UDC 621.43.052
DOI: 10.15587/1729-4061.2025.323891

DEVISING A METHOD FOR ASSESSING THE PERFORMANCE OF EXERGETIC EFFICIENCY OF A PRESSURE WAVE EXCHANGER

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With all their undeniable advantages, forced engines equipped with gas turbine supercharging (GTS) have a significant inherent drawback of the turbocharger (TC), which is associated with the inertia of the TC rotor, causing a discrepancy between the flow characteristics of the supercharger and the hydraulic needs of the engine under transient modes, during sharp acceleration of the vehicle.

As an alternative option and one of the effective methods for forcing the engine in order to obtain high technical, economic, and environmental performance indicators of the working process under transient operating modes, a wave pressure exchanger (WPE) is considered as the object of this study. However, the available information related to the energy exchange of working fluids in the units of the wave exchanger has not yet been sufficiently studied. To partially solve this problem, a method has been devised for assessing the exergetic efficiency of WPE, which takes into account the effect of partial exhaust gas recirculation, purging the rotor cells with a fresh charge.

Based on the results of development studies, in the presence of a pattern of change in these parameters (purging and recirculation), it is possible to influence the process of improving the working cycle and the exergetic efficiency of the pressure exchanger.

A rational combination of purging the rotor cells with a fresh charge (from 4 to 8 %) and reusing part of the combustion products (recirculation from 3 to 5 %) in the working process of the supercharger ensured an increase in the exergetic efficiency of WPE from 0.72 to 0.91 and partially solved the research problem.

The resulting data can be implemented both at the early stages of WPE design and for existing modifications of supercharging units, in the process of their further modernization and improvement

Keywords: exergetic efficiency, pressure exchanger, purging of rotor channels, fresh charge, recirculation of combustion products

Received 04.11.2024
Received in revised form 24.01.2025
Accepted date 18.02.2025
Published date 28.02.2025

How to Cite: *Manoylo, V., Korohodskyi, V., Voronkov, A., Avramenko, A., Nikitchenko, I., Shevchenko, I., Iesipov, O., Polyashenko, S., Teslenko, E., Lemishko, D. (2025). Devising a method for assessing the performance of exergetic efficiency of a pressure wave exchanger. Eastern-European Journal of Enterprise Technologies, 1 (5 (133)), 36–45. https://doi.org/10.15587/1729-4061.2025.323891*

1. Introduction

The problem of increasing the filling of the internal combustion engine (ICE) cylinders [1] has been partially solved by the obtained performance characteristics of the ICE with WPE, which made it possible to improve the indicators of thermodynamic cycles [2] and the efficiency of ICE.

An increase in charge density [3] and the amount of fuel supplied leads to an increase in the pressure of the working fluid during combustion and, as a consequence, to an increase in engine power [4]. However, with an increase in power, a problem arises associated with an increase in harmful emissions into the atmosphere, especially nitrogen oxides [3, 4]. An alternative is to use the supercharger WPE.

Excess air [5] and the organization of high-quality mixture formation [6] contribute to more complete combustion [7] of both liquid, gaseous [8, 9], and alternative fuel [10]. To increase engine efficiency by organizing effective combustion and reducing energy losses in ICE, modern fuel supply systems [11] are used. However, the problem of reducing the environmental performance of ICE is not solved [5–11]. A partial solution to the problem is the use of a pressure exchanger.

In a diesel engine, an alternative solution to increase the filling of the cylinders with a fresh charge is the use of WPE. The supercharger reduces the concentration of nitrogen oxides (NOx) and solid particles (soot) in the exhaust gases (EG) [12]. Excess air during filling leads to a decrease in the temperature during the combustion process and promotes more complete combustion of carbon compounds.

Efficient filling of the ICE cylinders using turbocharging from WPE reduces harmful emissions into the atmosphere and soil. ICEs are capable of meeting modern environmental standards, such as Euro-6, which is especially important when used in urbanized areas [13]. Reducing the amount of combustion products in the form of soot has a beneficial effect on reducing the wear of pistons, piston rings, and engine cylinders, as well as reduces the frequency and cost of maintenance.

The use of gas-turbine supercharging makes it possible to increase the filling of the cylinders with a fresh charge. However, gas-turbine supercharging has a number of fundamental disadvantages. One of the main disadvantages of the turbocharger is associated with the inertia of its rotor, which causes a discrepancy between the flow characteristics of the supercharging unit and the engine under transient operating modes and leads to a decrease in the efficiency of the turbocharger.

The most complete efficiency of using WPE [14] as a supercharging system in an ICE, taking into account changes in environmental parameters, can be estimated by the efficiency coefficient (EC).

Scientific research related to the energy exchange of working bodies in the nodes of the wave exchanger must be carried out due to the fact that they have not yet been fully studied. It is necessary to obtain answers to the following principal questions using these studies:

– what amount of supplied thermal energy is converted into usable types of work, i.e., into exergy; and it is desirable that this share approaches 100 %, then the values of the exergetic efficiency of the unit will also approach 100 %;

– the results of the studies will make it possible, by means of a calculation and experimental method, to select the most rational ranges of values of the processes of exhaust gas recirculation and purging of rotor cells with a fresh air charge, close to real operating conditions.

Therefore, establishing the dependences that make it possible to estimate the level of exergetic efficiency of WPE at different stages of designing the supercharger, as well as their further improvement, taking into account analytical and experimental data, is an urgent task of scientific and practical interest.

2. Literature review and problem statement

Paper [1] reports the results of studies of wave exchangers used as supercharging units in high-pressure combustion chambers in ultra-micro gas turbines. Experimental studies and results of numerical modeling are described. However, problems associated with the evaluation of the efficiency of WPE of these turbines remain unsolved. The likely reason is the difficulties associated with other labor-intensive types of research.

Increasing the specific power of the internal combustion engine together with a simultaneous reduction in harmful emissions are the main goals for specialists in the automotive industry [2]. In comparison with a turbocharger, an alternative option is the use of a wave pressure exchanger, which allows for a sharp increase in throttle response under (transient) acceleration modes of vehicles. Some technical solutions have been proposed, namely, geometric adjustment of the air, gas casings, and the WPE rotor. These measures have improved the performance of the working process and the efficiency of the drive supercharger.

High-power engines must comply with strict environmental standards, which requires improving the combustion concept [3]. Combustion systems with a pre-chamber provide improved combustion stability and reduced emissions, and their design parameters affect the technical and economic performance of the engine with a pre-chamber. The cited study was conducted at an engine shaft speed of 720 min^{-1} and 100 % load, both for dual-fuel and purely diesel engine operation modes. NOx emissions were reduced by 50 % in the diesel version. Evaluation of the exergetic efficiency of WPE is not provided for by the research program.

