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Optimization of Turbocharged Diesel Engines

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***Abstract*—**The turbocharger and turbocharging have been the inherent component of diesel engines, so that critical parameters of such engines, as BSFC (Brake Specific Fuel Consumption) or thermal efficiency, fuel consumption, BMEP (Brake Mean Effective Pressure), the power density output and emission level have been improved extensively. In general, the turbocharger can be considered as the most complex component of diesel engines, because it has closely interrelated turbomachinery concepts of the turbines and the compressors to thermodynamic fundamentals of internal combustion engines and stress analysis of all components.

In this paper, a waste gate for a conventional single stage radial turbine is investigated by consideration of turbochargers operation constrains and engine operation conditions, without any detail designs in the turbine and the compressor. Amount of opening waste gate which extended between the ranges of full opened and closed valve, is demonstrated by limiting compressor boost pressure ratio. Obtaining of an optimum point by regard above mentioned items is surveyed by three linked meanline modeling programs together which consist of Turbomatch®, Compal®, Rital® madules in concepts NREC® respectively.

***Keywords*—**Turbocharger, Wastegate, diesel engine, CONCEPT NREC programs.

I. Introduction

THE path of technological development for advanced internal combustion engines has increasingly based on modern turbochargers which optimized and controlled carefully. In addition to design progressing, many accessories have been innovated to adjust the turbocharger in order to operate in safe and efficient range without any defect. Each of components of the turbocharger such as the compressor and the turbine somehow designed to has high efficiency. However, overall turbocharger operation and interaction with the engine through the off-design operation condition and stress limitations are significant. Thus, it must be considered that turbocharger performance is investigated as integrated unit which has closely coherence with the engine operation.

Moreover, another restriction in operation conditions is environment problems. Emissions requirements are pushing compressor operability to the needs to reach higher pressure ratios and across typical stability boundaries into low-efficiency areas [1], [2]. Almost always, a continuing upward trend in boost pressure is demanded in order to achieve higher BMEP and reduce emissions levels. The boost pressure that can be achieved in a simple turbocharger is usually considered to be limited by the compressor, but it may also be limited by the turbine. A single stage centrifugal compressor is capable of working efficiently at high pressure ratios, but this is usually only achieved at the expense of range. The power required to drive the compression system increases with boost pressure. When high boost pressure is used, the focus of attention falls on the power that the turbine can effectively deliver [3].

In general, turbocharger itself has three major components and a controller part, called waste gate. Generally, turbine, compressor, and the relation bearings are same components in all kinds of turbochargers, while a controller device (waste gate) could be different. The waste gate is a simple device that must be matched with a turbocharger and hence the diesel engine. The waste gate application is essential when a diesel engine operates at commutable conditions. The setting point of actuator of wastgate is significant as far as existing of itself turbocharger.

II. Main Components

A. The Compressor, Turbine and the Engine

The purpose of the use of the turbocharger is to compromise the compressor, turbine performance and the engine operation, so that range constrains, durable life and maintaining costs must be regarded. The critical parameters that are significant for the compressor, the turbine and the engine, include the choking, surging, the turbocharger efficiency, BMEP, emission levels and the power density, respectively [4], [5]. The range of stable operation of a compressor is limited by choke at high flow rates and surge at low flow rates, and is defined as:

$$Range = \frac{\dot{m}_{choke} - \dot{m}_{surge}}{\dot{m}_{choke}} \quad (1)$$

As the speed of the turbocharger shaft increases, the amount of mass flow rate in turbine and compressor rises. Turbine inlet mass flow rate depends on exhaust gas mass flow of engine, existing of EGR (Exhaust Gas Recirculation), and waste gate systems on the engine circuit. Therefore, net turbine inlet mass flow rate can be calculated as:

$$\dot{m}_T = \dot{m}_{EG} - (\dot{m}_{EGR} + \dot{m}_{WG}) \quad (2)$$

The exhaust gas mass flow rate is evaluated as:

$$\dot{m}_{EG} = \dot{m}_a + \dot{m}_f \quad (3)$$

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where $\dot{m}_a$ which is either engine inlet mass flow rate, or the compressor mass flow rate, is evaluated as:

$$\dot{m}_a = \dot{m}_{C,e} = \eta_{vol} \cdot \rho_{C,e} \cdot V_{sw} \frac{N}{2} \quad (4)$$

Exit density of the compressor can be written as follows:

$$\rho_{C,e} \cong P_{C,e}/RT_{C,e} \quad (5)$$

The engine power is expanded as:

$$P_E = m_a . \eta_f . Q_f . (\frac{1}{AFR}) \quad (6)$$

As AFR (air fuel ratio), the energy available in the fuel per unit mass Q_f and a fuel conversion efficiency η_f are defined.

