THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
345 E. 47 St., New York, N.Y. 10017

82-GT-41

The Charging of Diesel Engines for Passenger Cars Using Turbochargers with Adjustable Turbine Guide Vanes

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Turbocharged passenger cars have been in use more than three decades. However, the behavior of the engine at low engine speeds is still unsatisfactory. Experimental work has been carried out on turbochargers aiming to improve the behavior of the engine at low speeds. For this purpose a turbine with adjustable guide vanes has been designed and tested. These experiments were done on a turbocharged 3 l diesel engine from Daimler-Benz. Three different turbine nozzle blades have been designed and tested without using a waste gate. The results are compared with those of the Garrett-turbocharger T 03 which was originally installed with the engine.

INTRODUCTION

The layout, the construction and the matching of the turbine to the compressor is of special importance for the increase of the engine boost pressure especially at low engine speeds (1,2,3,4).
The early types of turbochargers have been designed for the maximum mass flow rate and the maximum engine speed without using a waste gate. Therefore the turbine was rather large with a large inlet area. Such turbochargers have the disadvantage that the engine has only an increase in the power at higher speeds. Since at lower engine speeds the inlet velocity to the turbine was low because of the large inlet area and the low mass flow rate. Therefore the turbocharger was not able to produce a useful boost pressure. Such engines will work only as turbocharged engines in the high speed range, while at lower speed as a conventional engine without turbocharging.

To overcome this serious disadvantage, the modern turbochargers of passenger cars are designed for low mass flow rates through the turbine. In such a case the turbine will be a smaller one with a small inlet area of the nozzle ring. This will lead to still high inlet velocities to the turbine at low engine speeds and small mass flow rates. Accordingly enough power for the turbocharger is available to produce a useful boost pressure for the engine. This design philosophy necessitates the use of a waste gate in the higher speed range. Excessively high boost pressure and turbocharger speeds can be avoided.

Experiments have been done on a turbine with adjustable guide vanes to obtain a higher boost pressure in the low engine speed range compared with a turbocharger with a waste gate (waste gate closed). Also at higher engine speeds this type should lead to a lower specific fuel consumption than it is in the case of a turbocharger with a waste gate (waste gate opened). The inlet velocity to the turbine is controlled by the variable nozzle area to suite all mass flow rates for optimum operation. These experiments have been done in the Institute for Turbomachinery, Hannover University, on a 3 l turbocharged Daimler-Benz diesel engine.

TEST RIG

Fig. 1 shows a schematic layout of the engine, the turbocharger and the measuring equipments. The power of the engine is dissipated by an eddy-current brake (g) which is electronically controlled. The experiments have been done at constant engine speed and at full load. The pressures and the temperatures are measured in the stations 1 and 2 for the compressor; 3 and 4 for the Turbine as shown in figure 1.

The turbine is designed for the maximum mass flow rate of the engine, since no waste gate is used. The layout of the nozzle ring of the turbine is such that Mach one is not exceeded at the maximum mass flow rate and the maximum engine speed. The photo of the turbocharger (figure 2) shows its casing which is specially designed for these expe-