Wave pressure superchargers (WPSs) have proven to be an effective, cost-effective solution with simple geometry and fast operating response [4]. Continuous incentives to achieve energy efficiency along with replacing old technology with new and innovative ones have stimulated new interest in WPE rotor manufacturing technology. There is no information on the methods for assessing the WPE efficiency in the paper.

The working process [5] enables the formation of a stratified lean fuel-air charge at partial load modes and the energy composition of the fuel-air mixture at high load modes.

The supercharging scheme and electronic fuel supply control [6] is used as the main one on the engine when the ICE is running on a mixture of compressed natural gas (CNG) with 10 % hydrogen additive. Methods for improving the WPE efficiency were not considered in the paper.

Various structures of supercharging systems and engine modifications have been designed to improve the thermal and fuel efficiency of ICEs [7]. Various methods for analyzing the flows in the engine cylinder during air intake and compression, with simultaneous fuel supply to the engine, have been proposed. However, the research program did not provide methods for evaluating the efficiency of the supercharger.

To improve engine efficiency when running on natural gas, the Miller cycle was used in [8]. The systems were compared experimentally, and a 49 % increase in torque was achieved at a shaft speed of 1250 min^{-1} when Comprex TM was used in combination with the Miller cycle. Using the Miller cycle, the transient response from Comprex TM increased faster than that of the turbocharged engine. The turbocharged engine needed 2.5 times more time to achieve the same torque values than the one with a pressure exchanger. The exergetic efficiency of the superchargers was not assessed in the work.

A thermodynamic model was built based on the volume balance method to calculate the working process in the cylinder of a spark-ignition engine with internal mixture formation and stratified charging of the fuel-air mixture [9]. An equation for the balance of volumes of internal mixture formation processes during direct fuel injection into the engine cylinder was constructed, which takes into account the adiabatic change in the volume of the stratified charge of the air-fuel mixture, consisting of the volume of the air-fuel mixture and the volume of air. However, the issues of increasing the supercharger efficiency were not addressed in the work due to solving other problems.

The process of increasing the boost [10] leads to the formation of an excessive amount of harmful NOx emissions. Therefore, the boost intensity must be limited in order to avoid an excessive increase in NOx emissions since these emissions are sharply limited by the Euro 6 pollution standard. When switching from Euro 5 to Euro 6, the permissible NOx emission limits were reduced to 80 %. Diesel boost was effectively implemented using a wave pressure exchanger (WPE). Methods for assessing the efficiency of WPE were not provided in the work.

To increase the torque reserve of the turbocharger (TC) against surge, at relatively low pressure ratios, large swirl angles are required, as well as the supply of zero pre-swirl. The objective of study [11] was to design a device capable of efficiently generating large swirl angles to expand the torque reserve in the compressor part of TC. The efficiency of these turbochargers varied in the range of 75–82 %.

Paper [12] presents efficient mechanical automatic boost control systems installed on automotive and tractor diesel engines equipped with gas turbine supercharging or a wave exchanger. It is preferable to install boost systems from the WPE on these diesel engines since the vehicles move back and forth on short sections, for example, during road construction, etc. The work does not provide for an assessment of WPE efficiency.

Work [13] gives a diagram of a gas engine with a boost from WPE. The supercharging scheme equipped with electronic fuel supply control can be used as the main one on the engine, when the internal combustion engine operates on a mixture of compressed natural gas (CNG) with a 10 % hydrogen additive. The supercharging system with WPE enables the rotor operation at higher EG temperatures than the TC turbine, develops a higher boost pressure, while there is no dip in the power increase during a sharp opening of the throttle valve in the acceleration modes of the vehicle. This supercharger is serially manufactured by the only turbocharger company Asea Brown Boveri Ltd. (Switzerland). Its manufacturing cost is significantly higher than TC, so the use of these supercharging systems on automotive and tractor internal combustion engines is limited. The company pays special attention to making a working WPE sample to extract maximum profit. As a rule, several WPE variations are made, which are installed on non-motorized "hot" benches, on which the flow characteristics of the supercharger are collected. Variations with the most efficient consumption characteristics are selected and supplied to the sales market, and experts, as a rule, remain silent about the efficiency (this is the company's confidential data).

A likely option for resolving these issues is the approach reported in [14–16].

The overall efficiency of the pressure exchanger [14] is estimated by conditional, internal, and combined efficiency factor, taking into account the drive power of WPE.

A detailed estimate of energy losses in the pressure exchanger with subsequent consideration of them when calculating the efficiency is given in work [15], in which the founders of the supercharger (employees at the joint-stock company Brown Boveri Cop.) use the isentropic (adiabatic) efficiency, which is common in turbo engineering, given in works [14, 16].

When analyzing the efficiency of power plant cycles [15], exergy dependences are often used, which make it possible to judge the degree of reversibility of processes inside the unit based on an external characteristic – the difference in exergies at the input of the unit and its output.

For the process of air compression, in the case of a reversible isentropic process, in the absence of various flow losses and without heat exchange, the increase in the exergy of the air flow is equal to the difference in enthalpies at the outlet of the pressure exchanger i_{hpa} and at the inlet to it – i_{lpa}.

The actual process of air compression [15] is accompanied by the presence of friction forces, heat and mass transfer, causing an increase in its entropy and leading the process to irreversibility.

In the adiabatic expansion process [15], in the absence of various losses, the energy used is converted into exergy, i.e., $\left(i_{hpg}-i^{*}_{lpg}\right)$, where i^{*}_{lpg} is the enthalpy of low-pressure gas in the case of a reversible isentropic process.

All real processes are irreversible and for a thermodynamically isolated system are accompanied by an increase in entropy [15], then the used exergy $[i_{hpg}-i_{lpg}-T_0\cdot(s_{hpg}-s_{lpg})]$ will differ from the change in energy in the isentropic expansion process. This difference is due to the presence of friction forces of the particles of the working substance against each other, against the walls of the flow part of the pressure exchanger, as well as due to heat exchange of the working medium in it. The greater the values of these energy flows, the more significantly the real process will deviate from the ideal isentropic process. All losses associated with the flow of the working fluid in the flow part of WPE affect the value of efficiency through a change in entropy ($s_{\mathrm{hpg}}-s_{lpg}$).

The main purpose of the pressure exchanger, as a turbocharging unit of the internal combustion engine, is to increase the exergy of the air entering the engine cylinder, then the exergetic efficiency of WPE as a whole is defined as the product of the exergy efficiencies of the compression and expansion process.

