Volume XXV 2022
ISSUE no.1
MBNA Publishing House Constanta 2022

Scientific Bulletin of Naval Academy

SBNA PAPER • OPEN ACCESS

Turbocharger breakdown investigation

To cite this article: D. Popov, Scientific Bulletin of Naval Academy, Vol. XXV 2022, pg. 106-114.

Submitted: 24.03.2022
Revised: 29.07.2022
Accepted: 03.08.2022

Available online at www.anmb.ro

ISSN: 2392-8956; ISSN-L: 1454-864X

doi: 10.21279/1454-864X-22-I1-012

Turbocharger breakdown investigation

Dimitar Popov[1]

[1]Nikola Vaptsarov Naval Academy, 73 Vasil Drumev, Varna, 9002, Bulgaria
d.popov@naval-acad.bg

Abstract. The internal combustion engine (ICE) turbocharger plays an important role in ensuring the continuous and stable power of the diesel engine as well as in reducing the environmental impact of exhaust emissions. The aim of this paper is to provide a review of the symptoms of damage and the cause of damage of turbocharger. The case is a container vessel on which the turbocharger is damaged in "Full Ahead" mode. Engine and turbocharger parameters were collected and analysed prior to failure. The parameters of the engine and the turbocharger after repair of the turbocharger are collected and summarized. In the publication is presented a report of repair work performed on the damaged turbocharger. The relevant conclusions have been made.
Keywords: Turbocharger, Internal Combustion Engine (ICE), performance, fuel consumption.

1. Introduction

The turbocharger (TC) is one of the most sensitive components of the engine. The efficiency of the turbocharger depends on its degree of contamination, which determines whether the individual cylinders are supplied with a sufficient amount of air. Consequences of a poorly performing turbocharger can be:

- Drop in power produced by the engine
- Rising fuel consumption
- High temperatures of the combustion chamber components, which may significantly reduce service life particularly of the combustion chamber components.

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. When analyzing the nonlinear correspondence between the failure symptoms and failure causes, it is difficult for the existing theories to meet the actual diagnostic requirements [4, 5]. As one of the key systems of a marine diesel engine, turbocharger plays an important role in ensuring the continuous and stable power supply of diesel engine as well as in reducing the environmental impact of exhaust emissions. In operation, the turbine side of the turbocharger is connected to the exhaust pipe of the diesel engine. The exhaust gas turbocharger drives the centrifugal compressor impeller (n max. 348 s^{-1}) by using the exhaust gas energy (about 673K – 893K and 0.1–0.2 MPa) discharged from the diesel engine. The thermodynamic system of the turbocharger is shown in figure 1. The exhaust temperatures before and after the turbocharger are used to assess the thermodynamic load condition of the engine as they cover the overall thermodynamics of the engine, exhaust turbine and intake condition [2, 3].

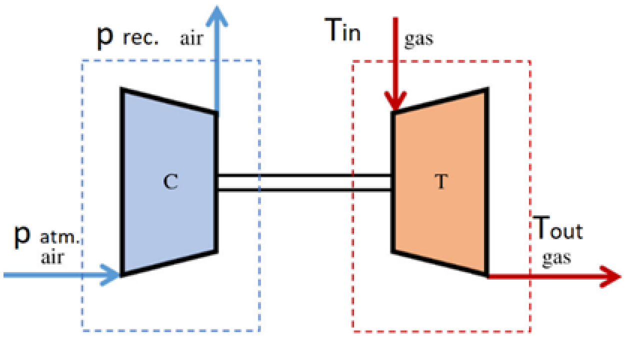

Figure 1. The thermodynamic system of the turbocharger.

The turbocharger components are shown in figure 2 as bellow [11, 12]:

01- Filter silencer
02- Radial plain bearing
03- Thrust bearing
04- Bearing bush
05- Radial plain bearing
06- Gas outlet casing
07- Gas inlet casing
08- Nozzle ring
09- Turbine wheel
10- Bearing casing
11- Diffuser
12- Compressor wheel
13- Compressor casing