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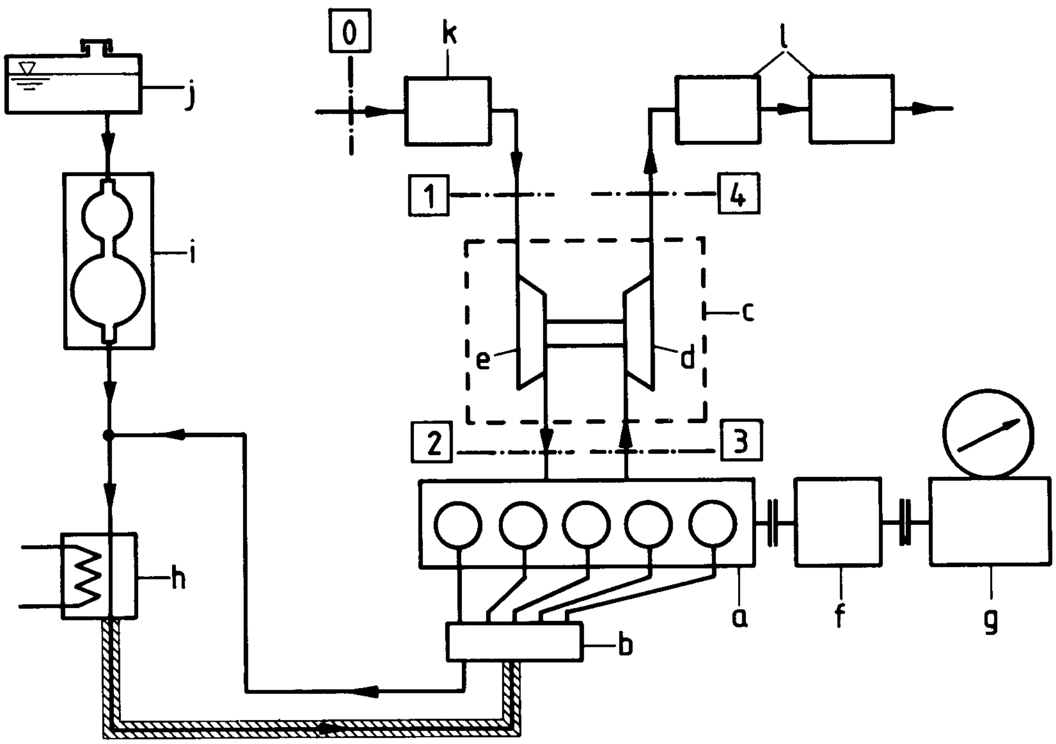

Fig. 1 Test set-up for the turbocharger with adjustable turbine guide vanes

(a) turbocharged diesel engine (b) injection pump (c) turbocharger (d) turbine with adjustable guide vanes (e) compressor (f) gear box (g) eddy-currant brake (h) thermostat (i) graduated vessel for fuel consumption measurements (j) fuel tank (k) air filter (l) silencer

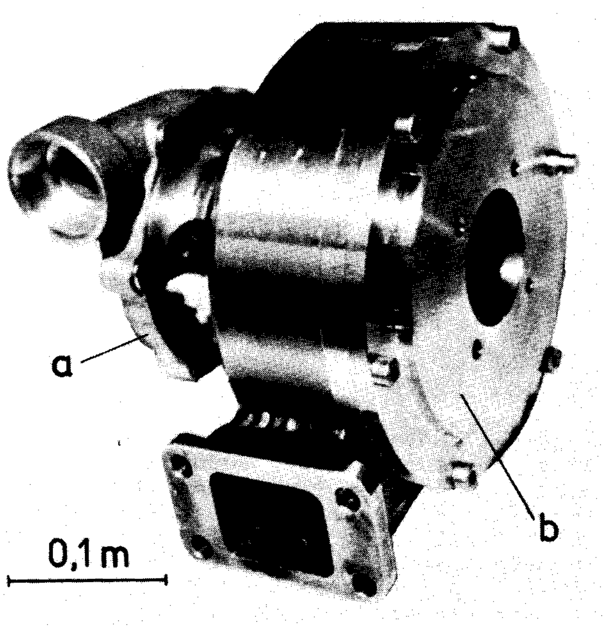

Fig. 2 Picture of the complete turbocharger with adjustable turbine guide vanes

(a) compressor (b) turbine (welded structures)

riments. The casing of the turbine is designed intentionally large so that different scrolls and nozzle rings can be fitted.

Fig. 3 shows a cross-sectional view of the turbine with adjustable guide vanes, while Fig. 4 shows the components of the adjusting mechanism for the guide vanes.
As can be seen from this figures the adjustable guide vanes (a) are welded on pins (b) which are fitted into the bore holes of the vane ring carrier (j). The opposite side of each pin is provided with a groove. Small eccentric levers (c) fitted with welded studs are sticked into these grooves. The studs of all eccentric levers (c) are interlocked to the adjusting ring (e) which is operated by the handlever (f) in connection with the adjusting lever (d).
Initially the clearance between the turbine casing and the nozzle ring does not exceed 0.3 mm. When the operating temperatures are reached, the clearance tends to zero mm. In this case the nozzle ring cannot be as easily rotated as in the case when the turbocharger is cold. Locking of the pins (b) or the adjusting mechanism (c,d,e) is impossible, since enough clearance is present.