The lack of a unified approach to determining the efficiency of the exchanger complicates analyzing the efficiency of WPE, making it difficult to choose the direction for its further improvement. Therefore, the main problem that requires a solution is to devise a method for assessing the exergetic efficiency of WPE, which makes it possible to take into account the effect of purging the rotor with a fresh charge and partial recirculation of the exhaust gas.

3. The aim and objectives of the study

The aim of our study is to devise a method for assessing the exergetic efficiency of a wave pressure exchanger, taking into account the effect of purging the rotor cells with a fresh charge and partial EG recirculation. The method will make it possible to obtain more reliable results of the exergetic efficiency of WPE.

To achieve this goal, it is necessary to complete the following tasks:

– to construct a diagram for selecting the locations of the outflow of gas-air flows in the supercharger units; indicating the operating parameters at the locations of the outflow of gas-air flows in the supercharging unit units;

– to draw a diagram of the exergy balance flows of the gas-air medium in the WPE units; indicate the outflow zones of the full exergy flows of the gas-air medium in the WPE units;

– to conduct a calculated and experimental assessment of the exergetic efficiency of WPE using purging the rotor cells with fresh air and partial EG recirculation, in order to improve the working process of the supercharging unit.

4. The study materials and methods

The object of our study is a wave pressure exchanger.

The hypothesis of the study assumes that taking into account the effect of partial exhaust gas recirculation and purging the rotor cells with a fresh charge could partially solve the problem associated with insufficient knowledge of the energy exchange of working fluids in the wave exchanger units.

In the process of studying WPE, in the theoretical part of the work, classical methods for assessing the determination of the exergetic efficiency of WPE are used, developed on the basis of such disciplines as heat engineering and heat and mass transfer.

On a personal computer (PC) with software, the Mathcad electronic shell was used, with the help of which a program for assessing the exergetic efficiency of WPE was developed.

As a simplification, it is assumed that leaks in the high-pressure and low-pressure parts of the supercharging unit are not taken into account. This is due to the complexity of manufacturing the middle housing of the supercharging unit, and the losses in it are insignificant.

To conduct experimental studies on WPE, we used a deployed bench with a 4ChN 12/14 tractor diesel engine, and a control panel equipped with a set of measuring and diagnostic equipment. The bench recorded the load characteristic of the diesel engine under the maximum torque mode at a crankshaft speed of 1200 min^{-1}. The engine is equipped with an experimental WPE sample with a rotor diameter of 112 mm.

5. Results of devising a method for assessing the exergetic efficiency of the supercharger

5. 1. Scheme for selecting the locations of the outflow of gas-air flows in the supercharger units

A real process occurring in the supercharger unit (in a thermodynamic, isolated system) under reversible compression is considered, schematically shown in Fig. 1. With the WPE in operation, using measuring equipment, the values of the parameters are determined: pressure, temperature, flow rates, and the exergies of the working fluid flows at the inlet and outlet of the WPE units are calculated.

Fig. 1 shows the places of outflow of gas-air medium flows in the units of the supercharger, where the transformation of one type of thermal energy into other positive types of energy and heat and mass transfer occur, and also shows leaks of the working fluid through the gaps between the rotor, air and gas housings of WPE.

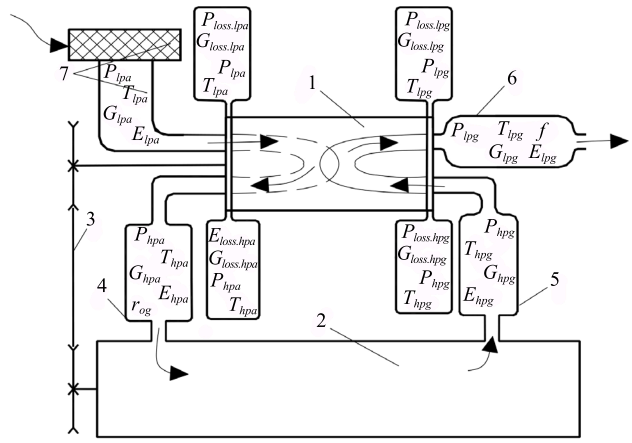

Fig. 1. Schematic showing the places of outflow of gas-air medium flows in units of the supercharger and leaks in gaps between the rotor and the pressure exchanger housings: 1 — wave pressure exchanger; 2 — internal combustion engine; 3 — mechanical drive of the water supply system; 4, 5 — inlet and outlet manifolds; 6 — inlet pipe with muffler; 7 — air filter with air supply branch pipe

The main losses of the working fluid in the gaps of WPE occur in the high-pressure parts between the rotor and the high-pressure gas and air channels. Losses in the low-pressure parts of WPE between the rotor and the low-pressure air and gas channels are neglected.

The exergy of the performed work of compression-expansion and heat and mass transfer of WPE E'_0, due to which the working cycle in the supercharger unit is carried out, can be expressed by the following relationship:

$$E'_0 = E'_{in} - E'_{out} + E'_r - E'_\psi - E'_{loss.high} - E'_{loss.low}, \tag{1}$$

where E'_{in}, E'_{out} – incoming and outgoing total exergies of the working fluid flows concentrated in the pressure exchanger units, W; E'_ψ, E'_r – total exergies of the flows of purging the rotor cells with a fresh charge and recirculation of the exhaust gas, W; $E'_{loss.low}$, $E'_{loss.high}$ – exergy losses arising in the gaps between the high-pressure and low-pressure channels of the water supply system and the rotor, W.

It should be noted that new components not previously taken into account have been introduced into formula (1) – E'_ψ, E'_r.

The incoming and outgoing total exergies of the working fluid flows, as well as the exergy losses through the gaps between the water supply system channels and the rotor can be expressed by the following formulas:

$$E_{in} = E_{lpa} + E_{hpg} + E_r, \quad E_{out} = E_{hpa} + E_{lpg} + E_\psi, \tag{2}$$

$$E_{loss.high} = E_{loss.hpa} + E_{loss.hpg} = 0,$$

$$E_{loss.low} = E_{loss.lpa} + E_{loss.lpg} = 0, \tag{3}$$

where E_{hpa}, E_{lpa} – total exergies of high and low pressure air flows in the air ducts of WPE, W; E_{lpg}, E_{hpg} – total exergies of low and high pressure gas flows in the gas ducts of WPE.

The total exergies of the working substance (body) flows, as well as the exergy losses through the gaps between the WPE ducts and the rotor, can be expressed using the expressions for determining the enthalpy of the working fluid flow.

