ZAGADNIENIA
EKSPLOATACJI
MASZYN
Zeszyt 1 (149) 2007

KRZYSZTOF DANILECKI*

Influence of algorithms of controlling turbo-charging unit on operational properties of an engine with sequential turbo-charging

K e y - w o r d s

Turbocharger, sequential turbo-charging, fuel consumption, electronic controlling.

S ł o w a k l u c z o w e

Turbosprężarka, doładowanie zakresowe, zużycie paliwa, elektroniczne sterowanie.

S u m m a r y

General assumptions for the microprocessor system for engine control with sequence supercharging are presented. Selection of control parameters and determination of the required operation characteristics for control of turbochargers providing highest engine performance is made.

1. Introduction

An important factor that determines the utility properties of traction engines is the graph run of torque that has got essential impact on the ability for acceleration and ability for climbing elevations. The most effective method of shaping of the engine torque is its supercharging to efficiencies adapted to the momentary conditions of the engine operation. Meeting of this condition is possible through use of supercharging adjustment systems. At present, more and more

* Faculty of Motor Vehicles Operation – Technical University of Szczecin, Al. Piastów 19, 70-310 Szczecin, Poland, e- mail: kdanilecki@ps.pl, tel. +48 (91) 4494077.

broadly used solution is to supercharge with turbocharger with variable geometry of guide apparatus of a turbine VGT. This enables increase in dynamics and torque of an engine within a wide range of engine speeds, and matching of the turbo-charger efficiency to the momentary engine load allows for reducing the NO_x emission. Shaping of the supercharging characteristics is also possible by means of systems significantly less complex in construction, and one of them is sequential turbo-charging that deserves particular attention [1–5]. Detailed description and adopted constructional solutions of the sequential turbo-charging system being the subject of the author's research have been presented under [6].

The aim of the research was to develop an electronic system of controlling of a turbo-charging unit for the SW 680 engine with sequential turbo-charging that enables matching the engine turbo-charging characteristics to the operational conditions. This has allowed for significant improving of operational properties of the engine with sequential turbo-charging consisting in lower fuel consumption and better dynamic properties.

2. Problem description

The research carried out by the author [6–8] have allowed for assessment of influence of constructional parameters of sequential turbo-charging on indicators of the SW 680 engine operation, showing significant benefits resulting from its use, particularly in the scope of heavy loads. However, it should be emphasised that the traction engine operates in such conditions extremely seldom. The largest portion of the general operation time is the low and the medium engine loads. This explicitly suggests directions of optimisation of controlling and constructional parameters of the engine in the field of characteristics where it is operated for the longest time [9].

One of the solutions is to develop a system for controlling of turbo-chargers operation that enables matching of the supercharging efficiency to the momentary load. According to the idea of the system operation at low engine loads, one turbocharger remains engaged. Engaging of the second turbocharger connected in parallel takes place only within the range of high engine speeds and heavy engine loads and aims at its protection against excessive increase of mechanical loads [1–2]. As it results from the research carried out by the author, engaging of two turbochargers into operation already within the range of low loads leads to drop in fuel consumption.

From the economical point of view, the engine operation in a given point of its characteristics with one turbocharger or simultaneously with two turbochargers engaged depends on the fuel consumption obtained in each of these fields.

The functional requirements of the controlling system for turbochargers in the engine with sequential turbo-charging meeting the criterion of minimisation of fuel consumption have been determined on the basis of load characteristics of fuel consumption [10]. For example, on Fig. 1, a load characteristic of fuel consumption has been presented for the tested SW-680 engine at the engine speed of 1200 min^{-1}, operating with one and with two turbochargers.