Fig. 5 shows the three different nozzle rings which were tested in this programm.

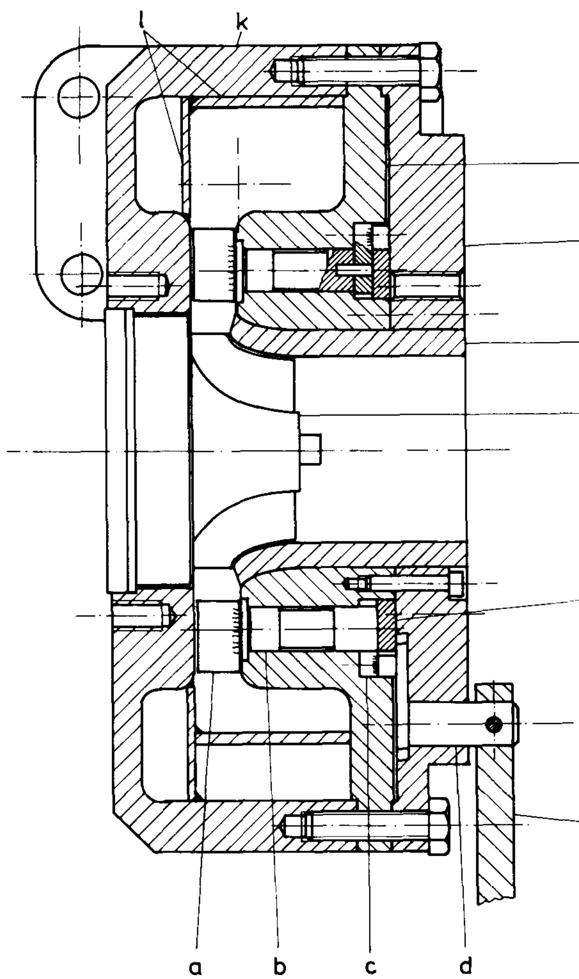

Fig. 3 Cross sectional view of the turbine with adjustable guide vanes

(a) adjustable guide vane (b) pin (c) eccentric lever (d) adjusting lever (e) adjusting ring (f) hand lever (g) turbine rotor (h) outlet insert (i) casing cover (j) vane ring carrier (k) turbine casing (l) volute insert

The experiments were carried out in the following manner: at first the experiments were done with the nozzle ring with 16 straight vanes (type A). The experiments were continued with the nozzle ring with 8 blade profiles type B and type C. In the choice of the profiles type B and type C the design of a favourable aerodynamic contour of a single profile was not so important as the design of a good nozzle between two profiles. Special care was given to the exit cross section area of the nozzles so that by decreasing the exit cross section area at the low mass flow rates the adjusted nozzle ring produces high exit velocities and small stagger angles.

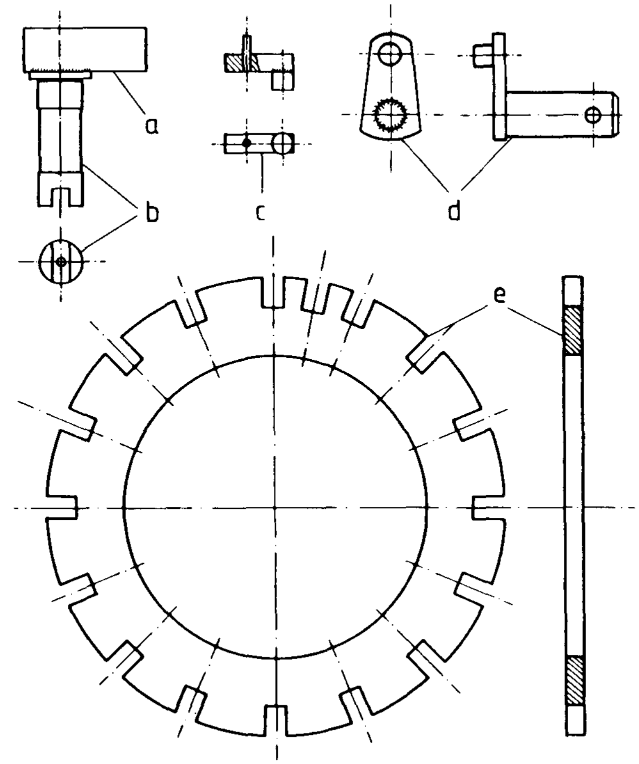

Fig. 4 Components of the adjusting mechanism

(a) adjustable guide vane (b) pin (c) eccentric lever (d) adjusting lever (e) adjusting ring