The enthalpy of the working fluid flow was determined from the well-known expression:

$$I = E - T_0 \cdot S,$$

where I is the total enthalpy of the working fluid flow, W; E is the total exergy of the working fluid flow, W; T_0 is the ambient temperature, K; S is the total entropy of the working fluid flow, W/K.

In each specific case, the enthalpy of the working fluid was determined for high- and low-pressure exhaust gas flows, high- and low-pressure air flows, the EG flow, the flow of purging the rotor cells with a fresh charge, and the flow of losses through the gaps between the high-pressure gas channels of WPE and the rotor.

The exergy of the working fluid flow was determined similarly:

$$\begin{aligned} E &= I - T_0 \cdot S = G \cdot i - T_0 \cdot G \cdot s = \\ &= G \cdot C \cdot T - T_0 \cdot G \cdot C \cdot \ln T = \\ &= C^1 \cdot T - T_0 \cdot C^1 \cdot \ln T = C^1 \cdot T \cdot \left(1 - T_0 \cdot \ln T\right), \end{aligned}$$

where G is the second mass flow rate of the working fluid, kg/s; i is the specific enthalpy of the working fluid flow, J/kg; s is the specific entropy of the working fluid flow, J/(kg·K); T is the temperature of the working fluid flow, K; C is the average isobaric heat capacity of the working fluid flow, J/(kg·K); the value $C`=C\times G$ is the total heat capacity of the mass flow rate of the heat carrier (working fluid flow) per unit of time, termed the consumable heat capacity of the working fluid, W/K.

The exergy of the working fluid was also determined for high and low pressure exhaust gas flows, high and low pressure air flows, EG flow, and the flow of purging the rotor cells with a fresh charge.

5. 2. Construction of a diagram of the exergy balance flows of the gas-air environment in the nodes of the wave pressure exchanger

With the help of the exergy balance of the energy flows of the working fluid (Fig. 2), it is possible to track (see) how the supplied exergy of EG E_{hpg} in the process of energy exchange in the working cycle is converted into other types of energy to perform usable work in WPE.

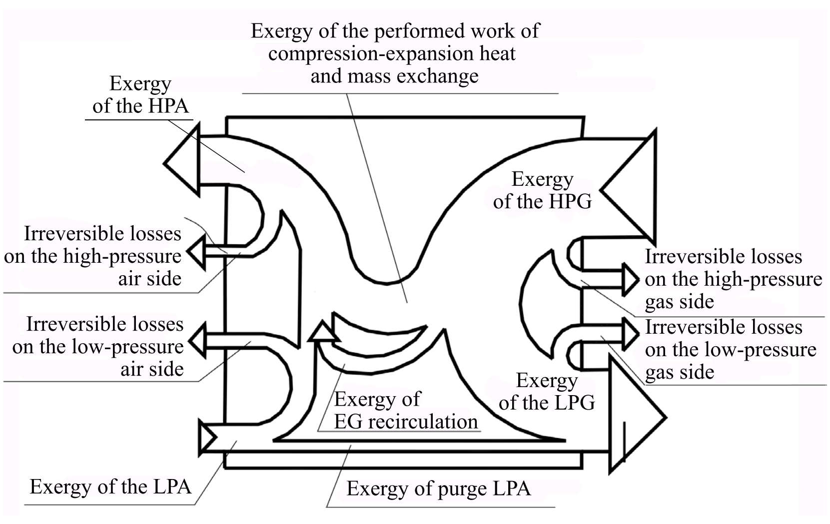

Fig. 2. Diagram of exergy balance flows of gas-air medium flows in the nodes of the wave pressure exchanger

With rationally selected design parameters of the gas-air tract and the supercharger rotor, the supplied exergy of EG flow E_{hpg} is used (converted) to perform the following processes of the supercharger working cycle:

– the process of filling the rotor cells of the water supply system with a fresh charge and partial recirculation of EG is carried out, by means of energy exchange the exergy E_{hpg} is partially converted into the exergy of low-pressure air E_{lpa} and the exergy of recirculation of combustion products E_r;

– the process of compression and injection of charge air into the engine cylinders is carried out, the exergy E_{hpg} is partially converted into the exergy of high-pressure air E_{hpa};

– the process of releasing and purging the rotor cells from combustion products occurs, the exergy E_{hpg} is partially converted into the exergy of purging E_φ and, having completely given up their exergy, the exhaust gases exit the supercharger in the form of the exergy of low-pressure gases E_{lpg}.

When performing a working cycle, leaks of the working fluid inevitably occur through the gaps between the gas and air housings and the WPE rotor. At this stage of the study, we neglect these losses.

Then, based on the reduced balance of energy exchange of the working fluid flows, the exergetic efficiency of WPE can be expressed using the following relationship:

$$\begin{aligned} \eta_{wpe} &= 1 - \frac{E'_{hpa} + E'_{lpg} + E'_{\phi}}{E'_{lpa} + E'_{hpg} + E'_{r}} = \\ &= 1 - \frac{\left[I'_{hpa} + I'_{lpg} + I'_{\phi} + I'_{loss.high} + I'_{loss.low} - T_0 \cdot \left(S'_{hpa} + S'_{lpg} + S'_{\phi}\right)\right]}{\left[I'_{lpa} + I'_{hpg} + I'_{r} - T_0 \cdot \left(S'_{lpa} + S'_{hpg} + S'_{r}\right)\right]}. \end{aligned} \quad (4)$$

It should be noted that new components, not previously taken into account, have been introduced into formula (4) – E'_ϕ, E'_r, I'_ϕ, I'_r, S'_ϕ, S'_r.

Note that when designing new models of WPE, developers, as a rule, do not have experimental data on the flow characteristics of the working fluid in the supercharger, so there was a need for the calculation formulas given below.

5. 3. Development of an algorithm for calculating the exergetic efficiency of a pressure wave exchanger using the devised method

The numbering of the positions of the algorithm for calculating the exergetic efficiency of a pressure wave exchanger is presented in the following sequence:

1. Start of calculation.

2. Initial data: η_v is the cylinder filling factor of the internal combustion engine; P_{hpa} is the boost pressure, Pa; V_h is the working volume of the engine cylinder, l; n is the rotation speed of the internal combustion engine crankshaft, min^{-1}; z is the number of cylinders in the engine, pcs; R is the characteristic gas constant of air, J/(kg·K); T_{hpa} is the temperature of the boost air, K; τ is the engine stroke.