After a while the mass flow rate gets fixed and do not grow, anymore. This point demonstrates the choking event. Fig. 1 illustrates stable operating range as a function of pressure ratio and specific speed. By knowing above mentioned parameters, surging mass flow rate can be obtainable.

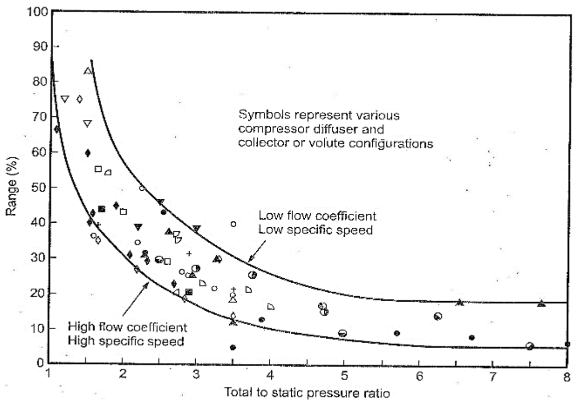

Fig. 1 Stable operating range against pressure ratio [6]

After obtaining the turbocharger optimum point, consideration of engine characteristics are essential. Because, the final goal of applying turbochargers in engines is improvement of engine performance. BMEP and output power per same fuel consumption must be enhanced. On the other hand, emission levels and overall engine downsizing have to be noticed.

B. Wastegates

The waste gate is simply a device, which bypasses some of the exhaust around the turbine, whenever opens. Fig. 2 illustrates the schematic diagram of exhaust waste gate. It is the most widely used of all turbocharger development concepts. Every manufacturer of small and medium sized turbochargers utilizes waste gate unit in production. The benefit that this brings to the turbocharger system stems from the different characteristics of the engine and the turbine. An internal combustion engine is a positive displacement device and, to a first approximation, the flow rate is directly proportional to the engine speed [7].

The waste gate is composed by a valve, the spring back of the valve, the diaphragm and a tube relating high pressure fluid space with the valve diaphragm. Fig. 2 shows internal components of the waste gate. Location of the installed waste gate can be different depending on the type of valve. The wastegate valve can be installed on the compressor or turbine side. Although an air-side waste gate is thermodynamically less efficient than the exhaust side from the inlet to bypass, it may be more durable because of operating in a lower temperature environment. Exhaust-side waste gate not only rises more rapidly, when engine speed increases, comparing to the other type, but also would give a better engine torque characteristic, despite having such a disadvantage that it requires exposing the diaphragm of the actuator to hot exhaust gases, which leads to problems of durability.

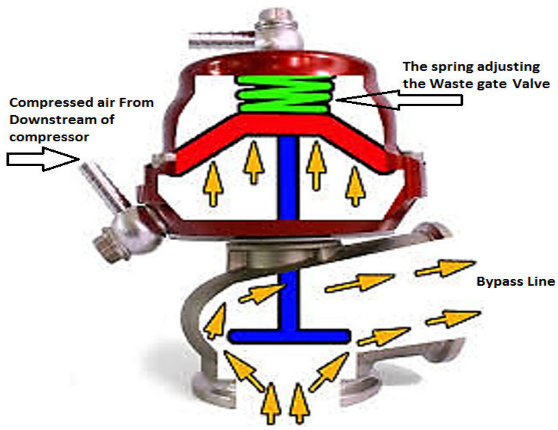

Fig. 2 General schematic of a valve and the wastegate operation

III. Mean Line Turbomatch® Program and Settings

In this study, for matching the turbocharger with diesel engines and investigate the effect of a waste gate on engine performance, package and design tools and modules in concept NREC® which contain TURBOMATCH® linked dynamically to COMPAL® and RITAL®, are applied. It allows the preliminary design of a new compressor and turbine to be done and generated performance maps, and studied the matching of the components interactively. The most effective turbocharger design is tightly linked with the overall engine system. The complex interaction between the compressor, turbine, internal combustion engine, and other components in the overall system requires an integrated approach to design, like TURBOMATCH®. Fig. 3 demonstrates general schematic of turbocharger with associated components in the mentioned program. A detailed description of the theory behind this program can be found in *Centrifugal Compressor Design and Performance* by [4].