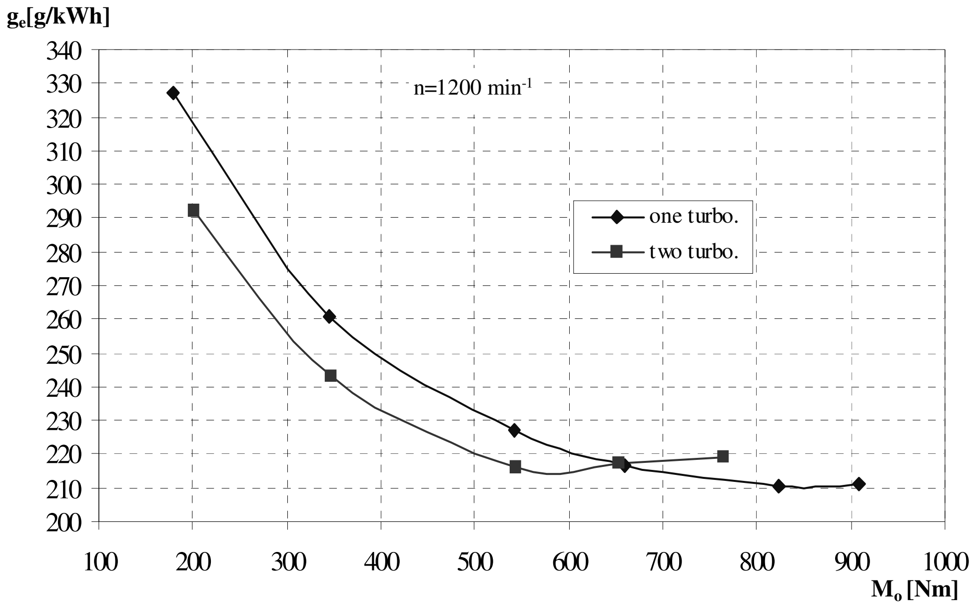

Fig. 1. Load characteristics of fuel consumption - ge of SW 680 engine with sequential turbocharging at the engine speed of 1200 min-1 for engaged one and two turbochargers
Rys.1. Charakterystyka obciążeniowa jednostkowego zużycia paliwa – g_e silnika SW 680 z doładowaniem zakresowym przy prędkości obrotowej 1200 min^{-1} dla włączonej jednej oraz przy dwóch włączonych turbosprężarkach

Fig. 2 shows universal characteristics of the tested engine. The co-ordinates (M_o, n) of the intersection points of the fuel consumption curves of the engine operating with one and with two turbochargers plotted on the universal characteristics determine the run of the boundary line that – due to economy – determines the fields of the engine operation with one or with two turbochargers. The field of characteristics below this line corresponds to the engine operation with one turbocharger, and above – with two turbochargers.