3. The consumption of high-pressure air (HPA) entering the cylinders of the internal combustion engine is determined using the following expression:

$$G_{hpa} = \frac{\eta_v \cdot P_{hpa} \cdot V_h \cdot n \cdot z}{R \cdot T_{hpa} \cdot 30 \cdot \tau} \cdot 3{,}600.$$

4. The second fuel consumption of the engine can be expressed as the following ratio, kg/s:

$$G_t = \frac{1}{l_0} \cdot G_{hpa},$$

where l_0 is the amount of air theoretically required for the complete combustion of 1 kg of fuel (kg fuel/kg air); G_{hpa} is the second flow rate of high-pressure air, kg/s.

5. Accordingly, the second flow rate of high-pressure gas (HPG) leaving the exhaust manifold of the internal combustion engine and going to the supercharger to perform usable work is determined by the relationship:

$$G_{hpg}=G_{hpa}+G_t.$$

6. The flow rate of low pressure air (LPA) entering the intake channel of WPE from the atmosphere, taking into account the purge, is determined using the following expression:

$$G_{lpa.p}=G_{hp}\cdot(\psi+1).$$

7. The flow rate of the working fluid used for purging and cooling the rotor cells with a fresh charge is expressed as the ratio:

$$G_\psi = G_{hpa} \cdot \psi,$$

where ψ=(0.03…0.1) is the coefficient of WPE purging (is 3…10 % of the high-pressure air consumption).

The coefficient of exhaust gas recirculation can be expressed by the following dependence: r_{og}=(0.02…0.05)G_{hpg}, kg/h, at steady-state operating modes of the supercharger, exhaust gas recirculation is 2…5 % of the high-pressure gas consumption.

8. Then, at steady-state operating modes of the supercharger, the consumption of exhaust products for exhaust gas recirculation can be written by the following dependence:

$$G_r=r_{og}.$$

9. The second flow rate of low-pressure gas (LPG) exiting the supercharger into the muffler inlet pipe is represented by the ratio:

$$G_{lpg} = G_{hpg} + G_\psi,$$

where G_ψ is the flow rate of the working fluid used for purging and cooling the rotor cells with a fresh charge, kg/s.

At the initial stages of designing the supercharger, the exergetic efficiency of WPE can be determined by calculation; for this purpose, it is necessary to express $G_{hpg.p}$ and $G_{lpg.p}$ taking into account recirculation and purging through G_{hpa}, and the exergy losses in the gaps of the supercharger unit can be neglected ($E_{loss.high}$=0, $E_{loss.low}$=0), then the expressions will take the form:

10. High-pressure gas flow rate with purging:

$$G_{hpg.p.} = G_{hpa} + G_t + G_r = = G_{hpa} + \frac{G_{hpa}}{l_0} + r_{og} = G_{hpa} \cdot \left(1 + \frac{1}{l_0} + r_{og}\right).$$

11. Low-pressure gas flow rate with purge:

$$G_{lpg.p.} = G_{hpg} + G_\psi = G_{hpa} \cdot \left(1 + \frac{1}{l_0}\right) + +G_{hpa} \cdot \psi = G_{hpa} \cdot \left(1 + \frac{1}{l_0} + \psi\right).$$

12. Specific enthalpy flows of the supply and outlet of the working fluid can be expressed by the following well-known expressions:

$$i = C_{P.} \cdot T.$$

13. And the specific flows of heat supply and removal to the working fluid are as follows:

$$q = C_{vm} \cdot \frac{n-k}{n-1} \cdot T = \frac{C_{Pm.}}{k} \cdot \frac{n-k}{n-1} \cdot T,$$

14. Accordingly, the specific entropy flows of the working fluid are represented as:

$$s = \frac{q}{T}.$$

15. In the final form, the following expression was obtained for the exergetic efficiency of WPE:

$$\eta_{wpe} = 1 - \frac{E_{hpa} + E_{lpg} + E_\phi}{E_{lpa} + E_{hpg} + E_r} = 1 - \frac{G_{hpa} \cdot e_{hpa} + G_{lpg} \cdot e_{lpg} + \phi \cdot e_{hpa}}{G_{lpa} \cdot e_{lpa} + G_{hpg} \cdot e_{hpg} + r_{og} \cdot e_{hpg}} =$$

$$= 1 - \frac{G_{hpa} \cdot \left[e_{hpa} + \cdot \left(1 + {}^{1}\!/\!_{l_0} + \psi\right) \cdot e_{lpg} \right] + \phi \cdot e_{hpa}}{G_{hpa} \cdot \left[(\psi + 1) \cdot e_{lpa} + \left(1 + {}^{1}\!/\!_{l_0}\right) \cdot e_{hpg} \right] + r_{og} \cdot e_{hpg}} =$$

$$= 1 - \frac{\left[(1 + r_{og}) \cdot e_{hpa} + \left(1 + {}^{1}\!/\!_{l_0} + \psi\right) \cdot e_{lpg} \right]}{\left[(\psi + 1) \cdot e_{lpa} + \left(1 + {}^{1}\!/\!_{l_0} + r_{og}\right) \cdot e_{hpg} \right]} =$$

$$= 1 - \frac{\left[(1 + r_{og}) \cdot i_{hpa} + \left(1 + {}^{1}\!/\!_{l_0} + \psi\right) \cdot i_{lpg} - T_0 \cdot \left\{ (1 + r_{og}) \cdot s_{hpa} + \left(1 + {}^{1}\!/\!_{l_0} + \psi\right) \cdot s_{lpg} \right\} \right]}{\left[(\psi + 1) \cdot i_{lpa} + \left(1 + {}^{1}\!/\!_{l_0} + r_{og}\right) \cdot i_{hpg} - T_0 \cdot \left\{ (\psi + 1) \cdot s_{lpa} + \left(1 + {}^{1}\!/\!_{l_0} + \psi + r_{og}\right) \cdot s_{hpg} \right\} \right]}.$$

16. End of calculation.

Fig. 3 shows a mathematical model of operation in the form of a block diagram of the algorithm for calculating the exergetic efficiency of WPE.

The numbering of the positions in the calculation algorithm for assessing the exergetic efficiency of WPE coincides with the numbering of positions shown in the block diagram of the calculation algorithm (Fig. 3).

The calculation and experimental study of assessing the exergetic efficiency of WPE was carried out on a 4ChN 12/14 tractor diesel engine under the maximum torque mode at n=1200 min^{-1}.