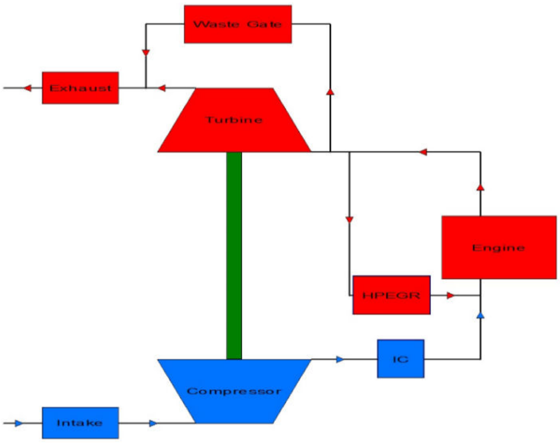

Fig. 3 General schematic of turbocharger

One of the most important options in TURBOMATCH® program is MODE option which consists of two main parts: 'design' and 'analysis' modes. In the 'design' mode of the system, the compressor and turbine can be sized to the required pressure ratios and automatically match the power and rotational speed of the two. The second mode of operation, the 'analysis' mode, allows to be manipulated the overall geometric characteristics of the compressor or turbine and examined the performance of the overall system as it interacts with the compressor and turbine maps. In this paper, the analysis mode for compressor and turbine models and also a conventional radial compressor and waste gated turbine are selected. Crank shaft speed, swept volume of cylinder and volume efficiency for a 4-cylider, four stroke engine are 3500 rpm, 4.4 liter and 0.86, respectively.

IV. Results and Discussions

TURBOMATCH® handles and runs a mentioned engine operating line with the specific turbocharger. It links dynamically to COMPAL® and RITAL® and do preliminary design of a new compressor and turbine for novel waste gated turbocharger. The waste gate is a simplex valve which be opening and closing to change mass flow rate around the turbine, and speed of turbocharger shaft and limit compressor boost pressure ratio according to required engine pressure ratio consequently. Mass flow rate of the turbine and the compressor against its shaft speed and iterations are shown in Fig. 4. Running the program for turbocharger and the engine along different limiting boost pressure ratio values are accomplished. It is changed from 1 to 3.4 value by variation of the waste gate setting.

Two points of the waste gate are very important, which indicate surge and choke margin and have to be prevented operating engine within these points. Figs. 5 and 6 demonstrate shaft speed and efficiency of the turbocharger which change during the variation of the limiting boost pressure ratios. The compressor and turbine mass flow rate will be fixed and continuing with same value at choking point. In this study, it is evident that choking point is 3.3 and its relevant values are 0.269948 kg/s, 0.280304kg/s according to Figs. 7 and 8, respectively. Figs. 9 and 10 show power density and BMEP, per constant fuel consumption for the turbocharged engine. All futures shown against run number have been plotted in the all Figures. Table I as a guidance illustrates the proportional limiting boost pressure ratios. Summary of below Figures and comparison of them along stable operation conditions have been collected in Table II.

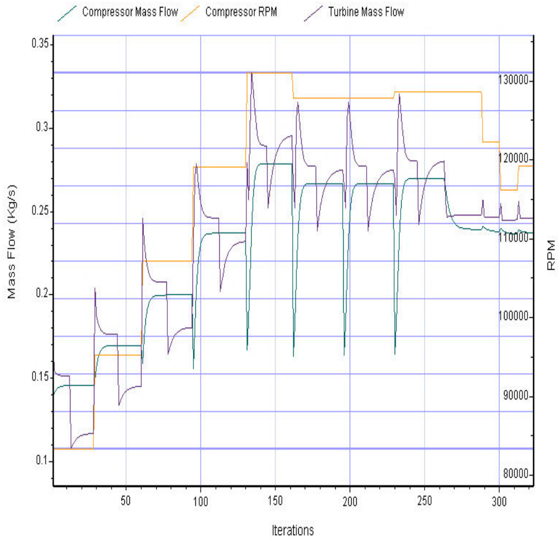

Fig. 4 TURBOMATCH® running and showing relationship between a compressor and a turbine