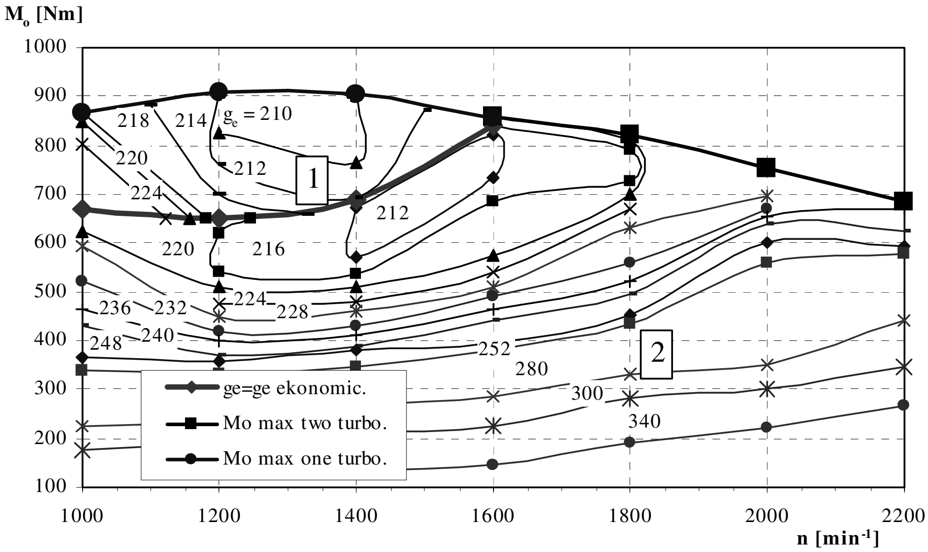

Fig. 2. Universal characteristics of the SW-680 engine with sequential turbo-charging with visible fields of the engine operation with one or two turbochargers with plotted boundary line of economical operation $g_e = g_{e\ economical}$, below which engaging of two turbochargers takes place
Rys. 2. Charakterystyka uniwersalna silnika SW-680 z doładowanie zakresowym, z widocznymi obszarami pracy silnika z jedną oraz z dwoma turbosprężarkami z naniesioną linią graniczną ekonomicznej pracy $g_e = g_{e\ ekonomiczne}$, poniżej której następuje włączenie dwóch turbosprężarek

3. Characteristics of supercharging control system

For controlling of operation of turbochargers an electronic controlling system has been developed, operating on the basis of certain programmed characteristics. For this purpose so called controlling maps are used that contain dependence of the output values on the controlling values. For measurement of the input values measuring sensors were used that placed in appropriate places control the run of the engine operation parameters.

For recording of signals, Advantech PCL-818LS converter card has been used. It has been assumed that the engine speed of the crankshaft of the engine and the supercharging pressure will be the control quantities for the controlling system of sequential turbo-charging. These quantities have been selected due to simplicity of measurement and wide accessibility of sensing elements.

Semiconductor strain gauge has been used for measurement of supercharging pressure, which has been placed in the intake manifold specially designed for the needs of sequential turbo-charging. Measurement of frequency of the crankshaft rotations of the engine was carried out by means of a magneto-inductive transmitter placed in the clutch housing near the flywheel gear.

Moreover, modifications aiming at adapting the SW-680 engine with sequential turbo-charging to electronic controlling included the exhaust system with junction to two turbochargers and the intake system of the engine, where valves enabling controlling of air flow and exhaust gases flow to turbochargers have been applied, activated by means of pneumatic actuators.

For automatic controlling of turbochargers operation in the tested engine, a controlling computer program has been developed that also enables recording of signals of the input and output quantities in the real time as well as their visualisation on the monitor screen. The layout diagram of the controlling system elements has been shown on Fig. 3.

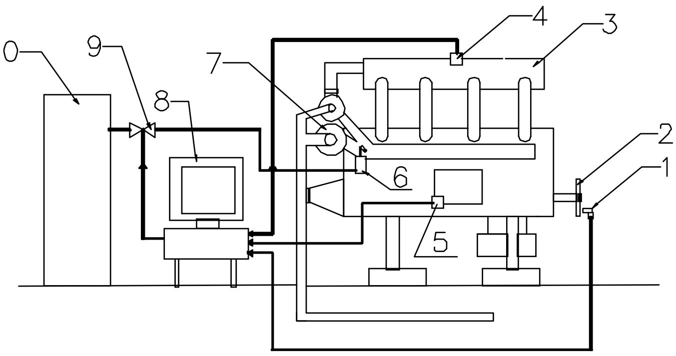

Fig. 3. Measuring sensors layout diagram. 1 – inductive sensor of engine speed, 2 – diffusing disk, 3 – intake manifold, 4 – pressure sensor, 5 – sensor of control lever position, 6 – pneumatic actuator opening the throttling valve, 7 – turbo-charging unit, 8 – controlling computer, 9 – valve cutting off inflow of compressed air to actuator, 10 – compressor

Rys. 3. Schemat rozmieszczenia czujników pomiarowych. 1 – indukcyjny czujnik prędkości obrotowej, 2 – tarcza rozpraszająca, 3 – kolektor dolotowy, 4 – czujnik ciśnienia, 5 – czujnik położenia dźwigni sterującej, 6 – siłownik pneumatyczny otwierający przepustnicę, 7 – zespół doładowujący, 8 – komputer sterujący, 9 – zawór odcinający dopływ sprężonego powietrza do siłownika, 10 – sprężarka

