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SIMULATION PREDICTION OF OPERATIONAL PARAMETERS OF A TRACTION DIESEL ENGINE WITH SEQUENTIAL TURBOCHARGING AT SELECTION OF TURBOCHARGERS

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Summary. The paper presents analytical and empirical model of the system: diesel engine, radial compressor, radial turbine and a numerical program enabling prediction of the engine operating parameters at the selection of turbochargers, adapted to the case of the sequential turbocharging. The essence of the presented model is the appropriate combination of balance equations enabling calculations of thermodynamic parameters in the control points of the system for both the single-stage supercharging, as well as in the case of the parallel combination of two different turbochargers. The numerical program enables selection of turbochargers and determination of functional requirements and the values of control signals for the supercharging adjustment system.

Key words: combustion engine, turbocharging, mathematical modelling.

INTRODUCTION

A parallel combination of two turbochargers, engaged successively with increasing the exhaust gas flow intensity (with the increase in the engine speed and the engine load) is most often the essence of sequential turbocharging [Wisłocki 1991]. In case of this method of supercharging, one of the most important problems is the discontinuity of the supercharging characteristics resulting from the jumping engagement of the second turbocharger into the cycle, which leads to an unfavourable course of the maximum torque curve [Borila 1986 a, b, c]. This draws attention to the special importance of a proper match of the characteristics of the turbochargers to the engine, and – additionally – to ensuring adequate conditions for cooperation between them [Danilecki K. 2008, Syomin D. *et al.* 2010:]. The selection of a proper supercharging system design is based on multiple determinations of rates of the engine operation for each successively analysed completion of turbochargers in order to find a solution to meet the assumptions. The solution of such task with an experimental method forces to carry out costly and time consuming engine bench testing, and is limited to available designs of turbochargers. Significant savings of time and financial resources can be obtained by solving this task through computer simulation tests, based on mathematical models of individual system components: diesel engine, radial compressor, and radial turbine. By adopting exactly this way of proceeding, one has assumed the possibility of simulation of operation of the engine with sequential turbocharging over the whole area of its general characteristics, and the ability to influence on the course of the external characteristics by changing the delivery of fuel or the excess air ratio. For this purpose, a numerical program has been developed that allows for quick prediction of the engine performance at the selection of turbochargers and their switching characteristics.

ASSUMPTIONS TAKEN AT CONSTRUCTING THE MODEL

The essence of the presented model is to combine (conjugate) dependencies known from the literature [Zinner K. 1985] describing the conditions of cooperation of the engine and turbocharger, forming a system of equations enabling the balance calculation of thermodynamic parameters in the control nodes of the system. The calculations have been limited to the situation of the energy balance corresponding to the steady conditions of operation. The diagram of the sequential turbocharging system, where relevant denotation of pressures and temperatures characterising the operational conditions of turbochargers have been plotted is shown in the Figure 1.

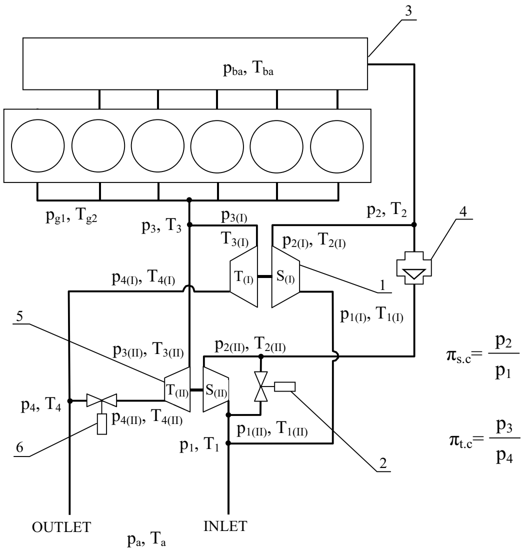

Fig. 1. Diagram for the analysis of the sequential turbocharging system performance: 1 – turbocharger of the first range, 2 – air release valve, 3 – air surge tank, 4 – valve engaging the compressor, 5 – turbocharger of the second range, 6 – valve engaging the turbine

