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Performance Characteristics of Turbocharged vs. Naturally Aspirated Marine Prime Movers

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Abstract: The International Maritime Organization (IMO), an apex global maritime regulatory body continuously promotes operational strategies aimed at reduction of Greenhouse Gases (GHG) emissions especially from commercial shipping operations. Shipping companies are responding in a number of ways which includes use of turbochargers as engine enhancers to improve fuel consumption efficiency and hence reduce carbon dioxide emissions. Turbochargers are also attached to enhance the output of internal combustion engines without increasing their cylinder capacity. Recent trends have pointed to increasing use of turbochargers as enhancers to prime movers of marine vessels. This paper analysed the relationship between outputs of turbocharged engine and naturally aspirated one employed as marine vessel prime movers. Data on engine parameters of turbocharged engine and the naturally aspirated one were collected from ship operational log and analyzed using mathematical models. Results showed that for the same sizes of marine engines, the turbocharged engine was more efficient than the naturally aspirated one. Specifically, the volumetric efficiency, the brakepower and the specific power were higher in the turbocharged engine when compared with the naturally aspirated one. Findings showed that turbocharged marine diesel engines based on their higher power output efficiency could continue to dominate naturally aspirated ones in marine prime mover applications. It is recommended that all ship operating companies should adopt turbocharger technology or retrofit their existing fleet to improve operational efficiency.

Keywords: Prime Movers, Turbocharger, Volumetric Efficiency, Power Output, Brakepower, Naturally Aspirated Engine

1. Introduction

Technological advancement has engendered continuous growth and rapid developments in maritime transport. Maritime transport being the most cost effective mode of moving large quantities of cargo has dominated global seaborne freight transportation. In terms of container shipping, container trade accounted for approximately 60% of the global seaborne trade. It is pertinent to note that there has been an almost 1,500% increase in the size of container ships. In attempts to meet service expectations, shippers have more interested in improvements in shipping tonnage capacity [1]. Although recent technological progress in shipping has led to increased capacity and size of ships, however, attention is now focused on improving the efficiency and performance of ship engines. To achieve this objective, engine manufacturers have opted to fitting engine performance enhancers like turbochargers. Thus, industry experts expect new builds to be fitted with turbochargers [2]. Engine turbocharger technology has reduced the constraints faced by early marine engines in terms of power outputs considering that a modern engine without a functioning ship turbocharger would be limited to about 25-30% of its potential power output. Turbochargers as essential component of marine engines [3] are devices attached to facilitate enhancement of an internal combustion engines' output without increasing cylinder capacity. The application of such mechanical devices has improved engine performance and reduced its fuel consumption. Use of this technology has also encouraged the downsizing of engine sizes such as those employed as prime movers in ships. Use of turbochargers in shipping industries is prevalent as emphasis has been placed on improvement of engine power outputs. Turbocharger uses exhaust heat from engine to get more air into the cylinder during induction stroke. More air translates to increased ability to burn more fuel which in turn increases the power output (brake horse power) of the engine. Turbocharging engine increases its power output for the same cubic capacity. The world largest container ships like the CSCL Globe, the MSC Oscar and MSC Oliver which were launched between 2014 and 2015 having a capacity ranging from 19,100 TEU to 19,224TEU are all fitted with turbocharged diesel engines. Fuel economy is the key objective in turbocharging these vessels. Fluctuating fuel prices and the need to meet stringent environmental regulations have put fleet operating companies under intense pressure to reduce operational cost and meet green standard. Turbochargers assist these companies in reducing their operational cost and meet the required environmental standard.

1.1. The Research Problem

Shipping industry being a very competitive sector now relies on speed efficiency, reduced fuel consumption and while meeting environmental regulations [4] ultimately contributes to global emissions reductions [5]. However, turbocharging technology among other factors contribute to the operational performance of vessels. In addition, turbocharging technology is critical to performance of vessels in terms of thermal efficiency, safety [6, 7], increasing power output, torque and reduction in fuel consumption. Much research has been done on effects turbocharging on vessels' engine performance. For example, [8] applied novel numerical models to improve the enthalpy and entropy calculation based on exhaust gas component of the engine. They find that turbocharger efficiency increases with improved fuel oil quality. There is dearth in literature on quantitative relationship between volume of air displaced in the combustion chamber of the engine, the specific power output and volumetric efficiency. In this paper we model the quantitative relationship existing among these parameters.