4. Algorithm of supercharging control

For realisation of electronic controlling of turbochargers of the SW 680 engine with sequential turbo-charging, a model and an algorithm of operation of electronic controller with solenoid regulating unit for valves of air and exhaust gases flow have been developed, with taking into consideration basic factors influencing the engine operation and control quantities adopted for controlling. This required determination of the characteristics of the control valve operation depending on the assumed control quantities. The run of the boundary of economical operation of the engine (Fig. 2) makes the engine operation with engaged one or two turbochargers dependant on the point of the engine operation determined by the co-ordinates of *(n, M_o)* – engine speed and torque, the values of which read within the range of engine speeds of 1000–1600 min^{-1} on the basis of load characteristics has been shown in Table 1.

Due to the selection of the supercharging pressure as one of the control quantities, it was necessary to determine distribution of the supercharging pressure values corresponding to each of the points of the engine operation located on the determined economy boundary.

The required values of supercharging pressures have been determined on the basis of the engine load characteristics obtained during the operation with one and with two turbochargers. An example run of the characteristics at the engine speed of 1200 min^{-1} has been presented on Fig. 4.

The values of supercharging pressures obtained in this way conditioning the operation of the engine with one or with two turbochargers form so called nodes of the controlling characteristics. Distribution of these points has been described in the controlling algorithm in the form of polynomial function that enables calculation of pressure conditioning the change of the operation mode of the supercharging unit for the engine speed situated between the nodes.

Table 1. The run of the boundary of economical operation of the engine in the *(n, M_o)* co-ordinates
Tabela 1. Przebieg granicy ekonomicznej pracy silnika we współrzędnych *(n, M_o)*

n [min^{-1}]	1000	1200	1400	1600
M_o [Nm]	670	650	694	840

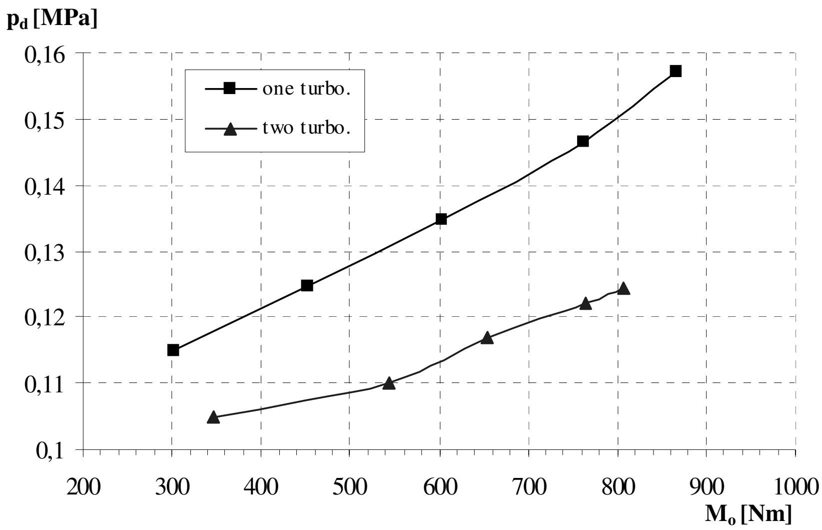

Fig. 4. Load characteristics of the SW 680 engine obtained during operation with one and with two turbochargers
Rys. 4. Charakterystyka obciążeniowa silnika SW 680 uzyskana podczas pracy z jedną oraz z dwoma turbosprężarkami

The values of the supercharging pressure (absolute pressure in the intake manifold), determined on the basis of the load characteristics of the supercharging pressure corresponding to these points of the operation for the engine operating with two turbochargers have been presented in Table 2.