EXPERIMENTAL RESULTS

For the sake of comparison, measurements were carried out on the test engine fitted with the Garrett-turbocharger (type T 03). This turbocharger is controlled by a waste gate. The obtained boost pressures in this experiment were not exceeded for the experiments done with the turbocharger having adjustable guide vanes. This was chosen as a basis for the comparison of the different types. All measured quantities such as engine torque, turbocharger speed, exhaust back pressure etc. are functions of the engine speed and the setting of the nozzle ring.
The operating points of the full load characteristics of the engine were obtained with decreasing engine speed.

Using the adjustable nozzle ring it was originally anticipated to achieve higher boost pressure and thus higher engine power at low engine speeds than that obtained with the waste gate controlled turbocharger. In spite of using extremely small stagger angles (measured from the peripheral direction) for the low mass flow rates, it was not possible to achieve the required boost pressures for the designed turbine rotor. Therefore the following three experiments carried out in this programm have been done with the smaller turbine

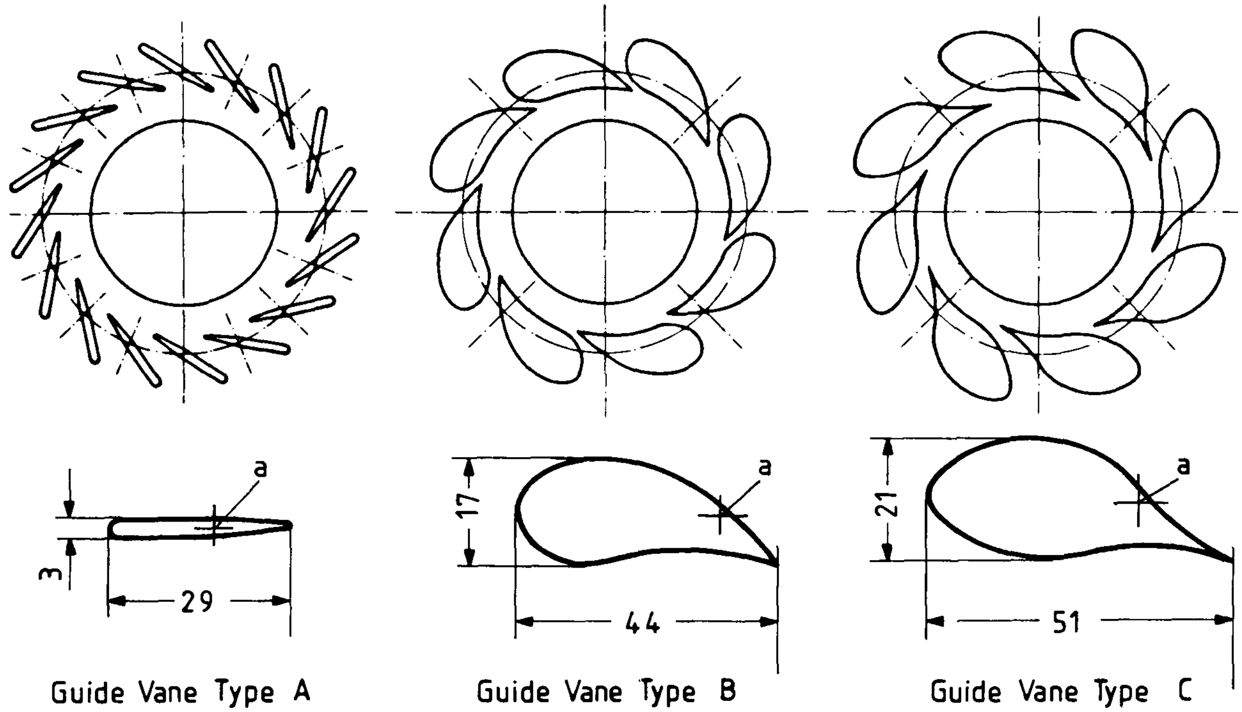

Fig. 5 Different shapes of the tested nozzle rings
(a) point of rotation

rotor of the waste gate controlled turbocharger. Thus it was necessary to make some changes in the design of the turbine casing to match the smaller turbine rotor. Particularly the volute insert (l) and the outlet insert (h) as shown in fig. 3 were fitted to the turbine casing. Also the adjusting range of the guide vanes was enlarged to ensure that at high mass flow rates and at high engine speeds higher stagger angles can be reached. This leads to the decrease of the turbine power, so that overspeeding of the turbocharger and the excessive increase of the boost pressure are excluded.

