Study of the effects on engine fuel consumption generated by turbocharger performance

Dimitar Popov
[1] Nikola Vaptsarov Naval Academy, Varna, Bulgaria
d.popov@nvna.eu

Abstract: *Damage to the turbocharger of the 8400kW diesel engine, which had operated about 66 640 running hours, has caused off hire of the vessel for 10 days and the turbocharger repair had cost more than half a million euros. The study performed on this work consists of evaluating the consequences of the low turbocharger performance on the fuel oil consumption and the reasons for this. Specific data were collected and analysed in order to create an appropriate mathematical model between the studied parameters. Measurements and data collected were performed a month before turbocharger damage and after the TC overhaul (with new cartridge). As results can be concluded that losses in turbocharger performance is very important for the efficient operation of the main engine, they must be monitored and analysed.*

Keywords*: TURBOCHARGER, MARINE DIESEL ENGINE, PERFORMANCE, FUEL CONSUMPTION, REGRESSION ANALYSIS.*

1. Introduction

Turbochargers (TC) are used with internal combustion engines to increase power output, reduce fuel consumption, and reduce emissions. As one of the key systems of the marine power plant diesel engine, the turbocharger directly affects whether the diesel engine can continuously and stably provide the power required for the ship. At present, the fault diagnosis of the marine turbocharger has not been paid enough attention yet and in most cases, the method of 'ex post diagnosis' is still adopted. The current turbocharger fault diagnosis method mostly adopts single-machine and offline mode and has certain hysteresis. Various performance parameters observed during the operation of the equipment are processed and analyzed to determine whether a damage has occurred, the type of fault and its cause. It is necessary to adopt a new method based on the existing fault diagnosis theory and technology, to obtain a diagnostic model that can solve practical problems [4, 5].

The aim of this research is to provide a review of influence of turbocharger technical condition on engine fuel consumption and the reasons for turbocharger low performance. Our target is by collected data to find appropriate mathematical methods to obtain qualitative relationships between the engine fuel consumption and turbocharger revolutions.

The objects of research was a four-stroke medium speed marine engines MAK 9M43C type with its ABB turbocharger TPL76-C33 type located on aft end of the engine (fig. 1) [2].

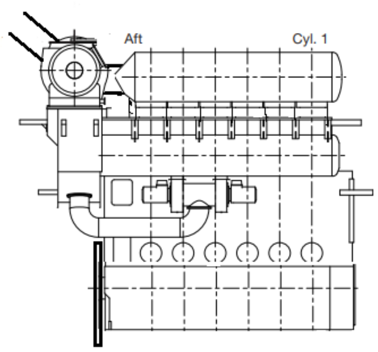
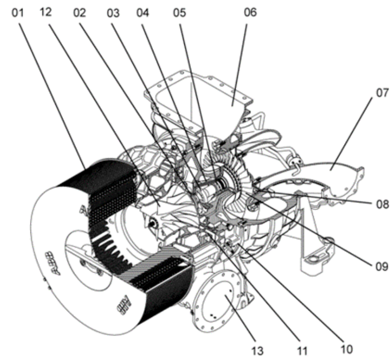


Fig. 1: *One turbocharger located on aft end.*

The turbocharger components are shown in fig. 2 as bellow [12, 13]:



1.Filter silencer
2.Radial plain bearing
3.Thrust bearing
4.Bearing bush
5.Radial plain bearing
6.Gas outlet casing
7.Gas inlet casing
8.Nozzle ring
9.Turbine wheel
10.Bearing casing
11.Diffuser
12.Compressor wheel
13.Compressor casing

During a sea passage of the vessel the main engine was operating at load about 50 % of nominal power. The TC temperature inlet (Tin) was 752K and TC outlet temperature (Tout) was 691K. The speed on the turbocharge was 148 s^{-1}. The data was still within the limits of normal operation. On 02nd February 2021 at 02:00 LT the duty engineer called the bridge to reduce the load of the engine as there was an unusual noise from the turbocharger side. After primary checking of the main engine had observed high exhaust gas temperatures and metal particles in the lube oil filter. Lube oil filter high differential pressure alarm had found active.

The subjected turbocharger was thoroughly inspected and investigated by the chief engineer on board of the vessel. The turbocharger / Cartridge was carefully disassembled for inspection and assessment of the components, findings have been documented by means of photographs. The components have been visually assessed. The investigation has been focused on possible causes and contributing factors. The objective of the investigation is to determine how the subjected issue had happen.

