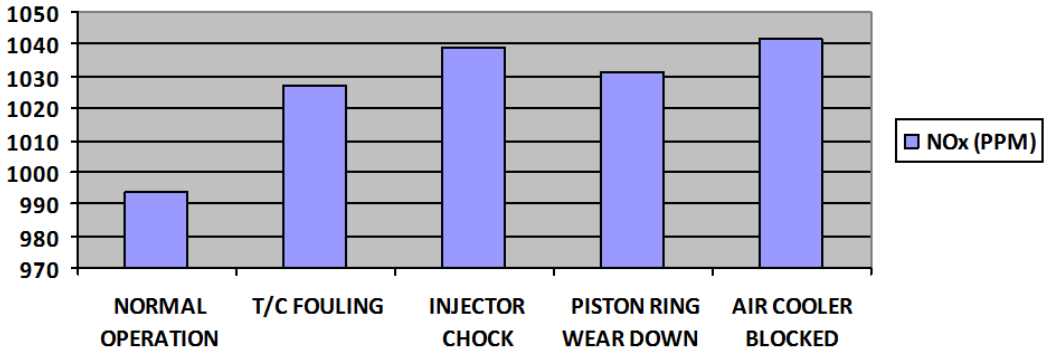

Figure 9: NOx Emission in Different Engine Faults.

CONCLUSIONS

The results from simulation and cases study concluded that the percentage of emission increase for NOx PPM, CO PPM and CO_2% as shown in figure 8&9, even though, all the ships having the IAPP certificate and complied with IMO requirement but due to wrong operation during sailing or human error or lack of maintenance, the emission increase and cannot reach to the aim of IMO to reduce the percentage of fuel consume to 25% by January 2025 to improve the energy efficiency and reduce the EEDI and EODI for the ship, regarding that this research recommended that every new designed ship should has exhaust emission monitors during sailing not only in ports, by this monitors Coast guards and ships flag authorities can detect any emission happened during sailing , this equipment recommended for that is exhaust gas analyzers with fixed memory cannot be deleted as used in oily water separator or by adding emission parameter to ships AIS (automatic identification system) showing the percentage of SOx, NOx, CO and CO_2 during sailing for all ships and area covered by port state control.

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