TABLE I
The Guidance of the Graphs

Run number	Limiting boost pressure ratio waste gate
1	1
2	1.1
3	1.2
4	1.3
5	1.4
6	1.5
7	1.6
8	1.7
9	1.8
10	1.9
11	2
12	2.1
13	2.2
14	2.3
15	2.4
16	2.5
17	2.6
18	2.7
19	2.8
20	2.9
21	3
22	3.1
23	3.2
24	3.3
25	3.4
26	3.5
27	3.6
28	3.7
29	3.8
30	3.9
31	4

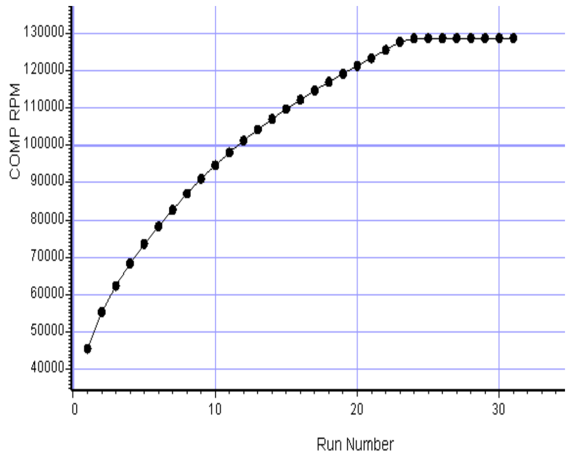

Fig. 5 Turbocharger speed against limiting boost pressure ratio

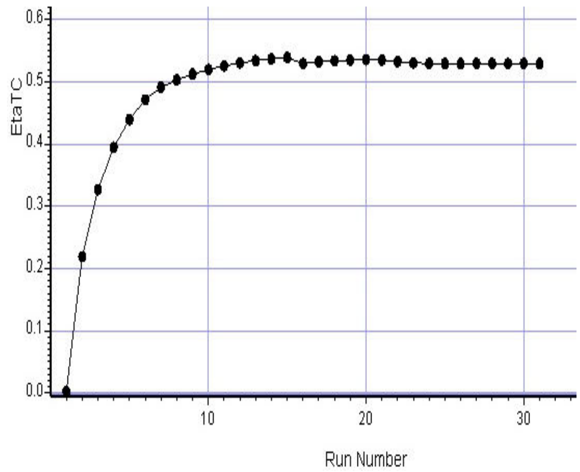

Fig. 6 Turbocharger efficiency against limiting boost pressure ratio

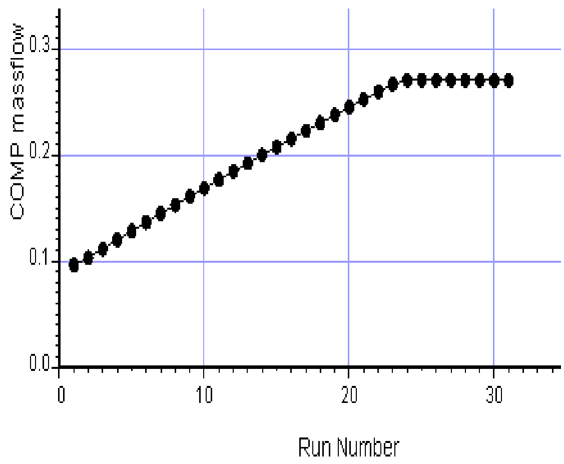

Fig. 7 Compressor mass flow against limiting boost pressure ratio.

