A TRIAL TO IMPROVE FUEL-EFFICIENCY RATES OF A TURBO-CHARGED ENGINE

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Abstract

The paper discusses theoretical bases and examples of practical application of the turbo-compound supercharging. The turbo-compound engines had been supposed to be used for propelling of buses, where it turned out that they were not fully meeting the expectations. This in particular applies to Volvo, where an axial-flow turbine was used as a power turbine. Such solution was given up in the construction of turbochargers for vehicles long time ago, for the benefit of turbines with radial flow (centripetal) due to much better dynamic rates of turbochargers with centripetal turbine and with centrifugal compressor. The solution with such turbocharger combined with the power axial-flow turbine impairs follow-up of the engine-turbocharger-power turbine set and hence the departure from such type of solution. As mentioned by the authors of the Volvo solution, it is much more suitable for aircraft engines (jet turbine engines) that operate at the maximum speed all the time, which is the most advantageous due to the efficiency of rotor machines. Application of the radial-flow turbine as a power turbine – as it is the case in the Scania engines - is much more advantageous solution. Results of simulation and operational tests of engines with such type of supercharging have been presented. A method of proceeding at determination of the engine operational parameters by means of simulation calculations has been described

Keywords *: engine, supercharging, turbo-compound*

1. Introduction

Requirements imposed on the modern engines are often contrary, which is clearly seen if one takes into account the continuously growing number of vehicles and difficulties in traffic related to that, and - on the other hand - the necessity to reduce the fuel consumption and the exhaust gases carried away to the environment. As far as the engines for propelling of cars and lorries are concerned, it comes down to take into account three the most important factors (Fig. 1):

- low fuel consumption,
- low toxicity of exhaust gases,
- good dynamic properties (engine response).

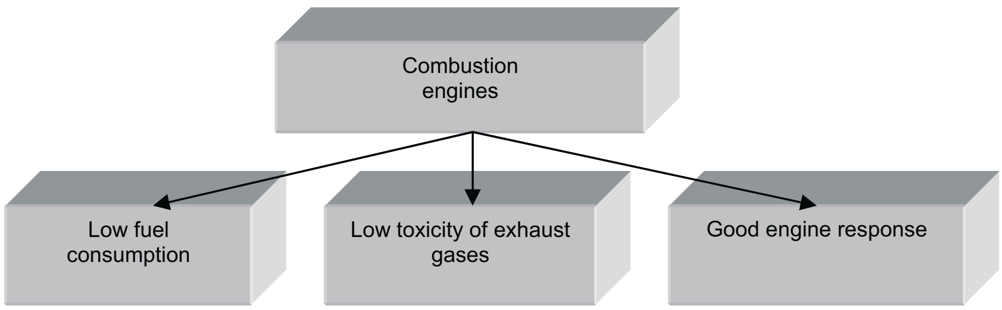

Fig. 1. Requirements imposed on engines

Complying with such requirements poses significant difficulties to constructors. It requires significant intellectual and financial efforts for research into new solutions and their implementation into production. Methods of solving of such a problem are different.

One of such methods is to reduce the heat losses of an engine that can be obtained by applying an additional power turbine, using for its propelling the exhaust gases flowing out of a turbocharger in a turbo-charged engine. Such turbocharger is mechanically coupled either directly or indirectly with the engine flywheel, transmitting an additional torque to it. It resulted from the theoretical assumptions that the increase of the thermal efficiency of an engine could be obtained by the increase of the exhaust gases temperature and by reduction of losses resulting from their cooling. The research into that has confirmed the assumptions that the most efficient method is to produce pistons consisting of two parts in order to have the piston head made of a material with low thermal conductivity (cast iron) in comparison to its remaining part (silumin). Such a method of the problem solution is troublesome both from the construction point of view and the engine operation. The results obtained for such solution have been presented on the Fig. 2 [1], and - at the same time - it turned out that one should reduce the heat exchange between the piston and the working medium in the combustion chamber. It was an engine with direct injection, and with the power of 309 kW at 2200 1/min.