Considering the information available following possible failure causes could have led to the failure of cartridge smooth rotation and the excessive axial movement of compressor wheel supports increase of clearances in radial and axial bearing beyond the limits. This further validates that the bearings and shaft have worn beyond usable limits. The rubbing of the compressor wheel (fig.3) with wall insert may be the consequential damage [3, 10, 11].

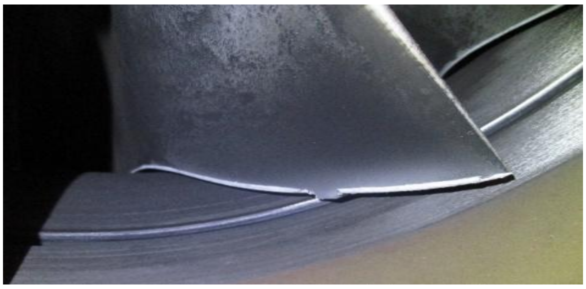


Fig. 3: Rubbing of the compressor wheel.

Fig. 4: Presence of unburnt oil along with carbon deposits.

Inspection of other components on board (refer figure 4) relates the fact that there was presence of unburnt oil along with carbon deposits. This could likely be the reason of unbalance in the shaft which might have led to rubbing of compressor wheel and ultimately leading to failure of other components.

From another point of view there is a possibility of lube oil starvation which would have led to the damages to the bearings and shaft ultimately resulting in failure of other components.

With regard to contamination (fig. 5), water has penetrated in the gas outlet housing, which has caused contamination by mixing with unburned oil and carbon [1], leading to unbalance in the shaft and further causing failure of other components.

Fig. 5: Contamination by mixing with unburnt oil, carbon, water.

With available information, failure of cartridge group could likely be from the 3 probable reasons: Presence of unburnt oil, Lube oil Starvation, Presence of water [14, 15].

2. Statistical analysis

It is very important to note that due to a good combination of circumstances, the presented data were collected a month before the accident as well as for a month after the repair of the turbocharger. Therefore, we can certainly exclude the influence of the technical condition of the engine (fuel valves, fuel pumps, piston-cylinder liner group, exhaust valves, etc.) [6, 7, 8, 9] on operation condition of the turbocharger. Moreover, the used data had been collected in almost the same load condition of the vessel.

The research technology covers two stages.

The first step is to gather appropriate information parameters before the turbocharger is damaged and the same information parameters after repairing the turbocharger.

In statistical modelling, regression analysis is a set of statistical processes for estimating the relationships between a dependent variable (often called the 'outcome') and one or more independent variables (often called 'predictors'). In our case a dependent variable "x" is the turbocharger revolutions (n, s^{-1}) from one side and from another an independent variable "y" – the engine fuel oil consumption (Bs, kg/s). Once a regression model has been constructed, we can confirm the goodness of fit of the model and the statistical significance of the estimated parameters. Commonly used checks of goodness of fit include the R-squared. The Pearson correlation coefficient (R), is a measure of the strength and direction of the linear relationship between x and y. This is the best-known and most commonly used type of correlation coefficient.

The collected data and the obtained mathematical model provide a basis for future analyzes and checks on the condition of the turbocharger, as well as for continuous monitoring. Logically, we can assume that an error in the data used in the range of 4-5 % is permissible within the measuring instruments, as well as the operator. Following the logical reasoning, we can conclude that the error above the mentioned 4-5 % is not due to the means of instrument error, but due to the causal relationship between the dependent variable x and the independent variable y. The larger error, the stronger relationship between x and y. The main advantage of regression analysis is that the contribution of each parameter can be quickly quantified.

The used data was collected one month before the T/C failure and the same data was collected after the T/C overhaul are given in the following table 2 and table 3.

***Table 2.** Before damage*

TCrev., [1/s]	Bs, [kg/s]
x1	y1
158,33	0,1383
158,33	0,1451
158,33	0,1473
163,33	0,1594
165	0,1722
191,67	0,2106
170	0,1684
175	0,1863
186,67	0,1865
186,67	0,184
203,33	0,2051
213,33	0,1979
215	0,2273
216,67	0,206
230	0,256
246,67	0,2667
248,33	0,3063
263,33	0,3215

***Table 3.** T/C overhauled.*

TCrev., [1/s]	Bs, [kg/s]
x2	y2
183,33	0,1919
213,33	0,2175
218,33	0,2434
230	0,2675
231,67	0,259
231,67	0,2528
241,67	0,2553
246,67	0,2754
248,33	0,2718
250	0,2628
250	0,2659
250	0,2688
251,67	0,2865
258,33	0,2821

The second step was to find mathematical models proving the causal relationship between the factor x_i and the objective function y_i. In order to run a statistical analysis a number of significant parameters, responding to equation (1), must be identified [16].

$$y = f(x_i) + e \qquad (1)$$

The regression analysis was run by excel app using the data in table 2 and table 3. The regression curve was drawn by a scatter plot and line equations and the R^2 value was displayed at figure 7.

