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Evaluation of the Factors Affecting Turbocharger Service Life

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***Abstract*—This paper introduces an experimental-based approach to measure the shaft/bearing clearance of turbocharger without dismantling the assembly. An experimental test rig was designed, constructed, and provided with computer-based sensors to measure and record the test data for further analysis and interpretation. The test rig consisted of a set of shaft/bearing assembly with known different clearances. It is connected to a constant volume air tank through piping and connectors to allow the tank to discharge through the known clearance. The tank pressure and temperature were measured using pressure and temperature transducers and their signals were transmitted to the computer through the proper interface. By means of the constructed test facility, the variation of the tank pressure and temperature are examined in the time domain and are related to the known clearances. Reference curves are constructed in order to use them to determine the shaft/bearing clearance of turbochargers in site without dismantling them, which fulfills the objective of this work. Good estimation is obtained and verified with theoretical analysis using isothermal, isotropic and poly-tropic models.**

Keywords: Turbocharger failure; Shaft/bearing clearance; Service life.

I. INTRODUCTION

Turbochargers are having increasing utilization in recent years for both petrol and diesel engines in order to boost their power rating without increasing their swept volume. In other words, specific power to weight ratio is noticeably increased.

Malfunctioning of the turbocharger will deter its advantages to a great extent. Malfunctioning may arise due to many factors, such as, foreign objects in the lubricating oil, foreign objects in the compressor or the turbine, turbocharger overspeed, and failure due to high temperature.The most important factor is the conventional method of measuring the shaft/bearing clearance which usually requires dismantling many engine components, and above all, disassemble the turbocharger into pieces. This process is costly and time-consuming. Realization of this fact stemmed the adaptation of the present approach to be very quick with minimal cost.

Turbocharger increases the total air flow through the engine. The more mass of air and fuel that flows to the engine, the more power output [2]. However, turbocharger matching principles affect the engine efficiency and performance. Installing any turbocharger does not guarantee good results. Turbocharger manufacturers provide compressor and turbine characterization maps to enable perfect matching to the engine. Usually, turbochargers run at very high speeds and temperatures. Any interruption of oil feed system or excessive clearance between shaft and bearing causes turbocharger mechanical failure, which leads to turbocharger damage resulting in engine damage. The purpose of this work is to measure the turbocharger shaft/bearing clearance, which affects the turbocharger performance and output power [3].

II. EXPERIMENTAL PART

A. Theoritical model

The objective of the present work is to find the turbocharger shaft/bearing clearance without disassembling the turbocharger. When discharging pressurized air tank with known initial pressure and volume through an orifice and measuring the pressure drop versus the time, the area of the orifice can be calculated [4].

Discharge of an air tank can be modeled using compressible flow thermodynamic equations for isothermal and adiabatic cases [4] and a polytropic model [5].

The governing equation of adiabatic model:

$$P = P_i \left[1 + \left(\frac{-1}{2}\right)\left(\frac{\gamma+1}{2}\right)^{\frac{-(\gamma+1)}{2(\gamma-1)}} \left(\frac{t}{t_{charc}}\right) \right]^{\frac{-2\gamma}{(\gamma-1)}} \quad (1)$$

The governing equation of isothermal model:

$$P = P_i \, . \, exp\left[-\left(\frac{\gamma+1}{2}\right)^{\frac{-(\gamma+1)}{2(\gamma-1)}} \left(\frac{t}{t_{charc}}\right) \right] \quad (2)$$

Where the characteristic time is given by

$$t_{char} = V / (A_t . a_i) \quad (3)$$

V, A_t and a_i are the tank volume, orifice area and speed of sound in gas initially in the tank respectively.

$$a_i = \sqrt{\gamma R T} \quad (4)$$

Substituting γ = 1.4 in equations (1 and 2) yields the two following equations.
The governing equation of isothermal model:

$$P = P_i \, . \, e^{c_1 t} \quad (5)$$

$$C_1 = \frac{-0.6847 \, . \, A_t \, . \, C_d \sqrt{R\,T_i}}{V} \quad (6)$$

The governing equation of adiabatic model:

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$$P = [P_i^{-\frac{1}{7}} + C_2\, t]^{-7} \quad (7)$$

$$C_2 = \frac{0.1369\,.\,A_t\,.\,C_d\sqrt{R\,T_i}}{V.P_i^{(\frac{1}{7})}} \quad (8)$$