Table 2. The run of the boundary of economical operation of the engine in the *(n, p_d)* co-ordinates for the engine operating with two turbochargers
Tabela 2. Przebieg granicy ekonomicznej pracy silnika we współrzędnych *(n, p_d)* dla silnika pracującego z dwoma turbosprężarkami

n [min^{-1}]	1000	1200	1400	1600
p_d [MPa]	0,115	0,117	0,124	0,143

Distribution of the values of the supercharging pressure obtained during experimental tests $p = f(n)$ indicated the possibility of approximation of their run with cubic polynomial in the form of:

$$p_1 = 10^{-10} \cdot n^3 - 5 \cdot 10^{-7} \cdot n^2 - 0{,}0005 \cdot n - 0{,}065 \qquad (1)$$

With increase of the supercharging pressure above the values calculated by means of the functional dependence (1) switching into the operation mode with one turbocharger should take place. Disengaging of one turbocharger and directing of the whole volume of exhaust gases to another one will lead to sudden increase in the supercharging pressure. During the engine operation with one turbocharger, the pressure values (absolute pressure in the intake manifold) corresponding to the determined boundary of economy have been presented in Table 3.

Table 3. The run of the boundary of economical operation of the engine in the *(n, p_d)* co-ordinates for the engine operating with one turbocharger
Tabela 3. Przebieg granicy ekonomicznej pracy silnika we współrzędnych *(n, p_d)* dla silnika pracującego z jedną turbosprężarką

n [min^{-1}]	1000	1200	1400	1600
Pa [MPa]	0,128	0,134	0,147	0,147

Distribution of the supercharging pressure values is described by the functional dependence determined as cubic polynomial in the form of:

$$p_2 = 10^{-10} \cdot n^3 - 4 \cdot 10^{-7} \cdot n^2 - 0{,}0005 \cdot n - 0{,}042 \qquad (2)$$

With the load drop and thus the supercharging pressure below the values calculated by means of the functional dependence (2), re-engaging into the operation mode with two turbochargers should take place, related to the abrupt reduction of the pressure to the value of p_1.

The characteristics of the supercharging unit control calculated on the basis of dependences (1) and (2) have been presented on Fig. 5.

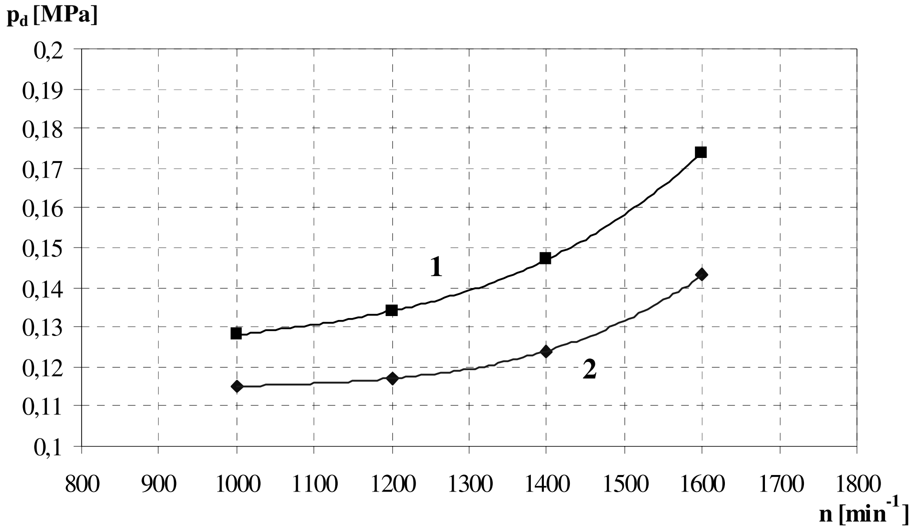

Fig. 5. Illustration of the representation of the characteristics of the supercharging unit control by means of polynomial function: 1 – for one turbocharger, 2 – with two turbochargers in operation
Rys. 5. Ilustracja odwzorowania charakterystyki sterowania zespołem doładowującym za pomocą funkcji wielomianowej: 1 – dla jednej turbosprężarki, 2 – przy dwóch pracujących turbosprężarkach