For the case of the sequential turbocharging at parallel combination of turbochargers, the calculations are carried out for specified conditions of the air and exhaust gase flow through turbochargers, which can be taken as: $p_{1(I)} = p_{1(\mathbf{I})} = p_1$, $T_{1(I)} = T_{1(\mathbf{I})} = T_1$, $p_{2(I)} = p_{2(\mathbf{I})} = p_2$, $p_{3(I)} = p_{3(\mathbf{I})} = p_3$, $T_{3(I)} = T_{3(\mathbf{I})} = T_3$, $p_{4(I)} = p_{4(\mathbf{I})} = p_4$. By solving the balance equations for turbochargers with specified flow cross-sections of turbines, one can determine the required breakdown of the excess air W_p and the exhaust gases W_t, and the values of the characteristics of each turbocharger, for which the condition of the power balance and mass at their cooperation with the engine is met. A detailed description of the assumptions of the method of analysis of this type, determining the conditions of supply of turbochargers with different flow characteristics has been presented in the paper of the author [Danilecki K. 2009].

DESCRIPTION OF THE MODEL DEPENDENCIES

For the simulation of the engine, one has developed an analytical and empirical model of a diesel engine limited to the calculation of the average parameters of the cycle [Ćwik B. *et al.* 1993, [Danilecki K. 2007, Sobociński R. *et al.* 1986, Yusupov Ramazan Ch. *et al.* 2003]. Such a simplification of the model has been a compromise between the required accuracy of calculations and the amount of work required for its development, while ensuring the proper interpretation of the results of the model tests. Carrying out the simulation calculations in accordance with the intended purpose of the numerical program required the inclusion of specified dependencies and auxiliary factors in the numerical model, describing the engine parameters.

The actual engine cylinder volumetric efficiency η_v being the basis for the calculation of the mass air flow intensity through the engine and the compressor has been presented in the form of empirical dependence on the engine speed n, the supercharging pressure $p_{ba,}$ the supercharging temperature T_{ba} and the average exhaust gases pressure p_{g1}:

$$\eta_v = F_2\left(n, p_{ba}, T_{ba}, p_{g1}\right). \tag{1}$$

The engine thermal efficiency $\eta_{c,}$ necessary to determine the indicated mean effective pressure is calculated depending on the speed n, the excess air ratio λ, the supercharging pressure p_{ba} and the supercharging temperature T_{ba}:

$$\eta_c = F_1\left(n, \lambda, p_{ba}, T_{ba}\right). \tag{2}$$

The average friction pressure has been expressed by linear dependence on the engine speed. Increase in the frictional resistance depending on the supercharging pressure has been determined by means of the empirical dependence given in the paper [Cichy M. *et al.* 1989]. In determining the mechanical losses one has also included the influence of the supercharging parameters on the conditions of the charge exchange. The average pressure of the charge exchange determined from the empirical dependence given in the paper [Симсон А. Э. *et al.* 1976] has been taken as the measure of the charge exchange losses.

The exhaust gas temperature T_t has been calculated depending on the speed n, the excess air ratio λ, the supercharging pressure p_{ba} and the supercharging temperature T_{ba}:

$$T_t = F_3\left(n, \lambda, p_{ba}, T_{ba}\right). \tag{3}$$

The dependencies of (1–3) have been determined by identifying the SW-680 engine using the “black box” method through the approximation with polynomials of discrete sets of values of $\eta_{c,}$ $\eta_{v,\,T\,t}$ obtained on the engine test bench in steady conditions of the engine operation. These values have been determined for 49 points of operation from the area of the general characteristics with keeping the principles of a planned experiment. The approximation of the empirical data has been made using polynomials of four variables of the second degree.