The governing equation of polytropic model:

$$\rho_{i+1} = \rho_i + \frac{\rho_i A_t M_{t,i*}\sqrt{(\gamma R T_i)}}{V}\left(1+\left(\frac{\gamma-1}{2}\right)M_{t,i}{}^2\right)^{-(\frac{1}{2})(\gamma+1)/(\gamma-1)} .\Delta t \quad (9)$$

$$P_{i+1} = P_i\left(\frac{\rho_{i+1}}{\rho_i}\right)^n \quad (10)$$

B. *Experimental setup*

The main concept of the experimental setup is based on the design and construction of a mobile kit consisting of an air compressor in addition to an air tank provided with controlled inlet and outlet valves. Proper piping and connectors are installed in their locations. Instantaneous pressure and temperature inside the air tank are measured and recorded via sensors, interface and a laptop computer. The kit is attached to the shaft/bearing with known clearance, which simulates the actual turbocharger package, shown as solid lines in Fig. 1.

The same kit is used to estimate the actual turbocharger shaft/bearing, but with replacing the assembly with a known clearance as shown Fig. 1 as dotted lines. The pressurized air tank with known initial pressure and temperature is allowed to discharge through the shaft/bearing clearances. The time required for the air tank pressure to drop from a predetermined value to a final value is determined. It worth mentioning here, that the clearance configuration is typically the same in both testing cases. That is, the clearance area is in the shape of a crescent and the circumferential clearance between the shaft and bearing is the same as shown in Fig. 2.

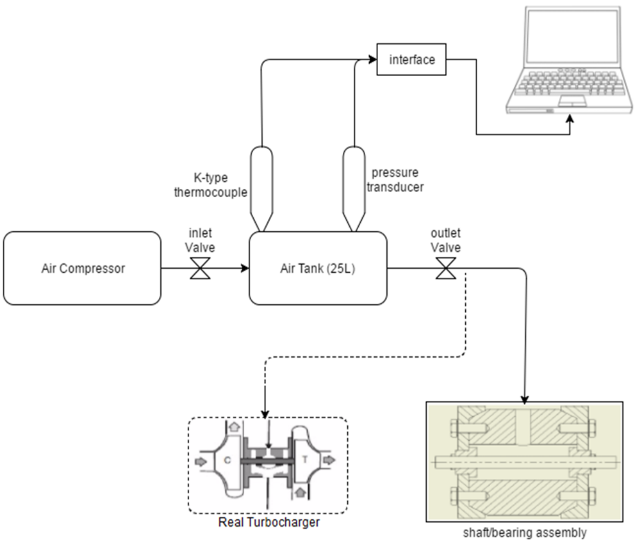

Fig. 1. Compressed air flows through turbocharger shaft/bearing clearance (dotted actual and solid designed set).

The components of the test rig used to establish the relationship between the shaft/bearing clearance and the discharging time consisted of four known different bearing inner diameters (7.54, 7.58, 7.69, 7.73 mm) and a shaft diameter of 7.52 mm. Two turbochargers of Toyota microbus model CT16 diesel were tested. The values of the parameters used in the experimental and theoretical results are shown in the appendix at the end of the paper.

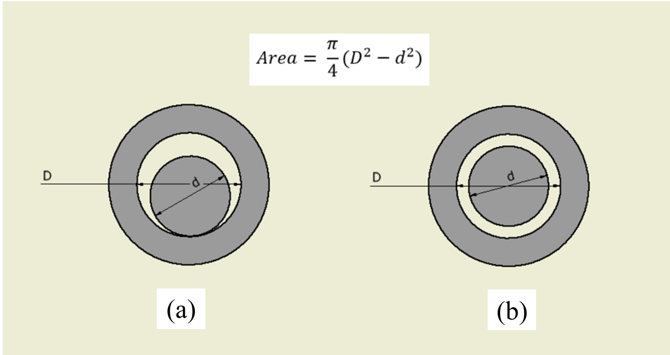

Fig. 2 shape of shaft/bearing clearance when; (a) the shaft is stationary (b) the shaft is rotating at a very high speed and lifted due to the lubricant.

C. *Experimental results*

In this section, the experimental results together with the corresponding theoretical results for diametrical clearances; 210, 180, 60 and 20 µm are shown respectively in Figs. 3, 4, 5 and 6. The discharge time was measured for the tank pressure to drop from 7 bar to 2 bar. This pressure drop is chosen to minimize the measurement error. Moreover, the theoretical flow equations are considered for isothermal, adiabatic and polytropic models.

Fig. 3 shows the relation between the pressure and discharge time for 0.21 mm shaft/bearing diametrical clearance.