It has been assumed in the adopted algorithm that the driver of a vehicle will control the engine by means of the accelerator pedal and a two-stage switch W_i enabling switching off the engine. During the engine operation its speed and supercharging pressure - p_d in the intake manifold will be measured. The algorithm of the program controlling the operation of turbochargers acting on the basis of the characteristics of (1) and (2) in the program record has been presented on Fig. 6. The program starts its operation when the driver starts the activities related to activation of supply and starting of the engine. Then, a micro-controller is activated that loads the program that controls supercharging of the engine. The operation of the program lasts until the moment of switching off the engine by means of the W_i switch.

At the moment of starting of the program, the current engine speed is measured as the first. If the engine speed was within the range of 1000 up to 2000 min^{-1} then the main program started the TURBO subprogram.

If the engine speed is greater than 1600 min^{-1} then the computer, through the power terminal, switches off the solenoid control valve, through which compressed air flows to the pneumatic actuators, causing engaging of two turbochargers independently from the momentary engine load. At the speeds lower than 1600 min^{-1}, the computer controls the operation of the turbocharger unit, taking the engine load into account through comparison of the actual value of the supercharging pressure for the momentary engine speeds to the controlling characteristics entered into the memory. If the momentary value of the supercharging pressure p_i is above the values calculated by means of the functional dependence (1), switching on of the solenoid control valve takes place, which causes venting of actuators and switching into the operation mode with one turbocharger. After switching into the engine operation mode with one turbocharger, the supercharging pressure drop below the values calculated by means of the functional dependence (2) causes re-switching into the operation with two turbochargers.

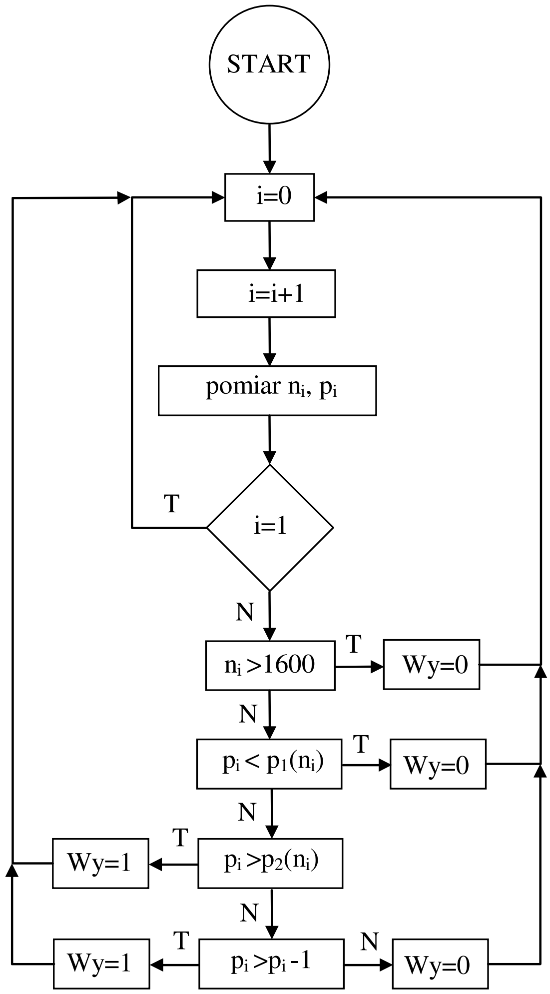

Fig. 6. Block diagram of the TURBO subprogram for controlling of the supercharging unit: Wy = 0 – two turbochargers engaged, Wy = 1 – one turbocharger engaged

Rys. 6. Schemat blokowy podprogramu TURBO sterowania zespołem doładowującym: Wy = 0 – włączone dwie turbosprężarki, Wy = 1 – włączona jedna turbosprężarka

5. Conclusions

The presented methodology allows for determining the required supercharging characteristics where the highest economy of the engine operation with sequential turbo-charging is reached. The simulation calculations done [//] have demonstrated that with the assumed model of the engine operation, controlling of the turbochargers operation according to the presented controlling algorithm allows for reduction of fuel consumption by approximately 4%. This gives approximately 15 litres of fuel saving during a ten hours long working day [11].