The compressor model has been presented in the form of polynomials developed on the basis of characteristics of the compressor as specified by the manufacturer [Ćwik B. *et al.* 1993, Kowalczyk M. *et al.* 1990, Moraal P. *et al.* 1999, Wirkowski P. 2005] describing the dependence of isentropic compression efficiency η_s and the compression ratio π_s on the reduced values of the air expenditure $\dot{m}_s$ and the speed of the turbocharger n_t:

$$\eta_s = f\left(n_t, \dot{m}_s\right), \tag{4}$$

$$\pi_s = f(n_t, \dot{m}_s). \tag{5}$$

The mathematical model of a turbine [Синявский В.В. 1986] is based on the experimentally obtained dimensionless characteristics developed on the basis of the theory of dynamic flow similarity, which describe the flow parameter values $F_p = \dot{m}_t \cdot \sqrt{T_t} / p_t$, the speed parameter $u_{t.kr} = u_t / \sqrt{T_t}$ and the expansion ratio π_t and the adiabatic efficiency $\eta_{ad.t}$ on the speed parameter u_t / c_{ad} and the $u_{t.kr}$ parameter:

$$\frac{\dot{m}_t \cdot \sqrt{T_t}}{p_t} = f\left(\frac{u_t}{\sqrt{T_t}}, \pi_t\right), \tag{6}$$

$$\eta_{ad.t} = f\left(\frac{u_t}{\sqrt{T_t}}, \frac{u_t}{c_{ad}}\right). \tag{7}$$

Functional dependencies (6), (7) have been presented by means of polynomial functions of the second degree. Identification of the coefficients of polynomials has been carried out using multiple regression method based on the characteristics determined for turbines with the outer diameters of rotors ranging from 0.05 to 0.09 m with different inlet box cross-sections.

Changes in the turbine power and flow capacity at the pulsating exhaust gas flow are taken into account by means of pulsatility indices of k_N and k_f given by Wanszejdt [Wanszejdt *et al.* 1977].

PROGRAM STRUCTURE

The calculations are carried out for a given engine operating point and a selected quantity and completions of turbochargers. The commencement of calculations requires the adoption of:

– the value of the engine speed n,
– the value of the excess air ratio λ or the fuel delivery q_o.

Moreover, it is necessary to adopt the initial values of: supercharging pressure p_{ba}, pressure p_t and temperature T_t of exhaust gases in the turbine inlet cross-section, the speed of turbocharger n_t and the volumetric efficiency η_v.

Bearing in mind the permissible conditions of operation of particular components of the engine and turbocharger set system, adequate protection has been provided for in the program. Such role is fulfilled by the conditions of not exceeding the pumping limit of the compressor and the permissible exhaust gases temperature before the turbine. Also restrictions due to the variation range of input values have been introduced, on the basis of which the identification of parameters of the functions of the engine model has taken place. These restrictions apply in particular to the permissible supercharging pressure values p_{ba} (compression of the compressor) and the excess air ratio λ that cannot exceed the area covered by the experimental conditions.

Due to the need to meet the basic balance dependencies of the turbocharger at its co-operation with the engine, and in case of sequential turbocharging – the balance of the supercharging pressure ($p_{2(I)} = p_{2(\mathbf{I})} = p_2$) and the exhaust gases pressure ($p_{3(I)} = p_{3(\mathbf{I})} = p_3$) of two supercharging devices, simulation has been carried out using an iterative calculation mechanism, until the assumed accuracy of the solution has been obtained.

