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SIMULATION ASSESSMENT OF OPERATION RATES OF AN ENGINE WITH SEQUENTIAL TURBO-CHARGING

Krzysztof Danilecki

Faculty of Automotive Vehicles Operation of the Technical University of Szczecin

Summary. The paper presents the results of the simulation tests of the SW 680 engine with sequential turbo-charging. Basic parameters of the turbo-charging set and the engine in the system with one and with two turbochargers in parallel arrangement have been presented.

Keys words: diesel engine, modeling, sequential turbo-charging.

INTRODUCTION

Now that the exhaust gas turbocharger with variable turbine geometry has established itself as the state of the art in diesel engines for passenger cars and to some extent for commercial vehicle applications, the limits of single-stage turbo-charging are becoming apparent. A higher nominal output leads in most cases to a deterioration in pull-away torque at low engine speeds. A good way of solving this conflict of objectives is to use regulated 2-stage (sequential) turbo-charging [Christmann *et al.* 2005].

PROBLEM DESCRIPTION

The sequential turbo-charging presented in the literature [Wisłocki 1991] comprises at least two turbo-charging units, in a parallel arrangement, all operating at rated power. A gas flow control system makes it possible to cut off sequentially, one by one, one or several of them as engine speed is reduced. Thus, a sequential reduction (in discrete steps) of the total turbine area is achieved with a corresponding rise of the turbine pressure ratio, and consequently of the compressor pressure ratio, for significant improvement of low-speed performance and response of the engine. Furthermore, the method allows for a very good matching of the turbochargers at rated power, thus showing a potential for lower fuel consumption and, therefore, for a lower thermal load at this operational point. The advantage of the sequential turbo-charging is the low modernisation cost as well as possibility of use of mass-produced turbo-chargers. The disadvantage of the sequential turbo-charging system resulting from the method of engaging of the second turbo-charger is the discontinuity of the turbo-charging pressure and the torque on the external characteristic of the engine. The advantages of the sequential turbo-charging make the system very attractive for highly-rated vehicle engines.

Development works on the application of sequential turbo-charging in the engines of lorries of high carrying capacities were carried out in the 80's by Volvo [Borila 1986 a, b, c]. However, applications of such system from that period are known mainly in case of cars with petrol engines of such companies as e.g. Audi, Fiat, Mercedes-Benz, and Porsche [Bluhm *et al.* 1988, Esch *et al.* 1987].

Solutions being modifications of the sequential turbo-charging system have been recently presented by e.g. Opel [Łęgowicz 2005] and BMW [Mährle *et al.* 2007,Steinparzer *et al.* 2005], designed for mass-produced cars with compression-ignition engines. They enable operation of turbochargers in a parallel and in-line arrangements. This allows for smooth engaging of the second turbocharger, which significantly reduces disadvantages of this system in its original version.

Works on application of sequential turbo-charging in the engines of utility vehicles have been also carried out for many years by the author at *Faculty of Automotive Vehicles Operation of the Technical University of Szczecin*. The very promising results obtained so far show high development potential of such system and the easiness of adaptation to the engines of diversified construction and applications. It has been observed at the same time that with directing of exhaust gases to both turbochargers within this area of the engine characteristic, despite the drop of supercharging pressure below the values obtained with conventional supercharging, one can observe improvement in the economy expressed by drop of specific fuel consumption that is, however, still higher than in a conventionally supercharged engine [Danilecki 1998]. Such curve of characteristic not only shows the necessity to investigate the possibility of the engine operation economy improvement within the range of partial loads but perhaps the necessity to carry out a detailed analysis of factors that are deciding about the effective rates of operation of the engine with sequential turbo-charging.

The obtained research results show that – regardless of the method of engaging of the 2nd sequence turbocharger, the power distribution between both turbo-charging sets or turbine sets respectively is particularly important, not only due to the efficiency but also due to the construction and properties of turbochargers. Hence a problem appears of selection of turbochargers and determination of functional properties of the control system for turbochargers that will enable matching the supercharging efficiency to the momentary engine load. Closer investigation of this issue required creation of effective computational methods enabling assessment of the quality of matching of turbochargers to the engine.