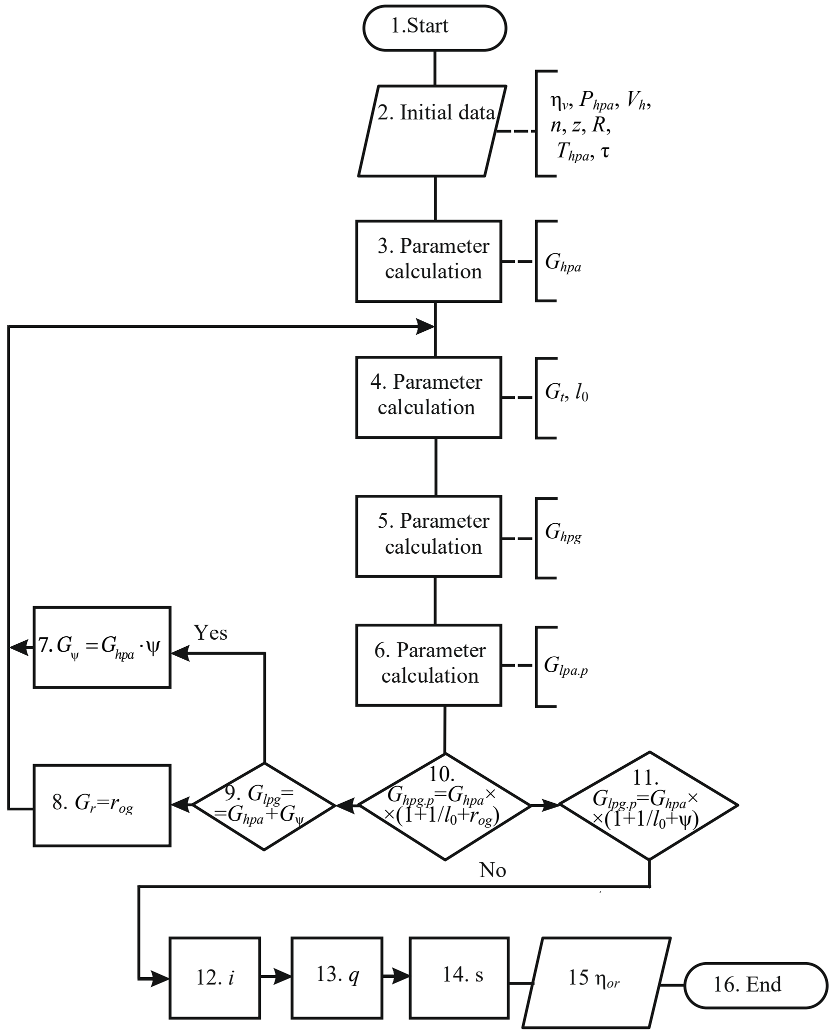

Fig. 3. Block diagram of the algorithm for calculating the exergetic efficiency of WPE

Fig. 4 shows the exergetic efficiency values for the maximum torque mode of an engine with a pressure exchanger. The purge coefficient varied in the range from 0 to 12 %, and partial exhaust gas recirculation accordingly varied in the range from 0 to 5 %.

Based on our calculation and experimental studies, it was found that the value of the exergetic efficiency of WPE is jointly influenced by both exhaust gas recirculation and purging of the rotor channels with a fresh charge.

At small values of r_{og} and ψ, the efficiency of WPE has low values, not exceeding 0.46 (section 1).

Purging ψ of the rotor cells was carried out in the range from 0.2 to 0.08. It was found that with a decrease in purging less than 0.4, a decrease in the values of the WPE efficiency to 0.728 is observed (section 2).

With a rational increase in the values of purging and exhaust gas recirculation, the efficiency of WPE sharply increases and reaches maximum values equal to 0.91 (section 3).

It is also noted that if the values of recirculation and purging begin to exceed the limit values of the given ranges, then the value of the exergetic efficiency of WPE practically does not change, it is a constant value, and their values do not exceed 0.91 (section 4).

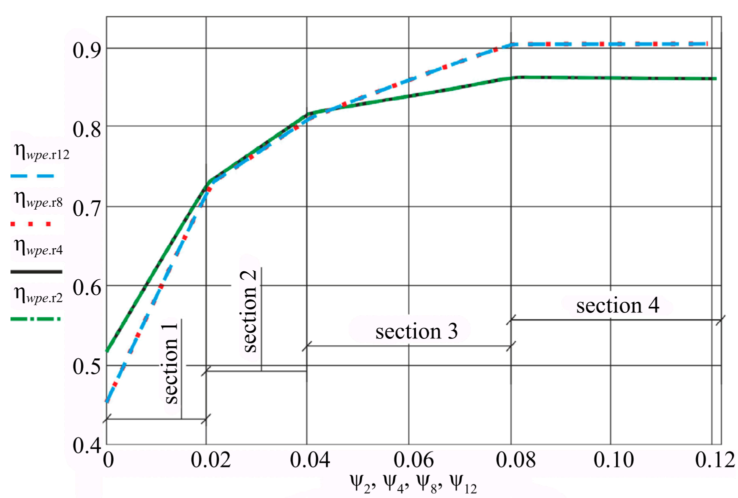

Fig. 4. Evaluation of the efficiency of the exergetic efficiency of WPE depending on the change in the intensity of purging the rotor cells with a fresh charge and recirculation of exhaust gases:
— values of four plots $\eta_{wpe.r2}$, $\eta_{wpe.r4}$, $\eta_{wpe.r.8}$ and $\eta_{wpe.r.12}$ of the exergetic efficiency of WPE with different degrees of recirculation;
— fixed values of recirculation with exhaust gases r_{og2}, r_{og4}, r_{og8} and r_{og12};
— purging the rotor channels of WPE with a fresh atmospheric air charge in nodal places ψ_2=0.02, ψ_4=0.04, ψ_8=0.08 and ψ_{12}=0.12 in different areas

To improve the efficiency of the working process of gas-dynamic machines, special "pockets" are used, shown in the form of a sweep in Fig. 5 [17].

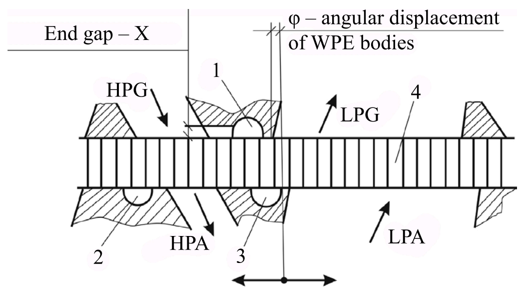

Fig. 5. Schematic (supercharger sweep along the average rotor diameter) of WPE with adjustment pockets: 1 — gas pocket, made in the gas casing; 2 — preliminary compression pocket; 3 — purge pocket, located in the air casing; 4 — sweep of the WPE rotor; HPG, HPG, HPA, LPA — directions of movement of working media flows in the channels

The operation of the "pre-compression" pocket causes the formation of a series of additional waves that improve the efficiency of the process of formation, compaction, and compression of the air charge in the cells of the WPE rotor.