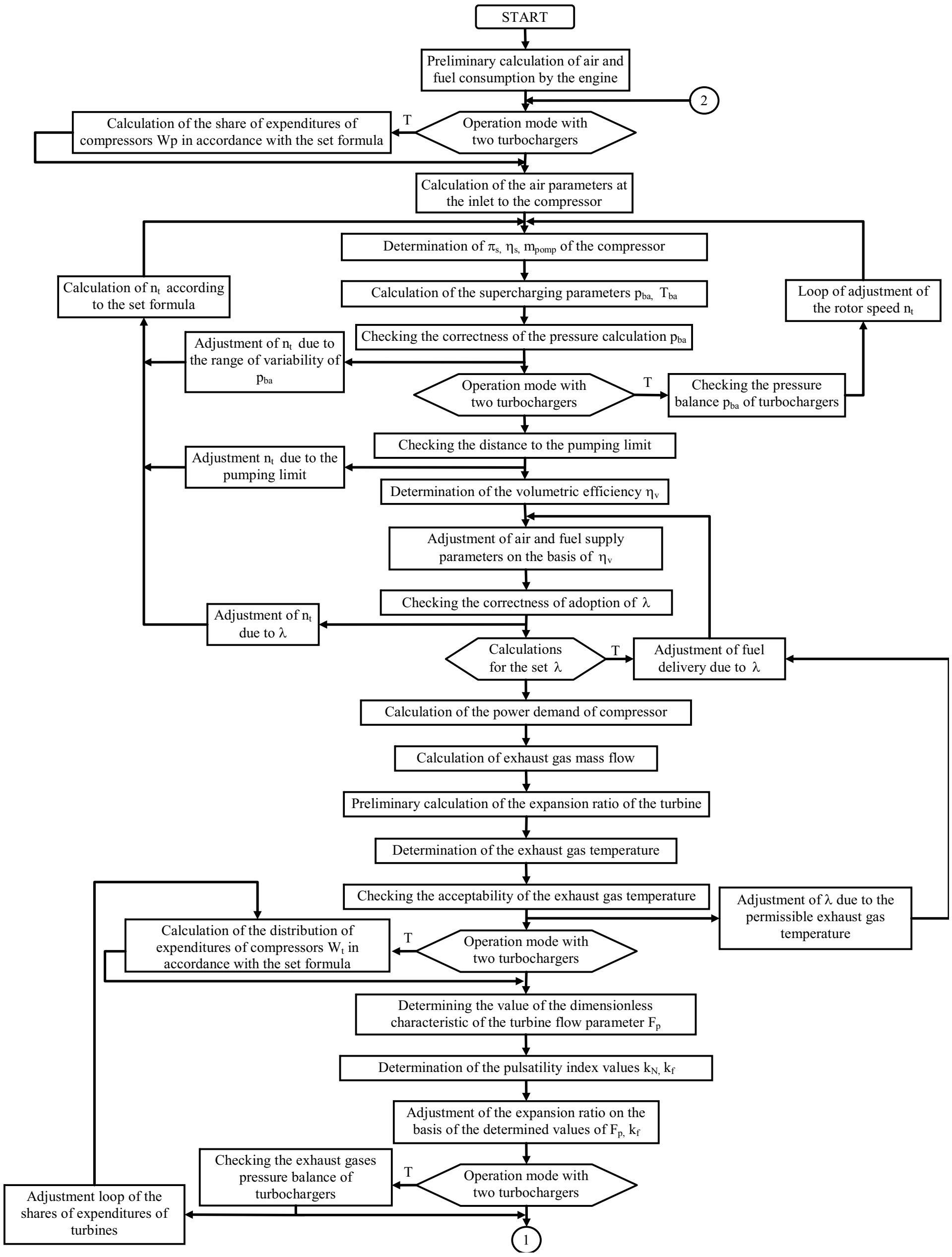

Fig. 2a. Block diagram of algorithm for calculating the characteristics of the engine and supercharging system operation

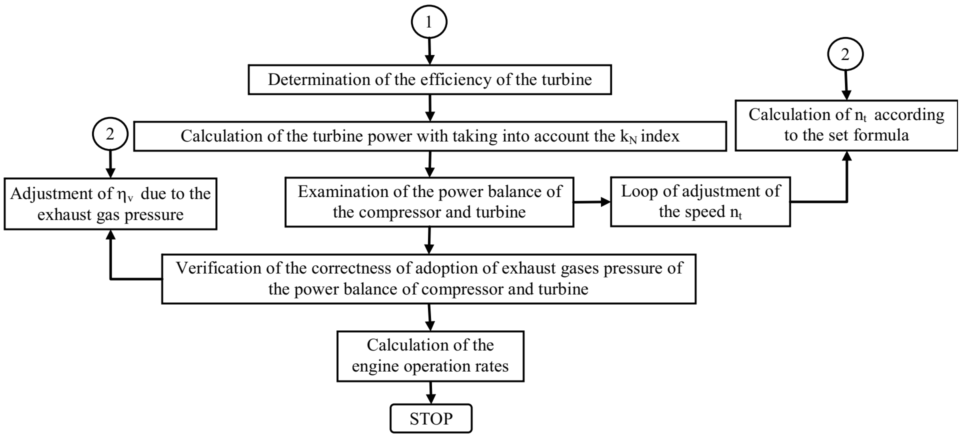

Fig. 2b. Block diagram of algorithm for calculating the characteristics of the engine and supercharging system system operation – continued of Figure 2a