SIMULATION TESTS

For simulation and assessment of operation of an engine with sequential turbo-charging, an empirical-mathematical model of the engine-turbo-charging unit has been elaborated, based on average parameters of the engine cycle. This model includes: subsystem of combustion engine that forms the volume of the cylinder, turbo-charging subsystem that are considered as objects of known and analytically described characteristics. The model is based on application of the engine characteristics obtained on the basis of average parameters of a cycle as well as flow characteristics of turbochargers, for the description of which the methods of multiple regression have been used. The conditions of the turbocharger co-operation with the traction engine have been taken into account by means of pulsation coefficients, which ensures sufficient convergence of numerical calculations with the results of experimental testing [Danilecki 2007]. The calculations are carried out for the determined conditions of the engine and the turbo-charging unit operation. The scope of the executed calculations related to the selection of a turbo-charging unit to the engine comes down to the assessment of matching of the flow characteristics of particular elements of the turbo-charging system, with taking into account the influence of changes on the efficiency of the engine, the compressor and the turbine.

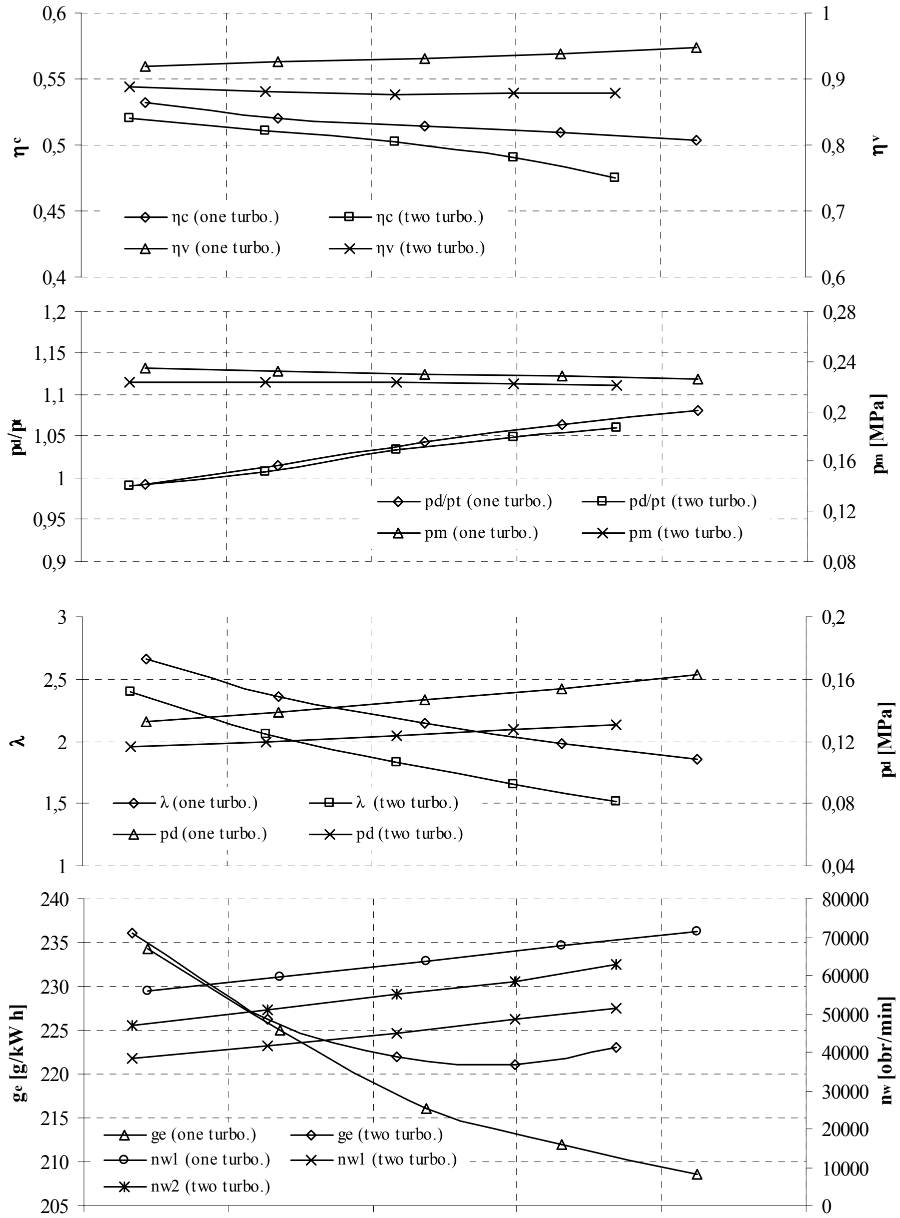

Fig. 1a. Comparison of calculated rates of operation of an engine with one and two turbochargers for the load characteristic (n=1400 rev/min): g_e – specific fuel consumption, n_{w1}, n_{w2} – rotational speeds of rotors of turbocharger of the 1st and the 2nd sequence, λ – excess air number, p_d – supercharging pressure, p_t – pressure of exhaust gases p_m – average pressure of mechanical resistance, η_v – filling ratio, η_c – thermal efficiency

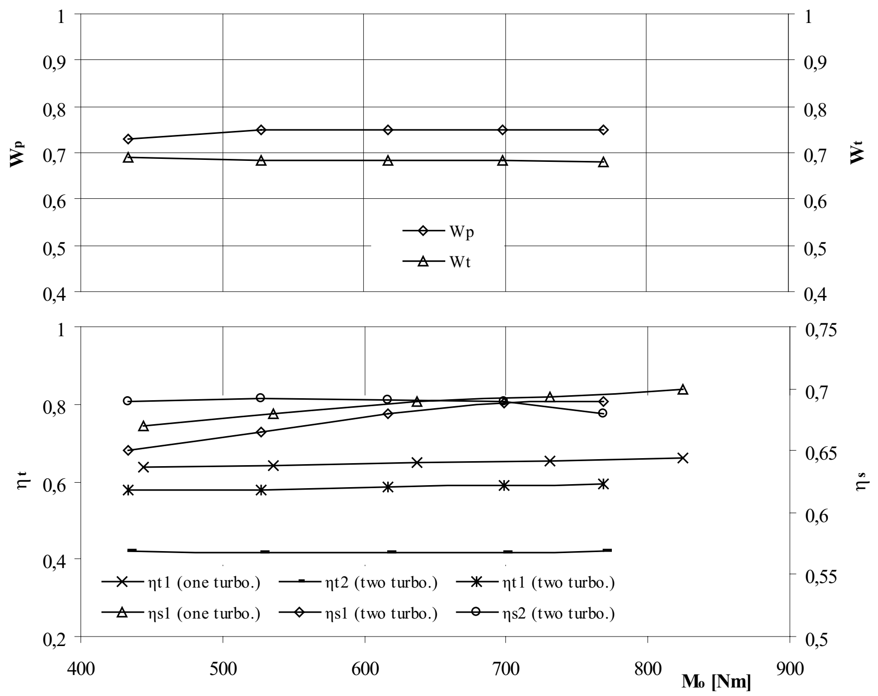

Fig. 1b. Comparison of calculated rates of operation of an engine with one and two turbochargers for the load characteristic (n=1400 rev/min): η_{t1}, η_{t2} – effective efficiency of the turbine of the 1st and the 2nd sequence, η_{s1}, η_{s2} – efficiency of turbocharger of the 1st and the 2nd sequence, W_p – rate of expenditure of the 1st sequence turbocharger, W_t – rate of expenditure of the 1st sequence turbine clearly higher. This mainly results from the increase of the thermal efficiency in the arrangement with one turbocharger