The most important criteria for the comparison of the different results were the engine power, torque, the boost pressure and exhaust back pressure, the turbocharger speed and the specific fuel consumption. The results of the turbocharger using adjustable guide vanes are compared with those of the of the turbocharger with the waste gate. The results of the turbocharger type A (straight vanes), type B (with blade profiles) and those with the waste gate are shown and discussed in the following figures. For the sake of brevity the results obtained with the turbine type C are not presented since they do not differ significantly from those with the type B, which are slightly better.

Figs. 6 and 7 show the engine power and torque as a function of the engine speed. It is clear that in the low speed range up to 2400 rpm, the turbocharger with the waste gate offers slightly better characteristics than those obtained with adjustable guide vanes versions. The reason for this can be explained with the help of figures 8 and 9 which show the boost pressure and the exhaust back pressure versus the engine speed. The turbocharger with adjustable guide vanes results in higher back pressure than the waste gate controlled turbocharger, because the nozzle ring presents a resistance to the flow and therefore gives a negative influence to the engine power as shown in fig. 6.
The turbocharger controlled by the waste gate delivers a higher boost pressure in the low engine speed range than the types A and B due to the higher turbocharger speed which can be seen from fig. 10.

In the low engine speed range it was not possible to achieve higher engine power with the turbochargers A and B than that obtained with the waste gate controlled turbocharger, because it was impossible to achieve a high boost pressure p_2 combined with a low exhaust back pressure p_3. However, higher boost pressure could be reached with the types A and B, but only with a serious penalty in the engine power, since the exhaust back pressure reached undesirably high values due to very small exit cross section area of the nozzles at low mass flow rates. This fact shows that the engine power depends on both boost pressure p_2 and exhaust back pressure p_3. Therefore the boost pressure was selected by adjusting the guide vanes for each operating point of the turbocharger such that the engine torque is maxi-

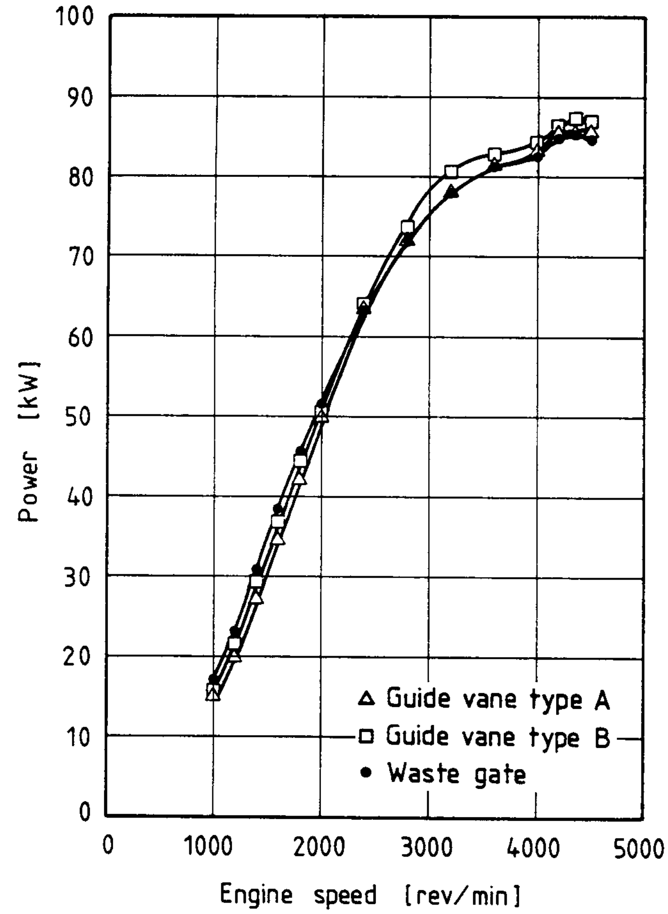

Fig. 6 Engine power vs. engine speed for turbines with waste gate or with guide vanes type A and type B