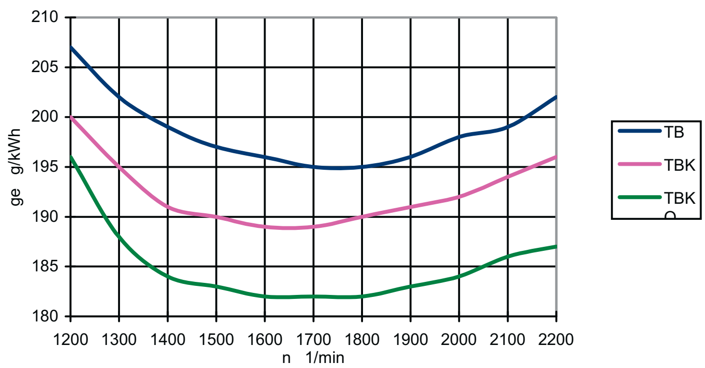

Fig. 2. Specific fuel consumption of an engine with the energy recovery

TB -turbo-charged engine, TBK - engine with combined piston,
TBKO -engine with combined piston and reduced heat exchange.

This is the result of simulation tests carried out on the basis of the forecast value of an average temperature of the head and the piston head. The dependence of the mentioned temperatures on the fundamental parameters of the engine operation has been determined according to the formula [2]:

$$T_{t-g} = A + B\left(\frac{p_s}{p_o}\right)^{0,35}\left(\frac{1}{\alpha}\right)^{0,42}\left(\frac{T_s}{T_o}\right)^{0,35}\left(\frac{c_s}{10}\right)^{0,5}\left(\frac{D}{0.1}\right)^{0,38}, \qquad (1)$$

where:

p_s -air pressure in the inlet manifold,
T_s -air temperature in the inlet manifold,
α -excess air number,
c_s -average piston speed,
p_o -0.1 MPa,
T_o -298 K,
A -constant determined during tests equal to 500,
B -constant determined during tests equal to 228.

From the theoretical point of view, such solution is very reasonable and should bring specific economical benefits, meeting the first requirement mentioned in the introduction, and indirectly also the second requirement.

2. Practical application

One of the types of supercharging, additionally using the energy of exhaust gases is the supercharging by means of a power turbine, so called „turbo-compound". It consists in propelling of the turbine with the flowing-out gases, where the turbine transmits the torque through direct or indirect mechanical coupling with the engine (e.g. by means of gear wheels). In 1991, Scania company applied supercharging with the power turbine as an additional device mounted behind the turbocharger in its engines, Fig. 3. The efficiency of the engine was 46% and was by 2% higher than that of the engine without such supercharging [2].

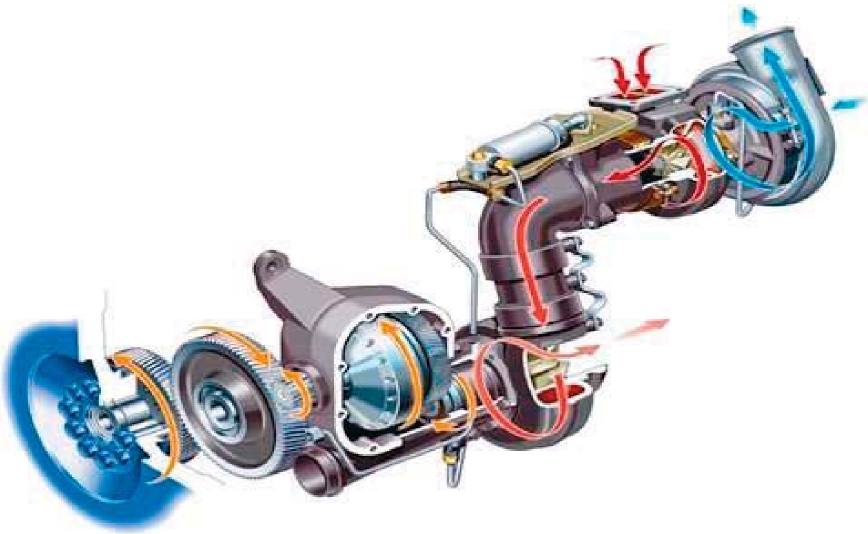

Fig. 3. Supercharging with power turbine (with two radial-flow turbines) worked out by Scania company [2]