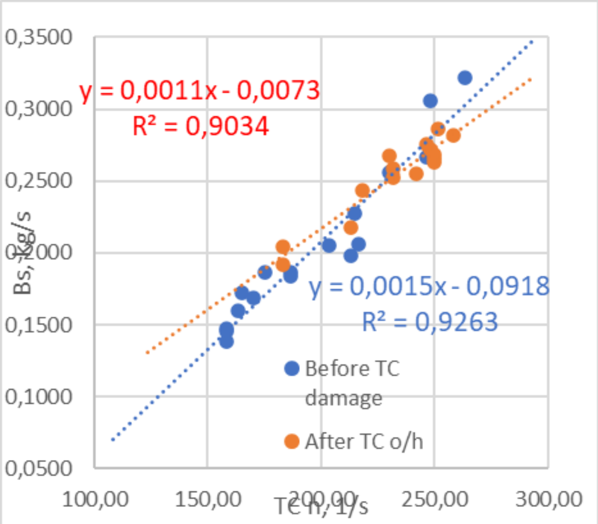


Fig. 7. Influence of fuel consumption Bs to the TC revolutions n.

Before TC damage we found a linear relationship between x and y as follows:

$$y1=0.0015*x - 0.0918 \qquad (2)$$

In case with repaired TC the linear relationship between x and y was found as follows:

$$y2=0.0011*x - 0.0073 \qquad (3)$$

According to the represented interest of TC revolutions in the range from 180 s^{-1} to 264 s^{-1}, using the dependences obtained from the regression analysis, we can record the obtained and predicted values for y1 and y2 by applying values for x (n). To determine the error in percentages (y_e) between y1 and y2, we need to calculate the difference between y1 and y2 (Δy) and then the error y_e, % by below equations (4) and (5) :

$$\Delta y= y1 - y2 \qquad (4)$$

$$y\_e= (\Delta y / y1)*100, \% \qquad (5)$$

The results obtained from the used formulas are shown in tabular form in table 4.

Fig. 8 represents polynomial dependence of the error in percentages to the TC revolution between a turbocharger with new cartridge and a turbocharger for forthcoming repairs. We have note that TPL 76-C33 max. revolutions are 342 s^{-1}. So, in the researched interval of rotation 180 – 264 s^{-1} the error is in range of 6.55 % to -7.45 %.

Table 4: *Predicted value y1, y2 and y_e.*

n, 1/S	Bs1, kg/s	Bs2, kg/s		
x	y1	y2	Δy	y_e, %
180	0,191	0,178	0,013	6,55
187	0,198	0,189	0,01	4,89
194	0,206	0,199	0,007	3,35
201	0,214	0,21	0,004	1,92
208	0,222	0,22	0,001	0,59
215	0,229	0,231	-0,002	-0,65
222	0,237	0,241	-0,004	-1,82
229	0,245	0,252	-0,007	-2,9
236	0,252	0,262	-0,01	-3,92
243	0,26	0,273	-0,013	-4,88
250	0,268	0,283	-0,016	-5,79
257	0,275	0,294	-0,018	-6,64
264	0,283	0,304	-0,021	-7,45

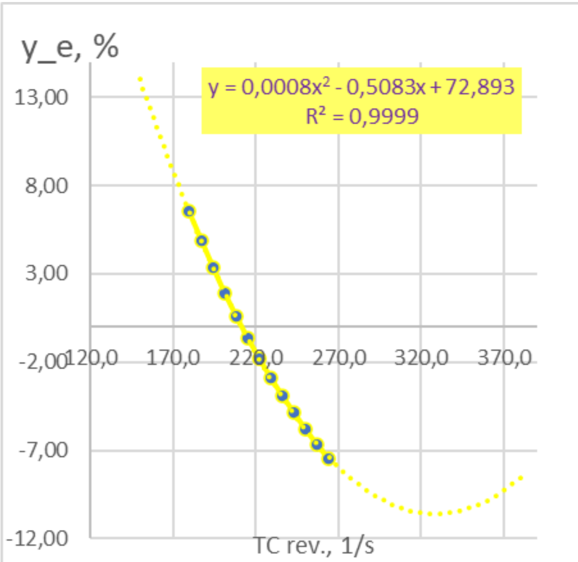


Fig.8: *Polynomial dependence of the error.*

3. Conclusion

3.1 According to the information and data collected, the damage to the cartridge group can be due to 3 possible reasons: - Presence of unburned oil, Lube oil starvation, Presence of water. Therefore, in case of suspicion of malfunction or deviation from the normal condition, the responsible engineers must carry out the appropriate checks and measurements prescribed by the manufacturer, regardless of the working hours provided for in the maintenance schedule.