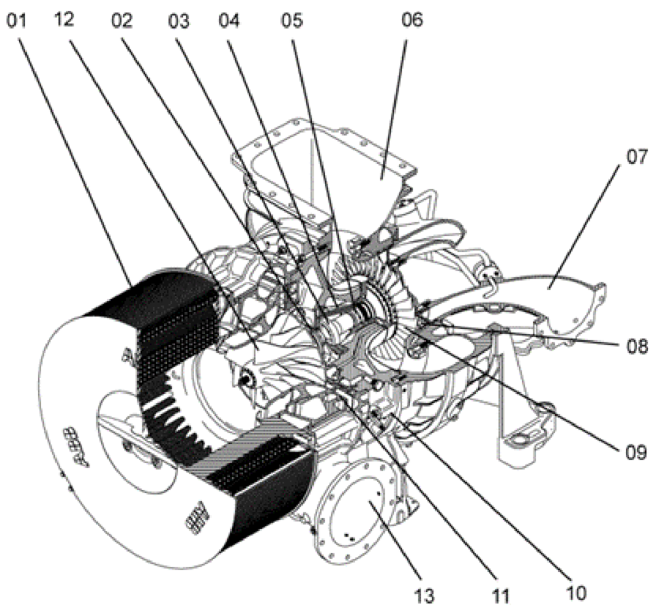

Figure 2. Turbocharger layout.

The aim of this research is to provide a review of the symptoms of damage and the cause of damage of turbocharger. Our target is by collected data to find appropriate mathematical methods to obtain qualitative relationships between engine fuel consumption and temperature drop in turbine side.

The objects of research were a four-stroke medium speed marine engines MAK 9M43C type with its ABB turbocharger TPL76-C33 type. The damage to the turbocharger of the 8400kW diesel engine, which operates for about total 66 275 hours, caused losses of over a half million euros.

The turbocharger details and replacement interval of rotating components as below in table 1 [1].

Table 1. TPL76-C33 replacement interval of rotating components

TC type	Serial no.	Exchange interval of Turbine (hours)	Exchange interval of Compressor (hours)	Actual TC (hours)
TPL76-C33	HT833849	50000	50000	43892

Operating a turbocharger with parts whose running hours exceed the recommended exchange interval increases the risk of turbocharger failure.

In this report we give a complete overview of the change of the turbine temperature drop (ΔT) from the state of a new turbine to state of a turbine for repair. By creating these mathematical models of the change in temperature drop, we answer to the question when the turbocharger should be repaired.

2. Root cause analysis

The data before the damage occurred was that the main engine was operating at a load of about 50% with the engine running hour being 66 275. The TC temperature inlet (Tin) was 752K and TC outlet temperature (Tout) was 691 K, so turbine temperature drop (ΔT) was calculated as 752-691= 61K. 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. After primary checking of the main engine was observed high exhaust gas temperatures and metal particles in the lube oil filter.

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 (figure 3) with wall insert may be the consequential damage [9, 10].

2.1. Presence of unburnt oil in nozzle ring, Gas outlet casing and Hood (figure 5 and 6)

Inspection of these 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. The source of oil leakage may not be traced back.

2.2. Lube oil starvation

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.

2.3. Presence of water

Referring the figures of contamination, there is likely the condition of water entry from the Gas outlet casing (figure 5) which has caused contamination by mixing with unburnt oil and carbon leading to unbalance in the shaft and further causing the other components to fail.

2.4. Findings

Figure 3. Compressor Wheel- found severely rubbed.

Figure 4. Hood and Turbine remarks.

Figure 5. Contamination with unburnt oil, carbon, water.

Figure 6. Gas outlet casing.

With available information. failure of cartridge group could likely be from the 3 probable reasons mentioned: - Presence of unburnt oil, Lube oil starvation, Presence of water.

There are several ways in which the turbocharger may fail and will require replacement. The first mode of failure is due to the degradation of the compressor vanes caused by rubbing of the compressor on the volute (figure 3). In order the turbocharger to be able to operate with stable mode, the internal bearing clearances must be kept within acceptable limits. Also, the compressor bearing clearance continues to wear and increase over time. As the internal compressor end bearing clearance enlarges, the sub synchronous conical whirl amplitude of motion continues to increase, causing the impeller to contact the volute. This causes damage to the compressor vanes and reduces performance. The reduced turbocharger output then requires that the turbocharger be replaced.

There is another mode of instant failure of the turbocharger which is associated with the turbine end bearing. In all of the failed turbochargers, evidence of heavy coking was observed at the turbine bearing locations. Because of the high temperatures of the exhaust gas in the turbine area, heat shielding is required for the turbocharger. It is possible for the high temperature to cause oil cooking, resulting in the turbine floating bush bearing to seize to the shaft. When this occur, we have a large clearance cylindrical bearing which is unstable at about 100 s^{-1}.