The turbo powering is capable of generating even up to 37 kW of additional power at full load. Also Volvo presented and introduced a turbo-charged D12D500 engine (Fig. 4) in 2002 with the cubic capacity of 12 000 cm^3 and the power of 368 kW [3]. It has got the minimum specific fuel consumption of 186 g/kWh. Similarly to the Scania lorries, the power turbine has been fitted behind the turbocharger. An axial-flow turbine has been fitted there that propels the flywheel by means of hydraulic coupling and a set of gear wheels. The axial-flow turbine is rarely encountered in turbochargers as it is adapted to very high flows (it is ideal for e.g. jet turbine engines in aircrafts).

3. Comparison of fuel consumption

The characteristic of the specific fuel consumption presented on the Fig. 1 has been obtained through simulation tests and these results ARE very promising. The specific fuel consumption varies from 182 up to 195 g/kWh, which results in the general efficiency from 51.28 up to 54.94%, i.e. very high. According to Scania, the efficiency in their Turbocompound engine was 46%, which is more realistic in the operational conditions. However, Volvo gives the specific fuel consumption equal to 186 g/kWh in its engine of such type, i.e. comparable to the consumption shown by new turbo-charged engines of the D13A series with the power from 294 up to 382 kW. For comparison purposes, characteristics of fuel consumption have been prepared for the Volvo and the Scania DC12 02 380 279 380 engines of power similar to the power of the engine described in the introduction, which has been presented on the Fig. 5.

Fig. 4. Volvo D12D500 engine [3]

The specific fuel consumption curve has been determined with simulation method [4] ensuring accuracy of results of approximately 2.12% on the basis of a modernised Leidemann's formula:

$$g_x = g_{eN}\left(1{,}25 - \frac{n_x}{n_N} + 0.75\frac{n_x^2}{n_N^2}\right). \tag{2}$$

According to the formula (2), the simulation characteristic of the specific fuel consumption for the Scania engine of similar power has been presented in the Tab. 1 and on the Fig. 5.

Tab. 1. Calculation of the fuel consumption of the SCANIA DC12 02 380 engine

n_x	n_N	g_e	n_x / n_N	$(n_x / n_N)^2$	g_x
800	1800	209	0.44	0.20	199.3
900	1800	209	0.50	0.25	195.9
1000	1800	209	0.56	0,31	193.5
1100	1800	209	0.61	0,37	192.1
1200	1800	209	0.67	0.44	191.6
1300	1800	209	0.72	0.52	192.1
1400	1800	209	0.78	0.60	193.5
1500	1800	209	0.83	0.69	195.9
1600	1800	209	0,89	0.79	199.3
1700	1800	209	0,94	0,89	203,7
1800	1800	209	1.00	1.00	209.0

A characteristic for the Volvo D500 engine prepared with the same method (minimum fuel consumption of 186 g/kWh was given) has been presented in the Tab. 2 as well as in the mentioned characteristic (Fig. 5), where also the most advantageous fuel consumption curve from the Fig. 1 has been plotted. Comparison of these three curves allows for drawing general conclusions as to the fuel consumption of the compared versions of engines. At the same time, a clear difference can be seen in the theoretical approach to the discussed issue.