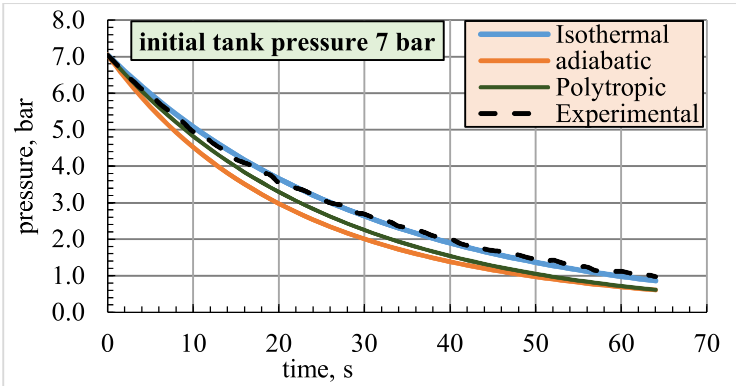

Fig 3. Pressure drop for clearance 210 µm

Fig. 4 shows the relation between the pressure and discharge time for 0.18 mm shaft/bearing diametrical clearance.

Fig. 5 shows the relation between the pressure and discharge time for 60 µm shaft/bearing diametrical clearance.

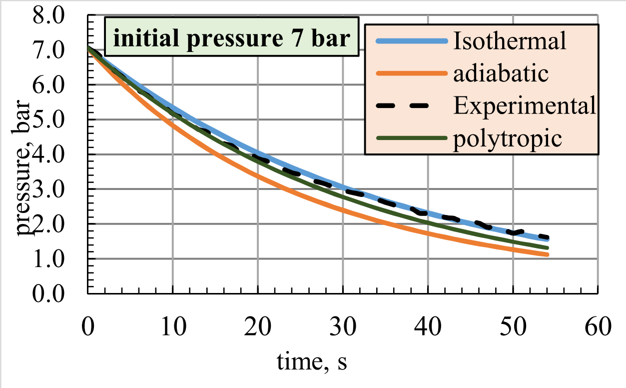

Fig 4. Pressure drop for clearance 180 µm.

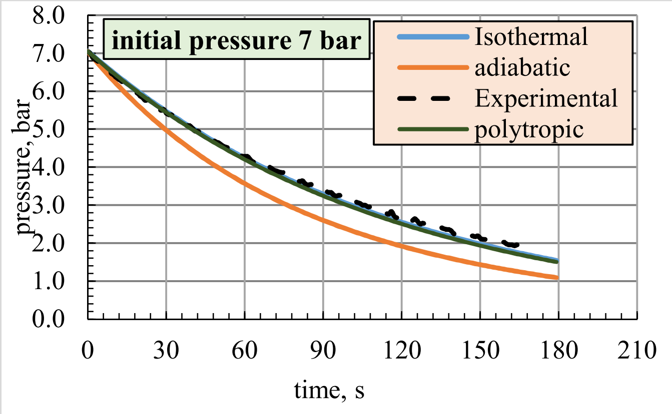

Fig 5. Pressure drop for clearance 60 µm.

Fig. 6 shows the relation between the pressure and discharge time for 0.02 mm shaft/bearing diametrical clearance.

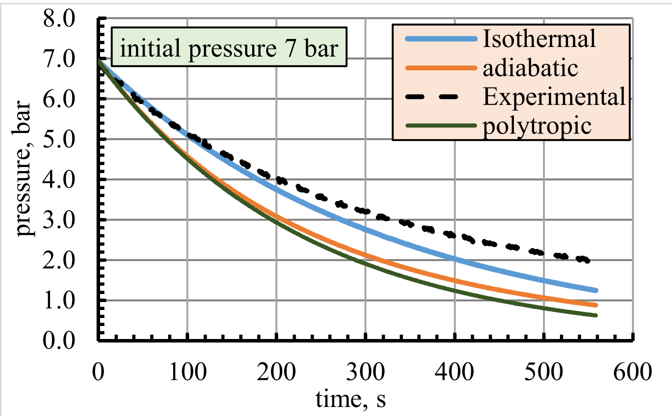

Fig 6. Pressure drop for clearance 20 µm.

A calibration curve was obtained from the experimental results as a relation between the shaft/bearing clearance and the discharge time as shown in Fig.7. By knowing the discharge time, the shaft/bearing clearance can be estimated and the remaining expected service life may be foreseen.

Time elapsed to reach tank pressure 2.0 bar from 7.0 bar.