At high engine speeds in established conditions of the engine operation, the standards of the smoke opacity of exhaust gases have been exceeded. However, these requirements also have not been met by the basic, conventionally turbocharged engine.

However, the executed survey tests show significant influence of the method of controlling of turbo-chargers operation on dynamic properties of the engine with sequential turbo-charging. As the result, reduced soot emission and faster gaining of the torque during sudden acceleration have been noted, especially when the controlling algorithm will provide for engaging of only one turbo-charger at this stage of operation [12].

Praca wpłynęła do Redkacji 03.04.2007 r.

References

[1] Bluhm K., Ganz M., Voght R.: Erfahrungen mit der Registeraufladung in einer Reiselimousine. Aufladetechnische Konferenz, Zurich ‘88.
[2] Borila Y.G.: A sequential turbocharging method for highly-rated truck diesel engines. SAE Pap. 860074.
[3] Galindo J., Lujan J., Climent H., Guardiola C.: Turbocharging System Design of a Sequentially Turbocharged Diesel Engine by Means of a Wave Action Model. SAE Technical Papers 2007-01-1564.
[4] Luttermann C., Mahrle W.: BMW High Precision Fuel Injection in Conjunction with Twin-Turbo Technology: A Combination for Maximum Dynamic and High Fuel Efficiency. SAE Technical Papers 2007-01-1560.
[5] Łęgowicz J.: Doładowanie typu twin-turbo. Auto Moto Serwis. 3/2005.
[6] Danilecki K.: Wpływ doładowania zakresowego na wybrane aspekty pracy silnika. Teka Komisji Naukowo-Problemowej Motoryzacji. Konstrukcja, badania, eksploatacja, technologia pojazdów samochodowych i silników spalinowych, Polska Akademia Nauk Oddział w Krakowie, Zeszyt 15, Kraków 1998.
[7] Danilecki K.: Analiza możliwości obniżenia zużycia paliwa silnika SW 680 z doładowaniem zakresowym. Zagadnienia Eksploatacji Maszyn. Zeszyt 3 (115). Wydawnictwo Naukowe PWN. Warszawa 1998.
[8] Danilecki K.: Wpływ turbosprężarki drugiego zakresu na zadymienie spalin silnika SW-680 z układem doładowania zakresowego. Czasopismo Techniczne 5M/1998, Zeszyt 5, Wydawnictwo Politechniki Krakowskiej, Kraków 1998.
[9] Kowalczyk M., Kozak W., Jaskuła A., Wisłocki K.: Warunki pracy silnika spalinowego jako podstawa doboru turbosprężarki. Silniki spalinowe 1/1986.

[10] Danilecki K.: Определение характеристики регулирования давления на впуске автомобильного дизеля с системой секвенционного турбонаддува. Problems of Applied Mechanics International Scientific Journal Nr 4(17)/2004. Georgian Committee of the International Federation for the Promotion of Mechanism and Machine Science, Tbilisi 2004.
[11] Mysłowski J.: Zastępcze jednostkowe zużycie paliwa. Eksploatacja silników spalinowych. Katedra Eksploatacji Pojazdów Samochodowych Politechniki Szczecińskiej. Zeszyt 11, Szczecin 2004.
[12] Danilecki K.: Ocena właściwości dynamicznych silnika z doładowaniem zakresowym. Archiwum Motoryzacji. Wydawnictwo Naukowe Polskiego Towarzystwa Naukowego Motoryzacji 2/2005.