1.2. Objective of Study

The main aim of this paper is to compare the performance characteristics of turbocharged vs. naturally aspirated marine diesel engines employed as prime movers marine vessels.

The specific objectives are:

To compute the parameters of volumetric efficiency, brake-power and engine power output of the specific engine types under study.

To compare the parameters of volumetric efficiency, brake-power and engine power output for the engine types.

This study will be limited to modeling the quantitative relationship between the volumetric efficiency, brakepower and specific engine power output.

2. Conceptual Reviews

2.1. Turbocharging and Efficiency of Marine Diesel Engines

One of the main technologies for engine downsizing is turbocharging. Engine downsizing means that the capacity of the engine is lowered but the power outputs remain the same or increase and fuel consumption decreases. All internal combustion (I-C) engines gain efficiency when turbocharged and the shipping industry has therefore been encouraged to adopt turbocharging on virtually all engines it uses. Modern diesel engines fitted with turbocharger have proven to be more efficient than early engines because of improvement in their operational capability and their ability to use little more than half of the energy contained in the fuel. Current literature establishes that a third of the energy in fuel is lost through the heat of exhaust; but turbocharger allows a high proportion of that to be recovered for performing useful work. A more efficient engine means that for the same power requirement a smaller engine is possible. Alternatively, the same size of engine can allow for a faster or larger ship with more earning capacity. Turbocharged engine consumes lower fuel for similar output torque and power as a result of better efficiency. Turbochargers have been found to reduce the exhaust emission of engines to meet the environmental related rules laid down by the International Maritime Organization (IMO). For instance A180-L turbocharger helps in the reduction of ships' fuel consumption to the tune of 35% and therefore generate less carbon dioxide, thus making a ship with such turbocharger very efficient [2], Some common turbochargers used in marine mover applications can be found in figures 1-3.

Figure 1. *MET Turbocharger.*

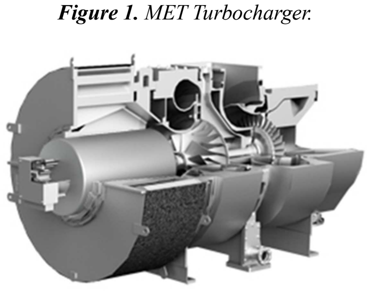

Figure 2. *Hybrid Turbocharger.*

Source: Mitsubishi Heavy Industries.

Figure 3. *Variable Turbine Inlet (VTI) Turbochargers.*

Turbocharged engine can be more powerful and efficient than the naturally aspirated engine because the turbine forces more intake air and proportionately more fuel into the combustion chamber than when atmospheric pressure is used. The turbocharging technology increases the volumetric efficiency of the combustion chamber. Parting et al., [9] state that turbocharging of internal combustion engines was an established technology meant for increasing both power density and in some cases the cycle efficiency of diesel engines relative to naturally aspirated engines. Using compressed air allows for a better fuel air mixture which translates to increased ability to burn more fuel which in turn increases the power of the engine. Muqueen [10] posits that turbochargers improve an engine's volumetric efficiency by increasing the density of the intake air. The rise in turbocharging technology application has been attributed to the need reduce to fuel consumption and emission from the ship engine. Abdullah [11] states that fuel economy and thermal efficiency are very vital to all engines as efficiency is increased with cooled air by intercooler. Thus, the expectation in the coming years is reduction in CO_2 emission via widespread adoption of turbocharging technology [12].