Tab. 2. Calculation of the fuel consumption of the Volvo D12D500 engine

n_x	n_N	g_e	n_x/n_N	$(n_x/n_N)^2$	g_x
800	1800	203	0.44	0.20	195.0
900	1800	203	0.50	0.25	190.3
1000	1800	203	0.56	0.31	187.3
1100	1800	203	0.61	0.37	186.3
1200	1800	203	0.67	0.44	185.0
1300	1800	203	0.72	0.52	186.8
1400	1800	203	0.78	0.60	186.8
1500	1800	203	0.83	0.69	190.3
1600	1800	203	0.89	0.79	193.4
1700	1800	203	0.94	0.89	198.4
1800	1800	203	1.00	1.00	203

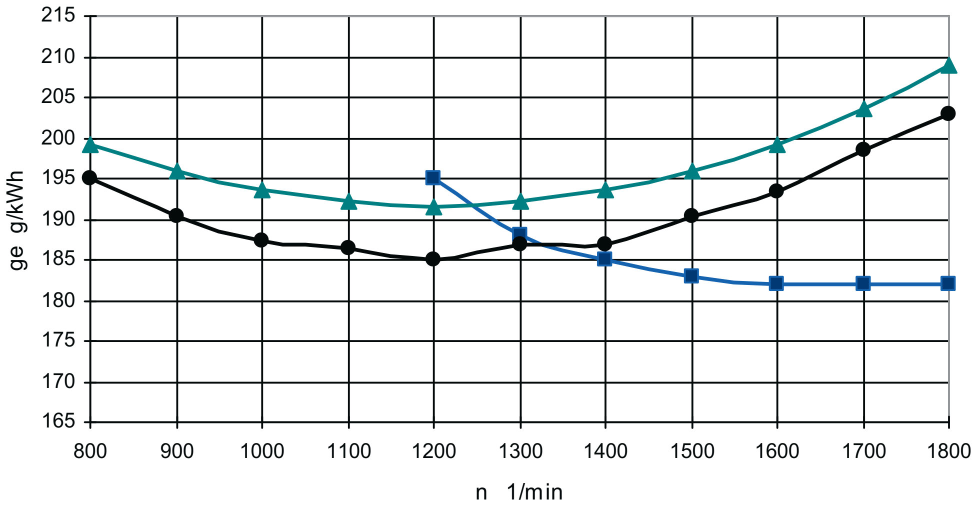

Fig. 5. Comparison characteristic of the specific fuel consumption of the described engines

- TBKO engine,
- Volvo D12D500 engine,
- DC12 02 380 engine

All the curves on the Fig. 5 have been obtained through computer simulation, and the authors of the TBKO engine tests do not give the accuracy of the applied method, whereas the two other curves have been obtained by means of a methodology that ensures 2.12% of accuracy. It seems that the results of the TBKO engine tests are too optimistic, whereas the Volvo engines are the engines of the most modern generation where the process of the air-fuel mixture preparation and the combustion itself have been improved, and their results correspond to the current state-of-the-art. The Scania engine is a bit older engine and hence the difference between it and the Volvo engine.

At the same time one should remember that these characteristics ARE statistical ones, corresponding to the statistics performed in the engine test house.

4. Operational aspect of the issue

The turbo-compound engines had been supposed to be used for propelling of buses, where it turned out that they were not fully meeting the expectations. This in particular applies to Volvo, where an axial-flow turbine was used as a power turbine. Such solution was given up in the construction of turbochargers for vehicles long time ago, for the benefit of turbines with radial flow (centripetal) due to much better dynamic rates of turbochargers with centripetal turbine and with centrifugal compressor. The solution with such turbocharger combined with the power axial-flow turbine impairs follow-up of the engine-turbocharger-power turbine set and hence the departure from such type of solution. As mentioned by the authors of the Volvo solution, it is much more suitable for aircraft engines (jet turbine engines) that operate at the maximum speed all the time, which is the most advantageous due to the efficiency of rotor machines. Application of the radial-flow turbine as a power turbine - as it is the case in the Scania engines - is much more advantageous solution. Nevertheless, the turbo-charging (turbo-compound) is a solution that gives better results in the engines of lorries of high carrying capacities dealing with long routes on motorways, without sudden changes in speed and load, similarly to the first turbo-charged engines used by both companies years ago.

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