Time (s)	Clearance (µm)
40	210
46	180
160	60
560	20

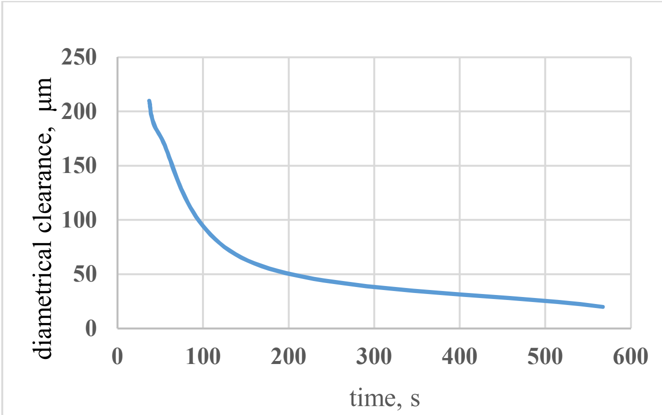

Fig 7. Shaft/bearing clearance versus discharging time.

Each of the two turbochargers mentioned in section B was connected to the test rig to discharge the air tank through it and find the time of discharge from 7 to 2 bar. The shaft/bearing clearance of each turbocharger was measured and compared with the results shown in Fig. 7. From the comparison it was found that the two turbochargers give good approximation to the isothermal model as shown in Figs. 8, 9.

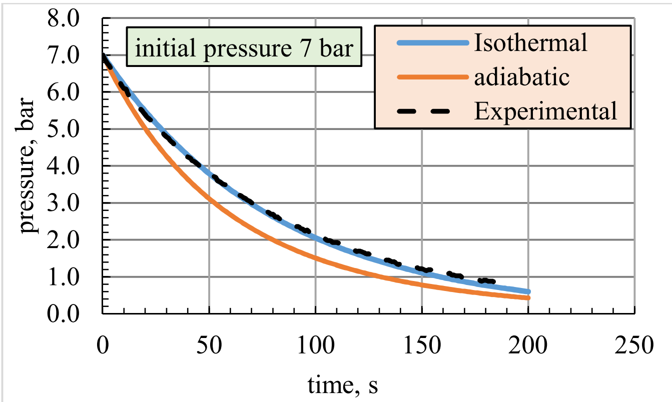

Fig. 8. First turbocharger test with shaft/bearing clearance (80 µm).

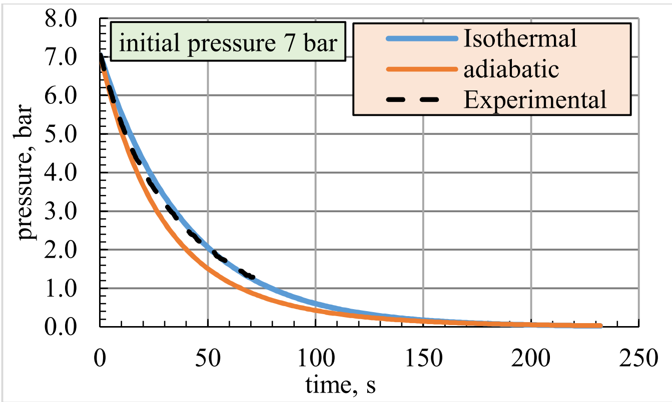

Fig. 9.Second turbocharger test with shaft/bearing clearance (160 µm).

III. CONCLUSION

New procedure for measuring the shaft/bearing clearance of a turbocharger has been presented. An experimental mobile kit is developed to easily estimate the clearance without dismantling many parts of the engine and turbocharger assemblies.

The mathematical modeling showed that the isothermal model is the nearest matching results with that of the corresponding experimental one. This simple approach can help to examine current shaft/bearing clearance against the maximum value allowed in the service manual and helps for the decision of turbocharger replacement.

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NOMENCLATURE

Symbol	***Description***	***unit***
P_i	***Initial pressure***	***Pa***
P	***Final pressure***	***Pa***
V	***Tank volume***	m^3
A_t	***Orifice area***	m^2
a_i	***Speed of sound initially in the tank***	***m/s***
R	***Universal gas constant***	***J/kg.K***
T_i	***Initial Temperature***	***K***
ρ_t	***Initial air density in the tank***	kg/m^3

APPENDIX

Parameters used in the model:

1. Adiabatic index, $\gamma = 1.4$
2. Discharge coefficient, $C_d = 0.8$
3. Universal gas constant, R = 287 J/kg.K
4. Air reservoir volume, V= 25 liters