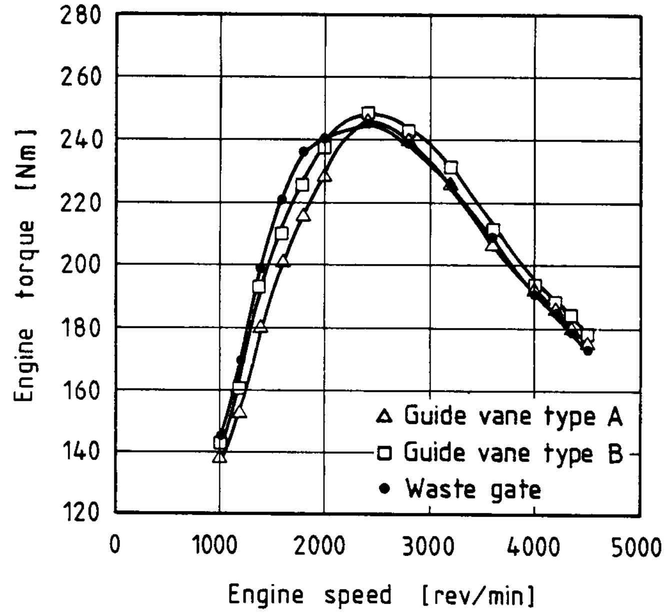

Fig. 7 Engine torque vs. engine speed for turbines with waste gate or with guide vanes type A and type B

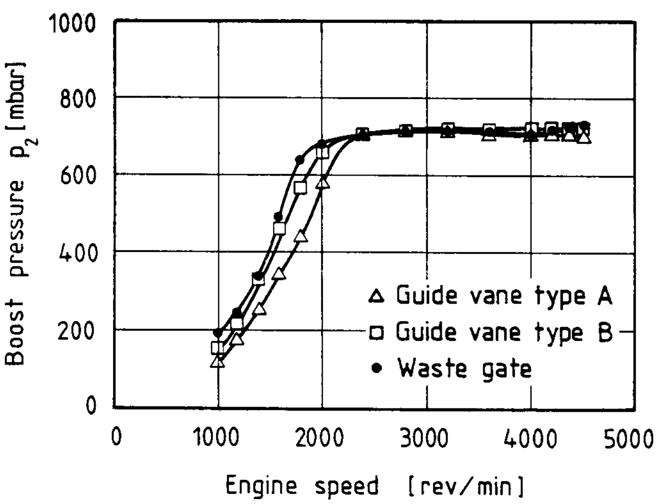

Fig. 8 Boost pressure vs. engine speed for turbines with waste gate or with guide vanes type A and type B

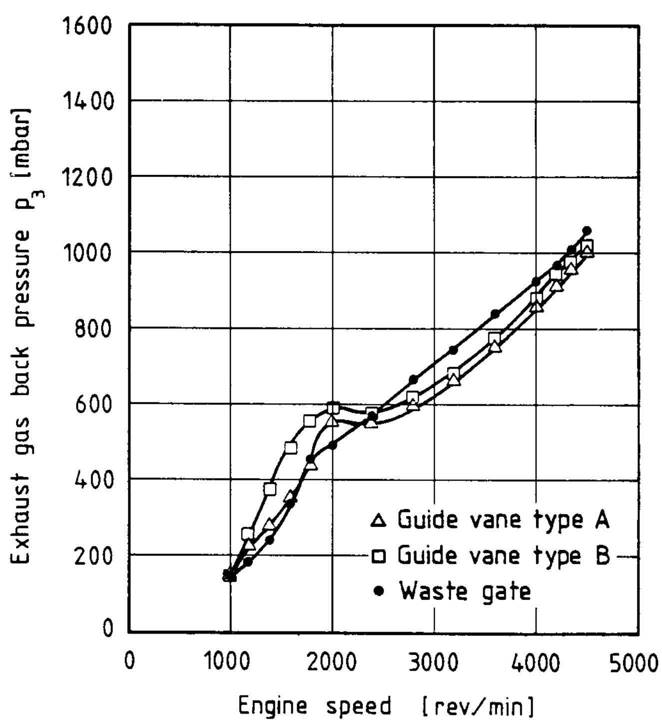

Fig. 9 Exhaust back pressure vs. engine speed for turbines with waste gate or with guide vanes type A and type B