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 turbine. Therefore, we can certainly exclude the influence of the main factor on operation of the turbocharger, namely a technical condition of the engine - fuel valves, fuel pumps, piston-cylinder liner group, exhaust valve, etc. [5, 6, 7, 8].

3. Statistical analysis

The research technology covers two stages. The first step is to gather appropriate information before the turbocharger is damaged and the same information after repairing the turbocharger.

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

Table 2. Turbocharger data collected before the damage.

Bs (kg/s)	x_1	0.1473	0.1546	0.1865	0.2051	0.2060	0.2168	0.2454	0.2464	0.2558	0.2569
ΔT_1 (K)	y_1	60	61	88	94	96	94	114	112	116	121

Table 3. Turbocharger data collected after TC repair.

Bs (kg/s)	x_2	0.1402	0.1944	0.2322	0.2553	0.2590	0.2642	0.2662	0.2675	0.2687	0.2821
ΔT_2 (K)	y_2	73	94	111	127	122	129	126	135	136	136

The second step is to find mathematical models proving the causal relationship between the factor *x* and the objective function *y*. The collected data were processed with appropriate mathematical methods to obtain qualitative relationships. Regression analysis was used, including processing of experimental data by the method of least squares and statistical analysis of the results. Regression analysis is used to predict a continuous dependent variable from a few independent variables. So far, such an approach has not been used to characterize the operation of the turbocharger. The main advantage of regression analysis is that the contribution of each parameter can be quickly quantified. In order to run a statistical analysis a number of significant parameters, responding to equation (1), must be identified.

$$y_i = f(x_i) + e_i \quad (1)$$

where, x_i are the explanatory variables (independent parameters) and y_i is the response variable [13]. The error terms, which are not directly observed in data is represented by e_i.

For universality in the records in all tables, x_i denotes the values of the fuel oil consumption per second - factor Bs, and y_i is the target a turbine temperature drop (ΔT).

$$\Delta T = Tin - Tout \quad (2)$$

where, Tin is the turbine inlet temperature, Tout is the turbine outlet temperature.

The research performed and the results obtained are given as tabular form in below table 3.

Table 3. Results from regression analysis.

	linear model	R^2
before T/C damaged	$y_1=531.91x_1-17.208$	0.9754
after T/C overhauled	$y_2=466.93x_2+5.4455$	0.9727

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.

From the obtained calculations it can be concluded that the dependence between the factor x and the target function y is linear function with a high degree of correlation.

In figure 3, ΔT_1 - line represents the temperature drops of turbocharger before the damage of the compressor impeller and ΔT_2 - line represents the temperature drops of repaired turbocharger (with changed cartridge) as a function of the fuel consumption per second of the main engine Bs (kg/s) [4].

The big difference between linear functions can be seen due to the significant influence of the technical condition of the T/C on the fuel consumption of the main engine.