2.2. Trends in Ships Turbocharging Technology

As a result of several restrictive regulations concerning emissions from ships such as Annex VI of MARPOL which limit emissions of NOx [13] and other pollutants, turbocharger was introduced with the expectation of facilitating higher engine efficiencies and reduced fuel consumption [14]. However, turbocharging technology had started taking shape from the year 1905 when Swiss engineer Alfred Buchi began work on a compressor driven by exhaust gases that forced air into a diesel engine to increase power output. The first turbocharged engine was tested which gained a power increase of about 42%. But in the shipping industry the first two passenger ships, the Preussen and the Hansestadt Danzig were turbocharged in 1926. The turbochargers were designed and built under Buchi's supervision. These two ships were the first in maritime history to be powered by turbocharged engines; improving the power output from 1,750 to 2500HP compared to the naturally aspirated engine. As from the year 1928 more motor ships were equipped with turbocharged engines. The development of a 2 stroke engine turbocharging took effect by 1934 by Sulzer brothers in Winterthur. In 1952 Dorthe Maersk with one 2 stroke, 6-cylinder tanker vessel was turbocharged with 2VTR-630 turbocharged (which improved the power output from 5530BHP to 8000BHP). By the 1930's turbocharging was a common feature on ships. Ship turbocharging trend continued to grow till the 1970's when steam engine had disappeared leaving the turbocharged diesel engine. The advancement and improvement on turbocharging technology in fuel economy has made it imperative for both ship builders and ship owners to adopt it. In the recent years, three largest container vessels: CSCL Globe, MSC Oliver and the MSC Oscar were turbocharged by ABB turbocharging A100-L type. This was to improve the fuel economy and also reduce emission in line with IMO's tier III regulation.

2.3. Ships' Compliance to IMO's Tier III Regulations

As a result of increase in the rate in which air is been polluted from ship's operations, regulations concerning emission of pollutants (such as nitrogen (NOx), sulphur Oxides (SOx) and particulate matter (PM) are forcing engine designers to provide engines which emit lower amounts of these pollutants [15] in accordance with global emission standards. IMO through it relevant convention ensures that ship pollution is properly controlled since it first became active in 1958, when it began enforcement of necessary emission standards for nitrogen oxides (NO_x) and sulphur oxides (SO_x) at sea. The regulation became tightened with IMOs Tier III emission standards. The new rule applies to marine diesel engine built from January 2016 upward. They are four times stricter than the current legislation and would require ships to drastically reduce their NO_x emission. Ship operators are likely to require specialized pollution reduction technologies on board their ship which include: selective catalytic reduction (SCR), exhaust gas reduction (EGR), scavenge air moisturizing, miller cycle, low pressure gas engines, Cs NO_x and combination technologies. Turbochargers are already an energy efficient technology and features in some of the pollution reduction system. By using the exhaust gas to drive a turbine and push extra air into the engines cylinders, a turbocharger effectively allows the engine to run at higher powers with less fuel. Turbochargers like ABB's series are specially designed to be fully Tier III compliant. The MSC Oscar which is turbocharged with a 180-L turbocharger from ABB series is seen to consume about 35% less fuel and therefore produce less carbon dioxide making it most efficient vessel. Turbochargers that make use of exhaust gas recirculation (EGR), a technology which if used in combination with other emission cutting system, can reduce NO_x from 50 - 60%. Turbochargers will continue to play significant role in Tier III emissions because they have the EGR turbo.

3. Methodology

Marine Diesel engines are the focus of this paper. Diesel engines are known as compression ignition engines. Marine engines are those which are used in marine vehicles namely boats, ships, submariners etc. These may be classified as 2-stroke as well as 4-stroke engines. The engine for the main propulsion or turning the propellers of normal ship are usually slow speed 2-srtoke engines while those used for providing auxiliary power are usually 4-stroke high speed.

The Preussen and Hansestadt Danzing passenger ship with the 10-cylinder Vulcan MAN four – stroke single acting models was turbocharged under a constant pressure system by Brown Boveric (BBC) turbochargers. The power output of the naturally aspirated engine was noted to be 1250kw but the turbocharged engine power output was recorded as 1840kw. In tables 1 and 2, we present data specific to engine type under investigation. These values will be used for computing outputs for performance comparisons: Naturally aspirated versus turbocharged engine types.

Table 1. *Engine Parameters of the Naturally Aspirated.*

Parameter	Value	Unit
Power	1,250	KW
Engine speed	240	rpm
Number of cylinders	10	-
Bore	540	mm
Stroke	600	mm
Air Flow rate	198	Kg/h

Source: authors compilations

Table 2. *Engine Parameters of the Turbocharged.*

Parameter	Value	Unit
power	1,840	KW
Engine speed	275	rpm
Number of cylinders	10	-
bore	540	mm
Stroke	600	mm
Air Flow rate	299	Kg/h

Source: authors compilations

Mathematical calculations will be done to obtain the following for the Naturally Aspirated Engine:

Volumetric efficiency
The Torque
Specific Power
Brake Power
Converting all numbers to meters (m)
For volumetric efficiency, we have as follows:

$$\eta_v = \frac{m_a\, x\, n_r}{\rho_{ai}\, x V_d\, x\, n_e}$$

Where
η_v=Volumetric efficiency
m_a=Air flow rate
n_r=Number of crankshaft revolution for each power stroke per cylinder.
For 4 stoke engine n_r=2 and for 2-stroke it is n_r=1
V_d=Engine Volume displacement
n_e=Engine speed (rpm)
ρ_{ai}=1.27kg/m^3

$$V_d = \frac{\pi}{4} \times (bore)^2 \times stroke \times n_c$$
$$= \frac{3.142}{4} \times (0.54)^2 \times 0.6 \times 10$$
$$= 1.37\text{m}^3$$

$$\eta_v = \frac{m_a \times n_r}{\rho_{ai} \times V_d \times n_e} = \frac{198 \times 2}{1.27 \times 1.37 \times 240}$$
$$= \frac{396}{417.5} = 0.949 = 0.95 = 95\%$$

Calculating the Torque (*T*)

$$\text{Torque} = \frac{\text{Power} \times 60{,}000/1000}{2\pi \times \text{RPM}}$$
$$= \frac{1{,}250 \times 9.5488}{240}$$
$$= 50\text{Nm}$$

Calculating the brake power:

$$Brake\ power = \frac{2\pi NT}{60},$$

Where
N: rpm,
T: Torque &
π: 3.142

$$Brake\ power = \frac{2\ x\ 3.142\ x\ 240\ x\ 50}{60} = 1{,}257kw$$

Calculating specific power

$$P_s = \frac{\text{Brake power}}{\text{Piston Area}}$$

Where

Area of piston= $\frac{\pi D^2}{4} = \frac{3.142 \times 0.54^2}{4}$ =0.23m

Therefore,

$$P_s = \frac{1{,}256}{0.23} = 5{,}461KW$$

Calculating parameters for the turbocharged engine, we have the following:

i. Volumetric efficiency

$$\eta_v = \frac{m_a \times n_r}{\rho_{ai} \times V_d \times n_e} = \frac{299 \times 2}{1.2 \times 1.37 \times 275} = 1.2 = 1.32 = 132\%$$

ii. Calculating Torque (*T*)

$$\text{T} = \frac{\text{power} \times 60}{2\pi \times \text{rpm}} = \frac{1{,}840 \times 60}{2\pi \times 275} = \frac{1{,}840 \times 9.5488}{275} = 64\text{Nm}$$

iii. Brake Power (P_b)

$$\text{P}_\text{b} = \frac{2\pi\text{NT}}{60} = \frac{2 \times 3.142 \times 275 \times 64}{60} = 1{,}843\text{kw}$$

iv. Specific Power (P_s)

$$P_s = \frac{\text{Brake power}}{\text{Area of pison}} = \frac{1,843}{0.23} = 8,013\text{kw}$$

4. Results Presentation and Discussion

The computed engine outputs for the two engine air intake type under comparison are shown in Table 3. It is observed that the values for specific power, brake power and volumetric efficiency are higher in the turbocharged diesel engine than the naturally aspirated engine. Given these results, it is evident that turbocharged prime movers will perform more efficiently than naturally aspirated ones. In terms of fuel combustion, turbocharged engines are more efficient. This is a very important attribute given the global need to reduce greenhouse gases generated through commercial shipping operations.

Table 3. *Distribution of Output Characteristics of Turbocharged Vs. Naturally Aspirated Engines.*

Output Parameters	Air Intake Type	
	Naturally Aspirated	Turbocharged
Power	1,250 KW	1,840 KW
Specific power	5,461KW	8,013 KW
Brake power	1,257 KW	1,843 KW
Volumetric Efficiency	95%	132%

Source: Authors

5. Conclusion and Recommendation

From the mathematical computation of output parameters and analysis of findings in this paper, we establish that: A turbocharger increases the power output for the same cubic capacity of the engine. This is understood given that turbocharged engines get the most possible air into the engine cylinder for effective combustion. Again, the volumetric efficiency of the I-C engine depends on the amount of compressed air forced into the cylinder. It is therefore recommended that modern container vessels be fitted with turbocharger enhanced prime movers, since this technology can improve the power output of engines in ship. More research should be carried out on range of scenarios (increased vessel sizes, powering with alternative fuels etc.) for turbocharging an engine for more effective utilization of the power output.

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