Numerical simulation carried out on the prepared turbo-charging model consisted in determination of load characteristics for medium and high rotational speeds, at which the parameters characterising the engine operation and the turbo-charging set with one and with two turbochargers have been determined. The calculated values of parameters have been presented on Figures 1 and 2. The obtained results show that for the rotational speed of 1400 rev/min at low loads, the specific fuel consumption for the set with one and with two turbochargers is comparable. Such situation takes place despite the fact that the supercharging pressures obtained in the system with two turbochargers are lower within the whole range of loads by approximately 16% than in the system with one turbocharger. With the drop of the excess air number λ, this leads to the decrease of the thermal efficiency η_c. However, the mechanical efficiency of the engine is of decisive influence on the total efficiency of the whole system of engine – turbo-charging set. At lower supercharging pressures obtained with two turbochargers, lower frictional resistance in the piston-crank set and the resistance of flow through valves lead to the reduction of general mechanical losses represented by the average pressure of mechanical resistance p_m that – for the set with one turbocharger – is higher by approximately 4%. As the result of interaction of these factors, the specific fuel consumption g_e of the engine with one and with two turbochargers is comparable. However, with the increase of the engine load the g_e values obtained for the set with two turbochargers are now

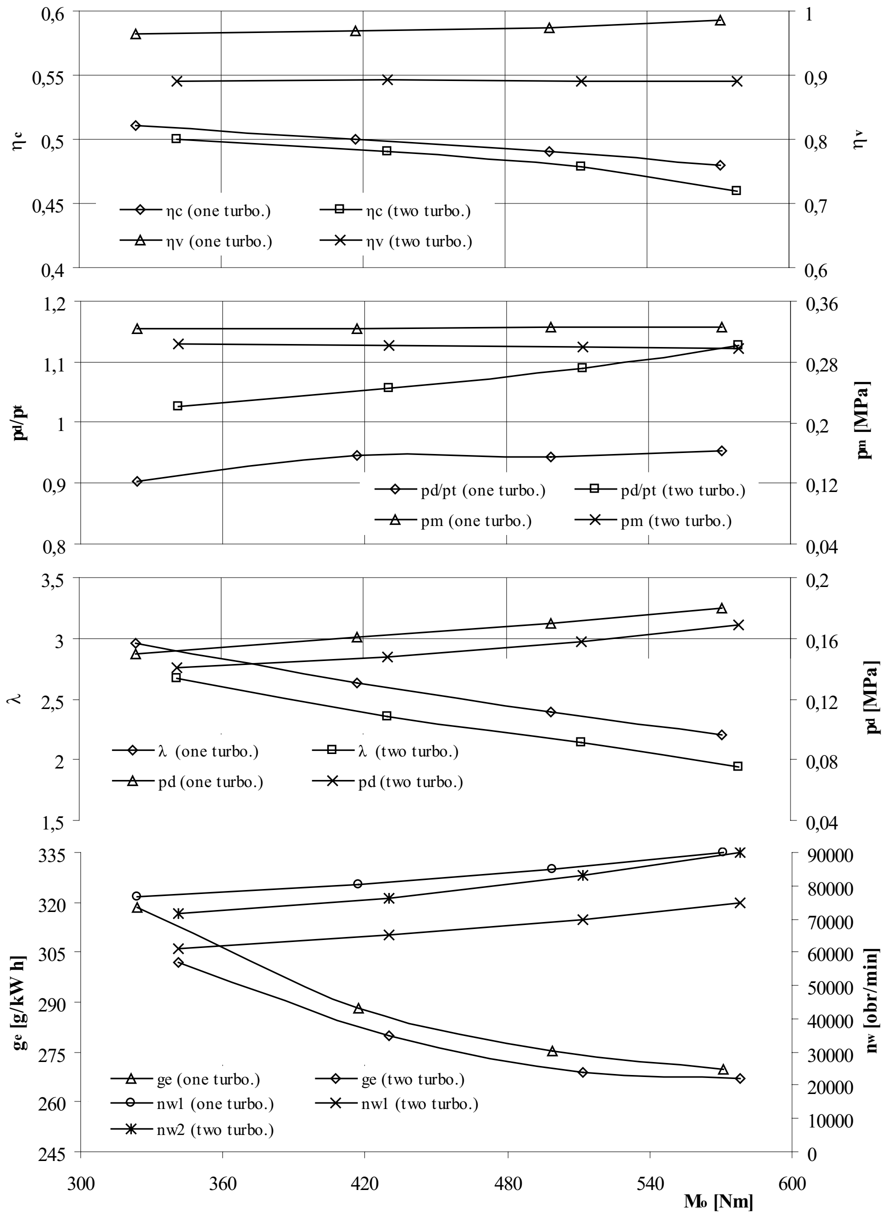