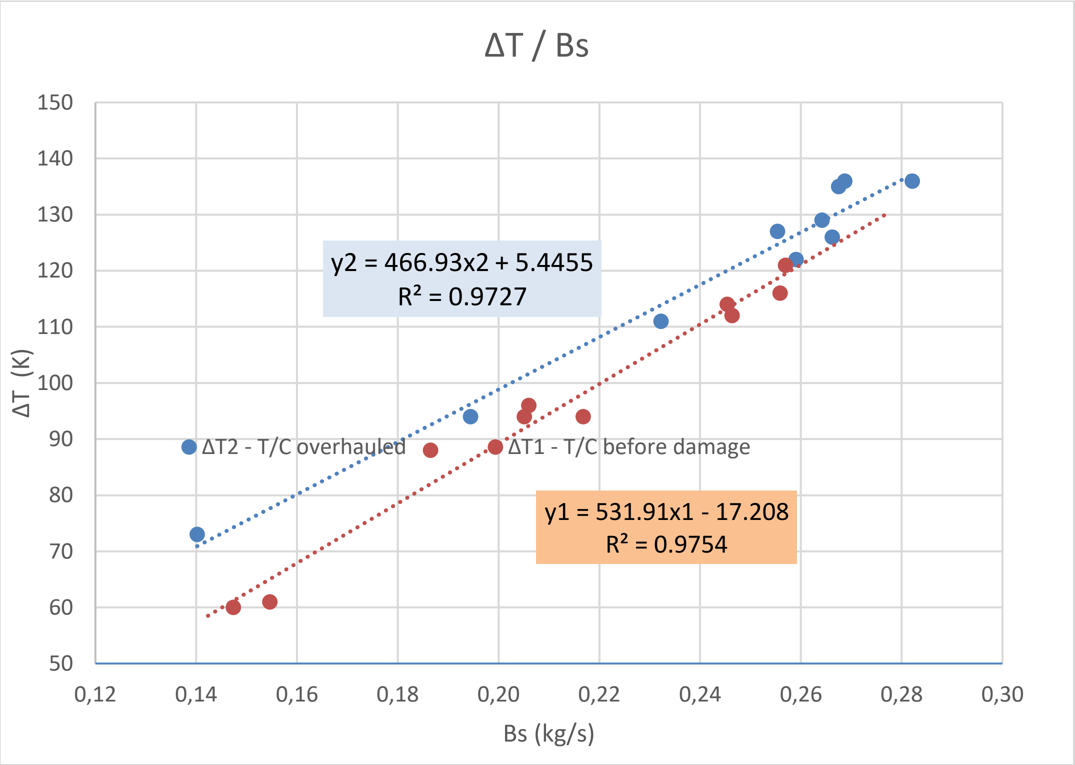

Figure 3. Influence turbine temperature drop to fuel consumption.

According to the collected data. when the fuel consumption Bs changes in range 0.1389 – 0.2778 kg/s, which is research interest. The values for ΔT_1 and ΔT_2 are given as vector rows in table 4.

Table 4. Predicted temperature drop.

Bs (kg/s)	x	0.139	0.153	0.167	0.181	0.194	0.208	0.222	0.236	0.250	0.278
ΔT_1 (K)	y_1	56.7	64.1	71.4	78.8	86.2	93.6	101.0	108.4	115.8	130.5
ΔT_2 (K)	y_2	70.3	76.8	83.3	89.8	96.2	102.7	109.2	115.7	122.2	135.1
ΔT_e (K)	y_e	13.6	12.7	11.8	10.9	10.0	9.1	8.2	7.3	6.4	4.6
ΔT_e%		24.05	19.87	16.55	13.85	11.62	9.74	8.13	6.75	5.54	3.53

The error between the two values ΔT_e (K) is given as a vector row in table 4 [14].

$$\Delta T\_e = \Delta T_2 - \Delta T_1 \tag{3}$$

The relative error of the temperature drops ΔT in percent, depending on the fuel consumption of the main engine Bs (kg/s), determined by the equation:

$$\Delta T\_e\% = (\Delta T\_e / \Delta T_1)100 \tag{4}$$

is given as a vector row in table 4.

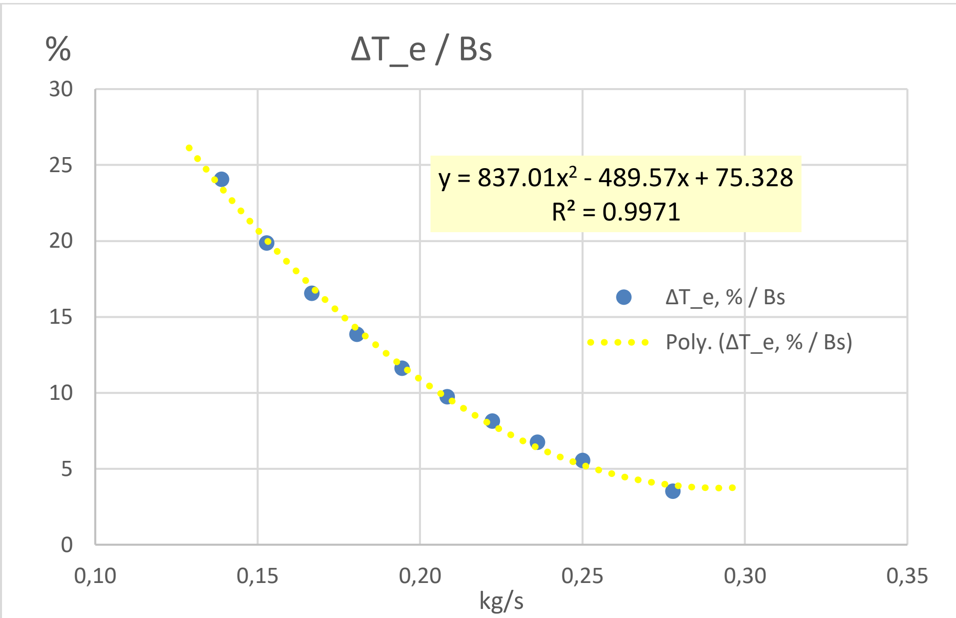

Figure 4. Relative error of the turbine temperature drops in percent.