The joint operation of the "gas" and "purge" pockets creates the formation of a series of additional compression waves that enhance the effect of the main compression waves, superimposing on them, thereby improving the efficiency of the process of filling and purging the rotor cells with a fresh charge, and also causes partial recirculation of combustion products in the supercharger.

Additional regulation of the air charge is ensured by angular displacement of the edges of the "purge" pocket of the air housing relative to the "gas" pocket of the gas housing by an angle φ (Fig. 4). The process of regulating the purging ψ of the rotor cells with a fresh charge is directly proportional to the angular displacement φ of the edges of the pockets of the air housing relative to the gas housing.

The change in the flow of exhaust gas recirculation in the supercharger is provided by means of a special end gap X (Fig. 5), made on the end surface of the front bridge of the "gas" pocket, located closer to the HPG channel in the gas body of WPE. The process of exhaust gas recirculation r is directly proportional to the value (magnitude) of the special end gap X, made on the bridge of the gas body.

6. Discussion of the method for assessing performance of the exergetic efficiency of a wave exchanger

The main results of our method development can be presented as follows:

– in the diagram of the outflow of gas-air flows in the supercharger, shown in Fig. 1, places (zones) are selected in the flow sections of the channels of the air and gas housings, in which the values of the parameters of WPE are determined using measuring equipment, including taking into account the recirculation of the exhaust gases and the purging of the rotor cells;

– in the diagram of the exergy balance flows in the WPE units, shown in Fig. 2, we indicated the redistribution of the flow of supplied exergy of exhaust gases E_{hpg}, the latter is converted to perform usable work on filling and compressing the air in the units of the supercharger unit, taking into account the implementation of recirculation of the exhaust gases and the purging of the rotor cells;

– a calculated and experimental assessment of the exergetic efficiency of WPE was carried out taking into account the purging of the rotor cells with fresh air and partial recirculation of the exhaust gas, in order to improve the performance of the supercharger unit.

Based on the numerical data of the array taken from the calculation and experimental method, graphical dependences of the exergetic efficiency of WPE were constructed, which are explained in Fig. 4, which shows four curves of the values of the exergetic efficiency of WPE, each curve is conditionally divided into 4 sections.

Curve $\eta_{wpe.r2}$ (green, indicated by a dashed – dotted line) represents the dependence of the exergetic efficiency of WPE on fixed values of exhaust gas recirculation, which changes in all 4 sections in a very narrow range $r_{og2}=0–0.0015\cdot G_{hpg}$ (no recirculation), and the purging of the rotor cells:

– in section 1 it is very small, it changes in the range $\psi_0–\psi_2=0–0.02$; therefore, the efficiency is also very small and changes in the range $\eta_{wpe.r2}=0.52–0.73$;

– in section 2, it is average, respectively, equal to $\psi_2–\psi_4=0.02–0.04$; and the efficiency, with some improvement in purging, increased its values and began to change within the range of $\eta_{wpe.r2}=0.73–0.82$;

– in section 3 it is high, changing in the range $\psi_4–\psi_8=0.04–0.08$; and the efficiency has not changed and remained within the previous limits $\eta_{\text{вод}.r2}=0.73–0.82$;

– in section 4 it is very high, changing in the range $\psi_4–\psi_8=0.08–0.12$; the efficiency has improved somewhat and changes in the range $\eta_{wpe.r2}=0.82–0.86$, has not reached maximum values due to the lack of effective recirculation.

The curve $\eta_{wpe.r4}$ (black, indicated by a solid line) represents the dependence of the exergetic efficiency of WPE on fixed values of exhaust gas recirculation, which changes in all 4 sections in a narrow range $r_{og4}=0{,}0015–0{,}01\cdot G_{hpg}$ (very poor recirculation), and the purging of the rotor cells:

– in section 1, very little purging, in the range $\psi_0–\psi_2=0–0.02$; the efficiency is also low and changes in the range $\eta_{wpe.r4}=0.52–0.73$;

– in section 2, average purging, changes in the interval $\psi_2–\psi_4=0.02–0.04$; and the efficiency has improved somewhat and changes within $\eta_{wpe.r4}=0.73–0.82$;

– in section 3 there is high purge, which varies in the range $\psi_4–\psi_8=0.04–0.08$; accordingly, the efficiency has also improved somewhat and varies in the range $\eta_{wpe.r4}=0.73–0.85$ and has not reached maximum values due to the lack of effective exhaust gas recirculation;

– in section 4, the purging is very high, it changes in the range $\varphi_8–\varphi_{12}=0.08–0.12$; the efficiency has improved slightly and changes in the range $\eta_{wpe.r4}=0.85–0.86$ but has not reached its maximum values due to insufficient partial exhaust gas recirculation.

The $\eta_{wpe.r8}$ curve (red, marked with dots) represents the dependence of the exergetic efficiency of WPE on fixed values of exhaust gas recirculation, which changes in all 4 sections in a wide range $r_{og8}=0.01–0.03\cdot G_{hpg}$ (effective recirculation), and the purging of the rotor cells:

– in section 1, the purging is very low, it changes in the range $\psi_0–\psi_2=0–0.02$; the efficiency is very low, it changes in the range $\eta_{wpe.r8}=0.45–0.73$;

– in section 2 – average purging, it changes in the range ψ_2–ψ_4=0.02–0.04; efficiency has increased, it changes in the range $\eta_{wpe.r8}$=0.73–0.82;

– in section 3 – high purging, changes in the range ψ_4–ψ_8=0.04–0.08; efficiency has increased sharply, it changes in the range $\eta_{wpe.r4}$=0.82–0.89; due to the favorable combination of 5 % purging and 3 % recirculation, the efficiency of WPE has very high values;

– in section 4 – very high purging, it changes in the range ψ_8–ψ_{12}=0.08–0.12; efficiency changes in the range $\eta_{wpe.r8}$=0.89–0.90; with very high purging of the rotor with a fresh charge over 8 % and recirculation of 3 %, the efficiency of WPE increases slightly.