Fig. 2a. Comparison of calculated rates of operation of an engine with one and two turbochargers for the load characteristic (n=2000 rev/min): g_e – specific fuel consumption, n_{w1}, n_{w2} – rotational speeds of rotors of turbocharger of the 1st and the 2nd sequence, λ – excess air number, p_d – supercharging pressure, p_t – pressure of exhaust gases p_m – average pressure of mechanical resistance, η_v – filling ratio, η_c – thermal efficiency

However, special attention is to be paid to the obtained values of efficiencies of turbines operating in a parallel arrangement. This in particular applies to the turbine of the 2nd sequence turbocharger, the effective efficiency of which η_{t2} does not exceed 42%. This is a very low value if one takes into account that in the parallel arrangement the efficiency of the 1st sequence turbine η_{t1} is 59%, and for the set with one turbocharger it amounts to 66%. Low values of η_{t1}, η_{t2} result from low mechanical efficiency of particular turbines – approximately 60% and 80% respectively. This leads to small participation of the expenditure (with the rate of expenditure of the 1st sequence turbine W_t of approximately 0.68) and the power of the 2nd sequence turbine, and causes that also the expenditure of the 2nd sequence compressor $1 - W_p$ is only approximately 25% of the total expenditure of the compressor set. Significant drop in the efficiency of the 1st sequence turbine and very low efficiency of the 2nd sequence limit the efficiency of the turbine set and the supercharging pressure obtained in the parallel arrangement.

However, the results of a numerical simulation carried out for the rotational speed of 2000 rev/min show different curve of the engine economy. For the set with two turbochargers, the specific fuel consumption g_e is clearly lower within the whole range of loads. At lower thermal efficiency η_c it mainly results from the values of the average pressure of mechanical resistance p_m lower by approximately 7%.