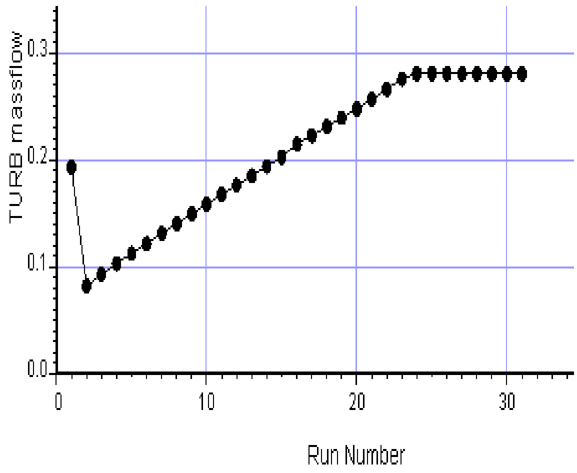

Fig. 8 Turbine mass flow against limiting boost pressure ratio

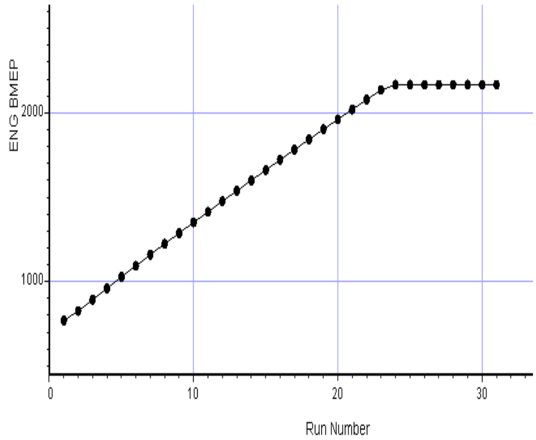

Fig. 9 Engine power against limiting boost pressure ratio

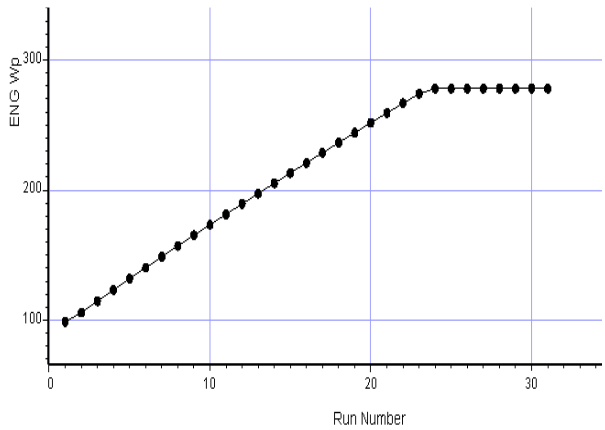

Fig. 10 Engine BMEP against limiting boost pressure ratio.

TABLE II
COMPARISON OF ENGINE FEATURES WITH THE TURBOCHARGER SPECIFICATIONS ALONG VALID PERIOD

Limiting boost pressure	status	Turbine mass flow(kg/s)	Compressor mass flow(kg/s)	Turbocharger RPM	Turbocharger efficiency (%)	BMEP(kpa)	Engine Power out(kw)
2.7	surging	0.230673	0.229811	116972	0.53341	1842.2	236.415
2.8	Normal	0.239	0.237231	119168	0.534792	1901.99	244.089
2.9	Normal	0.247579	0.244667	121269	0.535352	1961.37	251.709
3	Average	0.256478	0.251998	123380	0.534704	2020.16	259.253
3.1	Normal	0.265772	0.25919	125541	0.532454	2077.87	266.66
3.2	Normal	0.275234	0.26637	127651	0.530145	2135.52	274.058
3.3	choking	0.280304	0.269948	128656	0.529072	2166.53	278.038
3.4	choking	0.280304	0.269948	128656	0.529072	2166.53	278.038

V. CONCLUSION

The m_{surge} can be calculated based on m_{choke} and the range by Fig. 1. The range for 3.3 boost pressure ratio is almost equal to 14% and 32% for high specific speed and low specific speed, respectively. If the range is assumed 14% equally, the surge mass flow value will be 0.232155 kg/s. The proportional limiting boost pressure for latter one is 2.7. Therefore the confident waste gate working intervals is from 2.8 to 3.2. According to Table II, with more increased numbers along mentioned period, turbocharger speed goes up, which causes the maintenance costs to rise. On the other hand, with the more decreased ones, engine efficiencies go down. It would be an optimum point to get average of the limitation. As a result, the reasonable measure with consideration and compromise all other features is 3. The mentioned process should be accomplished and followed at the end of turbocharger detail designs. The spring settings on back of the waste gate can be done carefully by the quantity of limiting boost pressure. If the high performance of engine is considerable, maximum limitation of waste gate range (with 3.2 value) will be chosen. Otherwise, the costs and durable life to be significant, so that minimum limitation of waste gate range with 2.8 value to be selected. If neither the high performance of engine nor the costs has importance, then average limitation of the range (with 3 value) should be preferred approximately.

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