The curve $\eta_{wpe.12}$ (blue color, indicated by the dotted line) represents the dependence of the exergetic efficiency of WPE on fixed values of exhaust gas recirculation, which changes in all 4 sections in a fairly wide range r_{og12}=0,03–0.05·G_{hpg} (excessively high recirculation), and the purging of the rotor cells:

– in section 1 – very low purging, changes in the range ψ_0–ψ_2=0–0.02; the efficiency is very low, it changes in the range $\eta_{wpe.r12}$=0.46–0.73;

– in section 2 – average purging, it changes in the range ψ_2–ψ_4=0.02–0.04; the efficiency has sharply increased, it changes in the range $\eta_{wpe.r12}$=0.73–0.82;

– in section 3 – high purging of rotor cells, changes in the range ψ4–ψ8=0.04–0.08; the efficiency correspondingly changes in the range $\eta_{wpe.r12}$=0.82–0.90. That is, with a favorable combination of 8 % purging and 5 % recirculation, the efficiency of WPE has very high values;

– in section 4 – very high purging of rotor cells, ψ_8–ψ_{12}=0.08–0.12; the efficiency correspondingly changes in the range $\eta_{wpe.r12}$=0.90–0.91. However, with excessively high purging of the rotor with fresh charge over 10 % and recirculation of 5 %, the efficiency of WPE increased slightly.

The results of our studies show that it is most preferable to operate the supercharging unit using the range of section 3 (Fig. 4), where the highest level of change in the values of the exergetic efficiency of WPE is observed, which vary within the range of $\eta_{wpe.r8}$=0.82–0.90 (section 3).

For comparison, using the well-known method [15], an expression for the exergetic efficiency of WPE is given, which takes into account the exergy dependences that make it possible to judge the degree of reversibility of processes inside the unit based on the external characteristic; the latter is accordingly equal to 0.518.

In our method, in section 1 (Fig. 4), when there is no purging ψ_0=0 and no exhaust gas recirculation r_{og2}=0, the exergetic efficiency of WPE $\eta_{wpe.r2}$ is also very low and accordingly equals 0.52. Almost identical results were obtained by absolutely different methods. However, as soon as effective purging and exhaust gas recirculation are performed in the supercharger, the exergetic efficiency of WPE sharply increases to 0.89.

This is confirmed by experimental studies. The increase in the end gap X from 0 to 0.25 mm (Fig. 5) is achieved by step-by-step cutting of metal (with a finger cutter) from the end surface on the front bridge of the "gas" pocket of the WPE gas housing.

When the angular displacement (Fig. 5) changes within the range of φ=0–0.5°, and the end gap is in the range of X=0–0.05 mm, the range of values of purging, recirculation, and exergetic efficiency of WPE corresponds to the data given in section 1 (Fig. 4).

At the angular displacement (Fig. 5), which corresponds to the range of φ=0.5–1.0°, and the end gap varies within the limits of X=0.05–0.125 mm, then the range of values of purging, recirculation, and exergetic efficiency of WPE is similar to the data given in section 2 (Fig. 4).

If the angular displacement (Fig. 5) corresponds to the range of φ=1.0–1.5°, and the end gap fluctuates within the limits of X=0.125–0.15 mm, then the limit of values of purging, recirculation, and exergetic efficiency of WPE corresponds to the data given in section 3 (Fig. 4).

Note that in section 3, using the experimental method with the help of the bench equipment, the range of variation of the most effective operating parameters was recorded: P_{lpa}=0.1–0.098 MPa; P_{hpg}=0.158–0.160 MPa; P_{hpa}==0.159–0.161 MPa; G_{lpa}=252–271 kg/h; G_{hpa}=242–261 kg/h; G_{hpg}=259–278 kg/h; G_{lpg}=268–289 kg/h.

Experimental testing has shown that there is no balance of working fluid consumption in the air and gas parts of the supercharger. Due to recirculation and purging of the rotor cells of WPE, the efficient working process in the units of the supercharger itself is improved. At the same time, the energy indicators of the working process of the 4ChN 12/14 automotive and tractor diesel engine have increased and the environmental indicators of the working process have improved.

Accordingly, when the angular displacement (Fig. 5) corresponds to the range φ=1.5–2.5°, and the end gap varies within the limits X=0.15–0.25 mm, then the range of values of purge, recirculation, and exergetic efficiency of WPE corresponds to the data given in section 4 (Fig. 4).

Unlike existing methods for assessing the exergetic efficiency of WPE, the proposed method additionally uses exhaust gas recirculation and purging of the rotor cells with a fresh atmospheric charge.

Our method for assessing the exergetic efficiency of WPE makes it possible to assess the efficiency of the working cycle of the pressure exchanger with a smaller error and take into account the features of energy exchange in it more fully in comparison with the expressions reported in other technical sources [15]. It can be used both in the early stages of WPE design and for existing modifications of supercharging units, in the process of their further modernization and improvement.

The limiting measure is the exhaust gas recirculation in the WPE channels, which should vary within the range of (0.03…0.05)·G_{hpg}, and the purging of the rotor channels with a fresh charge should not exceed 4–8 % of the low-pressure air flow.

As a disadvantage of the method, it can be noted that the losses in the gaps between the air casing and the rotor, as well as between the rotor and the gas casing of WPE, have not been determined. To solve this problem, it is necessary to design and manufacture a special middle casing with double walls to separate the high-pressure parts from the low-pressure parts and install parameter measurement sensors in them. The main difficulties are determining the parameters of the working fluid in gaps between the rotor and the air, as well as the gas casings of WPE.

7. Conclusions

1. The constructed scheme makes it possible to select the places of outflow of gas-air medium flows in the flow sections of the supercharger units taking into account the purging of the rotor cells with a fresh charge and EG recirculation.

2. A diagram has been built that makes it possible to estimate the redistribution of the flow of supplied exhaust gas exergy E_{hpg}, which is converted to perform various types of usable work associated with filling and compressing the air in the supercharger unit units, as well as the implementation of EG recirculation and purging of the rotor cells with a fresh charge. The technical result has made it possible to solve part of the problem under consideration.

3. Our calculation and experimental assessment of the exergetic efficiency of WPE showed that if the angular displacement corresponds to the range of φ=1.0–1.5°, and the end gap fluctuates within the range of X=0.125–0.15 mm, and the limit of the purging values changes in the range of 4–8 %, respectively, the recirculation values change in the range of 3–5 %, then the values of the exergetic efficiency of WPE are within the range of $\eta_{wpe.r12}$=0.82–0.90, which is the most effective data.

Conflicts of interest

The authors declare that they have no conflicts of interest in relation to the current study, including financial, personal, authorship, or any other, that could affect the study, as well as the results reported in this paper.

Funding

The study was conducted at Department of Internal Combustion Engines of KhNAHU, without financial support.

Data availability

The data will be provided upon reasonable request.

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