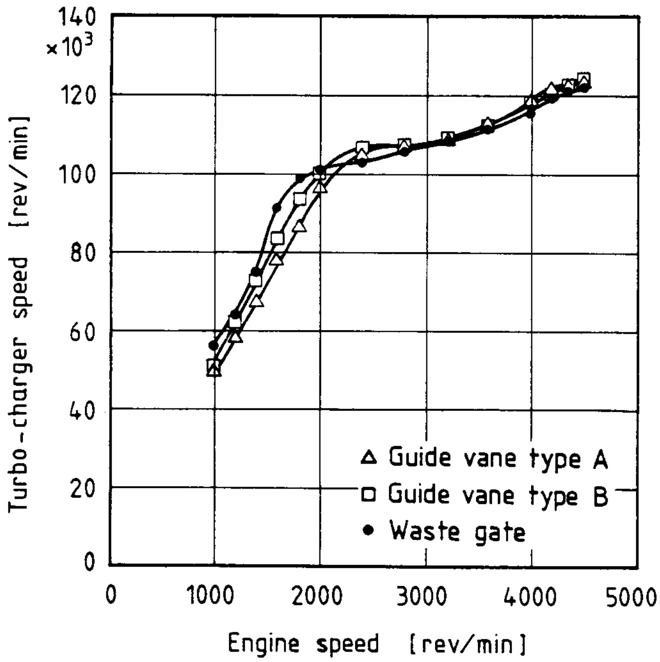

Fig. 10 Turbocharger speed vs. engine speed for turbines with waste gate or with guide vanes type A and type B

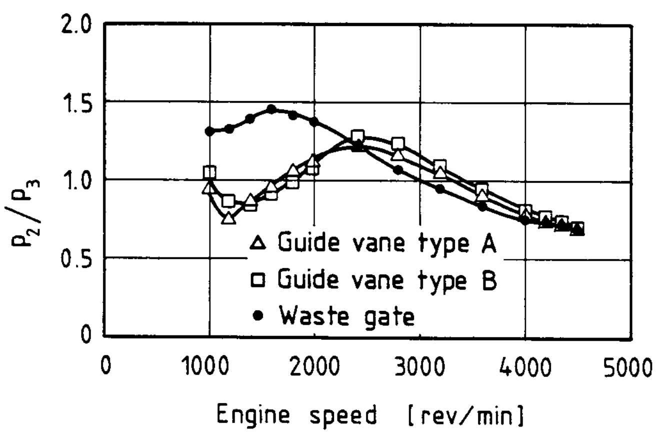

Fig. 11 p_2/p_3 vs. engine speed for turbines with waste gate or with guide vanes type A and type B

mum. These optimum operating points are obtained when the ratio of the boost pressure p_2 to the exhaust back pressure p_3 is maximum. The ratio p_2/p_3 describes the scavenging process in the cylinder. $p_2/p_3 < 1$ means a negative scavenging process. In such a case the scavenging cycle has an anticlockwise direction in the p,v-diagram and leads to a negative work which has to be delivered by the engine. On the other hand $P_2/p_3 > 1$ has a clockwise direction in the p,v-diagram and

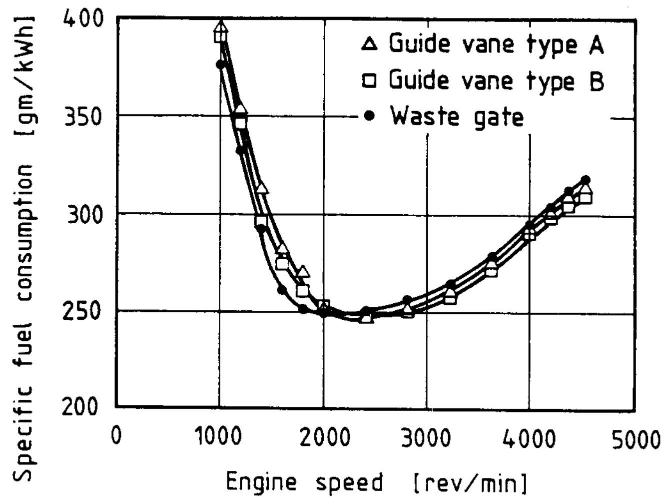

Fig. 12 Specific fuel consumption vs. engine speed for turbines with waste gate or with guide vanes type A and type B

means a positive work which is delivered by the turbocharger.