Figure 4 represents the error of the polynomial dependence in percentages of the temperature drop between a turbocharger with a new cartridge and a turbocharger for forthcoming repairs.

4. Conclusions

4.1. An overview of the reasons that led to the failure of the turbocharger

With collected information and data, failure of cartridge group could likely be from the 3 probable reasons: - Presence of unburnt oil, - Lube oil starvation, - Presence of water. Lube oil plays a critical role to reduce friction and to ensure the machines are more energy efficient in terms of fuel consumption and power output. The usage of compromised lube oil can result in malfunctioning and damage to engines and machinery.

4.2. Dependencies established as a result of the selected mathematical models and their relationship

The linear regression analysis for the single explanatory variables shows that these are strongly correlated. This supports the assumption of significant relationship existing between and the explanatory variables.

The technical condition of the turbocharger has a significant impact on the quality of the combustion process and fuel consumption. As can be seen from figure 4 curve, the influence of the technical condition of turbocharger is significant in small and medium loads, where it reaches 25 % and 10 %, respectively, and in large loads the influence decreases to about 4%.

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. Errors in the range of 3-4 % can be considered acceptable, while errors above 4% indicate deterioration of the turbocharger condition.

Acknowledgements

The presented data and parameters are processed and collected for months. Values taken under similar external conditions are selected. The main marine engine to which the research relates is a four-stroke medium-speed engine using ultra low Sulphur diesel oil. The research does not apply to two-stroke low-speed engines, but the conclusions and results can be assumed and accepted as valid with the corresponding approximation.

References

[1] Caterpillar Motoren GmbH & Co. KG 2006 *Engine operating instructions Type M43C*

[2] Cimac 2007 *Turbocharging efficiencies-definitions and guidelines for measurement and calculation*, www.cimac.com,

[3] 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

[4] Habib A 2012 *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

[5] Hristov D 2017 *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.", ISSN 2535-0021

[6] Hristov D, Ivanov I 2019 *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),

[7] Hristov D, Ivanov I, Hristov H 2018 *Study of the impact of air cooler contamination and piston rings wear on engine emissions*, Mechanics of the machines ISSN 0861-9727

[8] Hristov D, Ivanov I, Bakalov I 2018 *Turbocharger Technical Condition Influence on the Carbon Dioxide Emmisions on Natural Gas Fueled Engine*, First International Marine Engineering Conference, ISBN 978-619-7428-31-5

[9] Ibrahim M, Dimitri A, Bayoumi H, El-Shafei A, *Stable turbocharger bearings*, 12th International

Conference on Vibrations in Rotating Machinery ¬ Institution of Mechanical Engineers, ISBN 978-0-367-67742-8
[10] Iosifov I, Hristov D 2016 *Problems with the low temperature corrosion on the marine turbochargers,* XXIV International scientific-technical conference "trans & motauto” ISSN 1310-3946
[11] Jeonha-Dong, Dong-Ku, 2005 *Instructions Hyundai-MAN B&W diesel engines operation*, Hyundai Heavy Industries Co. Ltd., Ulsan, Korea
[12] Kusztelan A, Yao Y, Marchant D, Wang Y A 2011 *Review of Novel Turbocharger Concepts for Enhancements in Energy Efficiency*, Int. J. of Thermal & Environmental Engineering, Volume 2, No. 2
[13] Romagnoli A, Martinez-Botas R 2012 *Heat transfer analysis in a turbocharger turbine: an experimental and computational evaluation*, Department of Mechanical Engineering Imperial College London, UK
[14] Serrano J, Olmeda P, Arnau F, Reyes-Belmonte M 2013 *Importance of Heat Transfer Phenomena in Small Turbochargers for Passenger Car Applications*, Universitat Politècnica de València, saeeng.saejournals.org