In the inner iteration loop there are adjusted the values of such parameters as: speed of turbocharger $n_{t,}$ fuel delivery q_o, share of expenditure of the turbine W_t of the first range and the volumetric efficiency η_v. The turbocharger speed n_t is adjusted due to the compressor pumping limit and because of the permissible range of variation of the λ ratio, the supercharging pressure p_{ba} and the pressure of exhaust gases p_{g1} in the exhaust manifold. If the calculated values of the exhaust gas pressure p_{g1}, the supercharging pressure p_{ba} and the λ ratio were at the limit of the permissible range, then regardless of the balance of power and the mass intensity of flow, the turbocharger speed n_t would be adjusted on the basis of the set increase of the turbocharger speed $\pm \Delta n_{t.}$

In case of simulations performed for a system with two turbochargers, the speed n_t is also adjusted due to the supercharging pressure balance of each supercharging device. The fuel delivery q_o is determined in the loop of excess air ratio adjustment (in the calculations for a set value of λ) and with taking into account the permissible temperature of exhaust gases. In the calculations carried out for a system with two turbochargers, in the loop of adjustment of the share of the expenditure of turbines W_t, the pressure of exhaust gases in the outlet manifold p_{g1} is balanced for each turbine. Due to the pressure of exhaust gases, the filling ratio is adjusted.

In the outer iteration loop, the speed of turbocharger n_t is adjusted depending on the balance of the compressor power N_s and the turbine $N_{t.}$ With increasing the speed of the turbocharger n_t, the values of compression π_s increase, and consequently, the values of the λ ratio. However, the expansion ratio of π_t decreases, which should lead to a reduction in difference in the power of the turbine N_t and the compressor $N_{s.}$ In the calculations with two turbochargers on the basis of the determined values of the power of compressor and the turbine, also the expenditure is adjusted for each compressor by changing the share of the expenditure of compressors of the first and the second ranges ($W_{p).}$ The condition for completion of the calculations is to obtain for each turbocharger the required convergence of values of N_s and $N_{t.}$

The block diagram of algorithm for calculating the average values of selected parameters of the engine and the supercharging system is illustrated by the Figure 2.

POSSIBILITIES TO USE THE PROGRAM

The usefulness of the numerical program developed by the author for predicting the characteristics of the engine depending on the completion of turbochargers has been confirmed by comparing the calculated and the experimentally obtained external characteristics of the SW680 engine. It has been found that the deviations between them vary from less than 1 up to 3.5% depending on the observed parameter.

Use of the numerical program boils down to calculating the average values of operating parameters during the entire cycle for the given values of the fuel delivery q_o or the excess air ratio λ and the speed n. This allows for determination of the engine performance in the conditions of:

– external characteristics,
– load characteristics,
– general characteristics.

The numerical program, apart from the selection of turbochargers, also enables determination of functional requirements and the values of control signals for the supercharging adjustment system.

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SYMULACYJNE PRZEWIDYWANIA PARAMETRÓW PRACY TRAKCYJNEGO SILNIKA WYSOKOPRĘŻNEGO Z DOŁADOWANIEM ZAKRESOWYM PRZY DOBORZE TURBOSPRĘŻAREK

Streszczenie. Przedstawiono analityczno-empiryczny model układu: silnik wysokoprężny, sprężarka promieniowa, turbina promieniowa oraz program numeryczny umożliwiający prognozowanie parametrów pracy silnika przy doborze turbosprężarek, dostosowany do przypadku doładowania zakresowego. Istotą prezentowanego modelu jest odpowiednie połączenie równań bilansowych umożliwiających obliczenia parametrów termodynamicznych w kontrolnych punktach układu zarówno dla doładowania jednostopniowego, jak i w przypadku równoległego połączenia dwóch różnych turbosprężarek. Program numeryczny umożliwia dobór turbosprężarek oraz ustalenie wymagań funkcjonalnych i wartości sygnałów sterujących dla układu regulacji doładowania.

Słowa kluczowe: silnik spalinowy, turbodoładowanie, modelowanie matematyczne.