Fig. 11 shows the pressure ratio p_2/p_3 versus the engine speed for the different turbochargers. This figure indicates the expected results due to the measured boost pressure (fig. 8) and exhaust back pressure (fig. 9). For the waste gate controlled turbocharger and for the low speed range the ratio p_2/p_3 is greater than one while that of the turbocharger with adjustable guide vanes is less than one which causes the decrease in power and torque of the engine as was shown previously in figure 6 and 7.

For the higher engine speed range the turbocharger Type B is advantageous regarding the engine power and torque as can be seen in the same figures. The reason for this improvement is that the exhaust back pressure p_3 is lower and p_2/p_3 is higher for the turbocharger with adjustable guide vanes than it is in the case of the waste gate controlled turbocharger. This can be seen from figure 9 and 11.

Fig. 12 shows the specific fuel consumption versus the engine speed for the different turbochargers. The shape of this curves can be infered from fig. 6. Because the injected fuel quantity was constant for all experiments for a certain engine speed it follows in accordance with the engine power (fig. 6) that the waste gate controlled turbocharger has a lower specific fuel consumption for the low engine speed range while the turbochargers with adjustable turbine guide vanes offer lower consumptions at higher speeds. the very high value of the specific fuel consumption at the lowest speeds can be attributed to the presence of a rich fuel-air mixture.

CONCLUSIONS

An experimental turbine for a turbocharger was designed, manufactured and tested in the Institute for Turbomachinery, Hannover University. The turbocharger was fitted to a 3 l diesel engine from Daimler-Benz. Several full load experiments have been carried out to compare the behavior of the engine when the turbocharger is controlled with a waste gate or with an adjustable nozzle ring.

The experiments have shown that the waste gate controlled turbocharger offers a better engine characteristic at low engine speeds, because of a higher boost pressure p_2 and a lower exhaust back pressure p_3 while the turbocharger with the adjustable nozzle ring demonstrates better characteristics in the higher engine speed range, because of the lower exhaust back pressure p_3 in this speed range. The small exit cross section area of the nozzle ring at low mass flow rates presents a high flow resistance in this adjusting position. Therefore, the turbocharger with the adjustable nozzle ring leads to a higher exhaust back pressure p_3 at low engine speeds than that obtained with the waste gate controlled turbocharger. On the other hand, in the high engine speed range when the exit cross section area of the nozzle ring increases the exhaust back pressure p_3 is lower than that using a waste gate controlled turbocharger.

It is believed that through a proper design of the scroll casing of the turbine and a better layout of the nozzle ring profiles the engine characteristics can also be improved in the lower engine speed range. Especially a better accommodation of the scroll casing inserts should be useful to reach better flow conditions inside the experimental turbine. Also the turbocharger with adjustable turbine guide vanes offers an alternative solution to the conventionally controlled waste gate turbochargers but at the expense of a slightly poorer performance of the engine at low speeds.

REFERENCES

1 Gantz, J.L., "Garrett Turbolader für schnellaufende Verbrennungsmotoren", Motortechnische Zeitschrift, 40, 1979, 2.

2 Obländer, K., Fortnagel, M., Feucht, H.J., Conrad, U., "The Turbocharged Five-Cylinder Diesel Engine for the Mercedes-Benz 300 SD", Passenger Car Meeting, Troy Hilton, Troy MI., June 5-9, 1978.

3 Wallace, F.J., "Turboaufladung mit variabler Turbineneinstellung für Lkw-Dieselmotoren", Aufladetechnische Konferenz, Flensburg, May 11-13, 1981.

4 Berenyi, S.G., Raffa, C.J., "Variable area turbocharger for high output diesel engine", Turbocharger and turbocharged engines, Congress and Exposition, Cobo Hall, Detroit, February 26 - March 2, 1979.