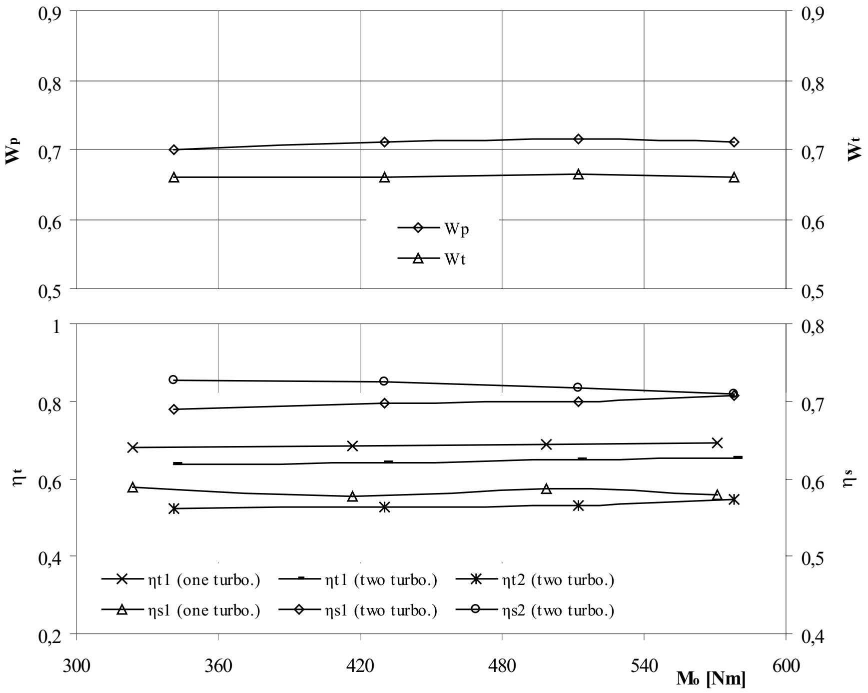

Fig. 2b. Comparison of calculated rates of operation of an engine with one and two turbochargers for the load characteristic (n=2000 rev/min): η_{t1}, η_{t2} – effective efficiency of the turbine of the 1st and the 2nd sequence, η_{s1}, η_{s2} – efficiency of turbocharger of the 1st and the 2nd sequence, W_p – rate of expenditure of the 1st sequence turbocharger, W_t – rate of expenditure of the 1st sequence turbine

The values characterising operation of turbochargers look much better. Increased expenditure of exhaust gases at high rotational speeds of the engine causes significant increase in the efficiency of the 2nd sequence turbine up to the values reaching 54%. At high efficiency of the 2nd sequence compressor (more than 70%), this leads to its participation in the total expenditure of the set of compressors. The efficiency of the 1st sequence compressor in a parallel arrangement also exceeding 70% with its efficiency of 65% in case system with one compressor significantly compensates lower efficiency of the turbine set. Moreover, due to the better use – at low supercharging pressures in the system with two turbochargers – of the energy of the pressure pulse of exhaust gases supplying the turbine, the conditions of the charge exchange improve. This leads to the increase of the ratio of supercharging pressure to the exhaust gases pressure p_d/p_t. These are the factors that cause increase of the mechanical efficiency of the engine with two turbochargers and compensate lower thermal efficiency when compared to the engine supercharged with one turbocharger. As the result, at high rotational speed improvement of the economy of operation of the engine in the arrangement with two turbochargers is obtained.

CONCLUSIONS FROM THE NUMERICAL SIMULATION

The presented results of simulation calculations show that one of the essential factors deciding about the characteristic curves of the engine with sequential turbo-charging is the mechanical efficiency of the engine that is depending on the obtained supercharging pressures and the applied arrangement of operation of turbochargers and their sizes. It is important at the same time to obtain the total efficiency of the turbo-charging set as high as possible. As the simulation calculations show, confirmed by the results of experimental research, this leads to the expected improvement of scavenging conditions and filling of the engine cylinders with simultaneous decrease of the charge exchange. The influence of the mechanical efficiency is particularly noticeable at low loads and high rotational speeds of the engine as the increased supercharging pressures in the arrangement with one turbocharger lead to the increase of resistance of the charge flow through the engine valves and to the decrease of the degree of use of the energy of the exhaust gases pressure pulse. The total efficiency of the turbine set for the parallel arrangement is to the great degree depending on the efficiency of the 2nd sequence turbine that – at low exhaust gases expenditure within the range of low rotational speeds and engine loads – reaches very low values. This limits the obtained supercharging pressure. Therefore one should consider a possibility of application of identical turbochargers. If – at the same time – turbochargers of the sizes of larger turbocharger of the 1st sequence are used, it will be necessary to reduce the area of the minimum intersection of the inlet boxes of the turbines down to the values, where the supercharging pressures will be close to the values obtained in the arrangement with two turbochargers of different sizes. Calculations carried out for such an arrangement show that this solution does not bring the expected results. Despite higher efficiencies of each of the turbines in relation to the efficiency of the smaller turbine in the arrangements with two turbochargers of different sizes, the total efficiency of the turbine set remains lower. However, application of identical turbochargers of smaller series of types can cause problems with obtaining the required supercharging characteristics at high engine loads as engaging of the second turbocharger will be necessary already at low rotational speeds and it will lead to more sudden break of the supercharging characteristic.

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