Wpływ algorytmów sterowania turbosprężarkowym zespołem doładowującym na właściwości użytkowe silnika z doładowaniem zakresowym

S t r e s z c z e n i e

W artykule przedstawiono wpływ sposobu sterowania pracą turbosprężarek na przebieg charakterystyk silnika SW 680 z doładowaniem zakresowym. Z uwagi na to, że zużycie paliwa w przeciętnych warunkach eksploatacyjnych określane jest w głównej mierze pracą silnika przy obciążeniach częściowych, przeprowadzone zostały badania dla zakresu małych i średnich obciążeń silnika. Wynika z nich, że w tym obszarze charakterystyki skierowanie spalin do obu turbosprężarek jednocześnie, mimo spadku ciśnienia doładowania, wpływa na poprawę ekonomiczności wyrażającą się spadkiem jednostkowego zużycia paliwa. Wskazano, że warunkiem uzyskania żądanej charakterystyki doładowania jest zastosowanie elektronicznego systemu sterowania, który umożliwia dopasowanie wydajności doładowania do chwilowego obciążenia. Z ekonomicznego punktu widzenia, praca silnika w danym punkcie jego charakterystyki z jedną lub jednocześnie z dwiema włączonymi turbosprężarkami uzależniona jest od osiąganego w każdym z tych obszarów jednostkowego zużycia paliwa.

Określono wymagania funkcjonalne układu sterowania turbosprężarek w silniku z doładowaniem zakresowym, spełniające kryterium minimalizacji zużycia paliwa.
Do sterowania pracą turbosprężarek opracowano elektroniczny układ sterowania działający w oparciu tzw. mapy sterowania zawierające zależność wartości wyjść od wielkości sterujących. Przedstawione zostały modyfikacje mające na celu przystosowanie silnika SW-680 z doładowaniem zakresowym do elektronicznego sterowania, które polegały na zastosowaniu czujników oraz zaworów umożliwiających sterowanie przepływem powietrza oraz spalin do turbosprężarek, uruchamianych za pomocą siłowników pneumatycznych.

Do automatycznego sterowania pracą turbosprężarek w badanym silniku opracowano model i algorytm działania sterownika elektronicznego z nastawnikiem elekromagnetycznym zaworów sterujących, określono charakterystyki pracy zaworów w zależności od prędkości obrotowej oraz ciśnienia doładowania, które wyznaczają obszary charakterystyki silnika z włączoną jedną lub z dwiema turbosprężarkami. Rozkład tych punktów został opisany w algorytmie sterowania w postaci funkcji wielomianowej.

Opracowany elektroniczny system sterowania pozwalają na określenie wymaganej charakterystyki doładowania, przy której osiągana jest najwyższa ekonomiczność pracy silnika z doładowaniem zakresowym. Przeprowadzone obliczenia symulacyjne wykazały, że przy założonym modelu eksploatacji silnika, sterowanie pracą turbosprężarek według przedstawionego algorytmu sterowania pozwala na obniżenie zastępczego o około 4%. Daje to średnio około 15 litrów oszczędności paliwa przy dziesięciogodzinnym dniu pracy.

Przy dużych prędkościach obrotowych w ustalonych warunkach pracy silnika przekroczone zostały normy zadymienia spalin. Jednak wymagań tych nie spełnia również silnik bazowy doładowany konwencjonalnie.

Natomiast przeprowadzone próby pomiarowe wskazują na znaczny wpływ sposobu sterowania pracą turbosprężarek na właściwości dynamiczne silnika z doładowaniem zakresowym. W rezultacie notuje się zmniejszoną emisję sadzy oraz szybsze uzyskiwanie momentu obrotowego podczas gwałtownego przyspieszania, szczególnie gdy algorytm sterowania przewidywać będzie włączenie w tej fazie pracy tylko jednej turbosprężarki.