3.2 The present result shows that there is no relationship between the change in turbine speed (due to poor technical condition) and the fuel oil consumption of the engine. The calculated error y_e is in the range +/- 7% only at low and high loads of the main engine. In the most used engine modes (30% - 80%) the error is less than 4%, which confirms the conclusion.

4. References

1. Bakalov I., Constructive solutions to reduce the NOx and SOx in the marine boiler burners. Varna, 2016, ISSN: 1310-3946
2. Caterpillar Motoren GmbH & Co. KG, Engine operating instructions Type M43C, 17.05.2006
3. Cimac, Turbocharging efficiencies - definitions and guidelines for measurement and calculation, www.cimac.com, May 2007
4. Cui X., Yang C., Serrano J., Shi M., A performance degradation evaluation method for a turbocharger in a diesel engine, , rsos.royalsocietypublishing.org R. Soc. open sci. 5: 181093
5. Habib A., On-Engine Turbocharger Performance Considering Heat Transfer, TRITA – MMK 2012:08, ISSN 1400-1179, ISRN/KTH/MMK/R-12/08-SE, ISBN 978-91-7501-332-9, 22nd of May 2012.
6. Hristov, D., Examination of the influence of the air cooler contamination and the piston rings wear on the marine diesel engines BSFOC, NOx and SOx, Scientific proceedings XIV international congress "Machines. Technologies. Materials." 2017, ISSN 2535-0021
7. Hristov D., Ivanov, I. Study of the impact of technical condition of the turbocharger unit on nitrogen oxides emissions of engine running on natural gas with pre-chamber ignition and lean fuel-air mixture, Nikola Vaptsarov Naval Academy, Doctoral scientific conference 18-19 Nov, Varna p.30-35 ISBN 978-619-7428-45-2 (print) ISBN 978-619-7428-44-5 (online), 2019
8. Hristov, D., Ivanov, I., Hristov, H. Study of the impact of air cooler contamination and piston rings wear on engine emissions, Mechanics of the machines, 2018, v. 24, № 2. ISSN 0861-9727
9. Hristov D., Ivanov I., Bakalov, I. Turbocharger Technical Condition Influence on the Carbon Dioxide Emmisions on Natural Gas Fueled Engine, First International Marine Engineering Conference, 21-23 November 2018 at the Engineering Faculty Nikola Vaptsarov Naval Academy. Varna: NVNA, 2018, pp. 187-191. ISBN 978-619-7428-31-5.
10. Ibrahim M, Dimitri A.S., Bayoumi H.N., El-Shafei A., Stable turbocharger bearings, 12th International Conference on Vibrations in Rotating Machinery Institution of Mechanical Engineers, ISBN 978-0-367-67742-8
11. Iosifov I., Hristov D., Problems with the low temperature corrosion on the marine turbochargers XXIV international scientific-technical conference "trans & motauto ’16" 2016 ISSN 1310-3946
12. Jeonha-Dong, Dong-Ku, Instructions Hyundai-MAN B&W diesel engines operation, Hyundai Heavy Industries Co., Ltd., Edition 0005, Ulsan, Korea
13. Kusztelan A., Yao Y.F., Marchant D.R., Wang Y.,A Review of Novel Turbocharger Concepts for Enhancements in Energy Efficiency, Int. J. of Thermal & Environmental Engineering, Volume 2, No. 2 (2011) 75-82
14. Romagnoli A. and Martinez-Botas R., Heat transfer analysis in a turbocharger turbine: an experimental and computational evaluation, Department of Mechanical Engineering Imperial College London, UK, 2012
15. Serrano,J., Olmeda P., Arnau F., Reyes-Belmonte M., Importance of Heat Transfer Phenomena in Small Turbochargers for Passenger Car Applications, Universitat Politècnica de València, saeeng.saejournals.org, 2013-01-0576
16. Бакалов И., Р. Бакалова. Използване на алтернативни горива в корабните дизелови двигатели, икономически фактор. Шумен, "Маттех 2014", ISSN: 1314-3921