Analysis of Efficiency of Rotary Piston Engines Use at Power Plants for Surplus Electrical Energy Accumulation

Mytrofanov O., Proskurin A.
Admiral Makarov National University of Shipbuilding
Mykolaiv, Ukraine

Abstract. This article is devoted to the methods for enhancing the power plants' efficiency in accumulation of a surplus electrical energy obtained using the renewable energy sources. The study is aimed at analyzing the efficiency of perspective power plants for accumulation of the surplus electricity in the form of compressed air based on rotary piston engines. To achieve the goal a comparative analysis of efficiency of diabatic and adiabatic schemes of the electric energy storage was performed. The analysis was found to reveal the major advantages and disadvantages, along with the design features of each type of schemes. The main ways to increase the efficiency of the compressed air storage units, using the rotary piston engines as the electrical energy generators, were established. The experimental operational characteristics of the rotary piston engines showed that they are relevant to the parameters of the power units of air accumulation. The most significant results reveal that the methods for the analysis and of generalization have been used to develop the principal schemes of diabatic and adiabatic power plants for the accumulation of the surplus electrical energy in the form of compressed air using rotary piston engines, which require no additional air heating prior to expansion. The significance of the results obtained is that the use of the rotary piston engines being a part of the diabatic accumulation unit, allowed a complete exclusion of CO_2 emission into the atmosphere.

***Keywords*:** renewable energy sources, power plant, energy accumulator, rotary piston engine, compressed air, heating temperature.
DOI: 10.5281/zenodo.4317046
UDC: 621.438

Analiza eficienței utilizării motoarelor cu piston rotativ pentru centralele electrice pentru acumularea excesului de energie electrică

Mitrofanov A.S., Proskurin A. Iu.
Universitatea Națională de Construcții Navale amiralul Makarov
Nikolaev, Ucraina

Rezumat. În lucrarea se discută modalități de îmbunătățire a eficienței centralelor electrice care acumulează excesul de energie electrică obținută din surse regenerabile de energie. Scopul principal al studiului este de a analiza eficiența centralelor electrice promițătoare pentru acumularea excesului de energie electrică sub formă de aer comprimat pe baza motoarelor cu piston rotativ. Pentru a atinge obiectivul stabilit al studiului, a fost efectuată o analiză comparativă a eficienței schemelor diabatice și adiabatice de acumulare a energiei electrice, care a relevat principalele avantaje și dezavantaje, precum și caracteristicile de proiectare ale fiecăreia dintre scheme. S-au stabilit principalele modalități de creștere a eficienței unităților de stocare a aerului comprimat prin utilizarea motoarelor cu piston rotativ ca generator de energie electrică. Din caracteristicile experimentale prezentate de performanță ale motoarelor cu piston rotativ, rezultă că acestea corespund pe deplin parametrilor centralelor electrice de stocare a aerului. Rezultatul cel mai semnificativ este că, prin metode de analiză și generalizare, au fost elaborate diagrame schematice ale centralelor electrice diabatice și adiabatice pentru acumularea excesului de energie electrică sub formă de aer comprimat utilizând motoare cu piston rotativ care nu necesită încălzire suplimentară a aerului înainte de expansiune. Semnificația rezultatelor obținute constă în faptul că utilizarea motoarelor cu piston rotativ ca parte a unei unități de stocare diabetice a făcut posibilă eliminarea completă a emisiilor de CO_2 în atmosferă, asigurând în același timp eficiența energetică globală a unității la nivelul de 41%. Sunt prezentate ecuațiile de bază ale modelului matematic al ciclului de lucru al unui motor cu piston rotativ.

Cuvinte-cheie: surse de energie regenerabile, centrală electrică, acumulator de energie, motor cu piston rotativ, aer comprimat, temperatura de încălzire.

Анализ эффективности применения роторно-поршневых двигателей для энергетических установок аккумулирования избыточной электрической энергии

Митрофанов А. С., Проскурин А. Ю.
Национальный университет кораблестроения имени адмирала Макарова
Николаев, Украина

Аннотация. В данной статье рассмотрены способы повышения эффективности энергетических установок аккумулирования избыточной электрической энергии, полученной с возобновляемых источников энергии. Основной целью исследования является анализ эффективности перспективных энергетических установок аккумулирования избыточной электрической энергии в виде сжатого воздуха на базе роторно-поршневых двигателей. Для достижения поставленной цели исследования проведен сравнительный анализ эффективности работы диабатической и адиабатической схем аккумулирования электрической энергии, который выявил основные преимущества и недостатки, а также конструктивные особенности каждой из схем. Установлены основные пути повышения эффективности установок аккумулирования сжатого воздуха за счет применения в качестве генератора электрической энергии роторно-поршневых двигателей. Из представленных экспериментальных эксплуатационных характеристик роторно-поршневых двигателей следует, что они в полной мере соответствуют параметрам энергетических установок аккумулирования воздуха. Наиболее существенным результатом является то, что методами анализа и обобщения разработаны принципиальные схемы диабатической и адиабатической энергетических установок аккумулирования избыточной электрической энергии в виде сжатого воздуха с использованием роторно-поршневых двигателей, не требующих дополнительного подогрева воздуха перед расширением. Значимость полученных результатов состоит в том, что применение роторно-поршневых двигателей в составе диабатической установки аккумулирования позволило полностью исключить выбросы CO_2 в атмосферу при обеспечении общей энергоэффективности установки на уровне 41 %. Приведены основные уравнения математической модели рабочего цикла роторно-поршневого двигателя. Представлены результаты математического моделирования рабочего процесса роторно-поршневого двигателя при использовании адиабатической схемы аккумулирования. Согласно представленным результатам исследования, подогрев воздуха перед расширением позволяет повысить эффективность преобразования энергии в роторно-поршневых двигателях. Рост индикаторных показателей при увеличении температуры сжатого воздуха перед расширением на 80ºC составил 11 %, а общая эффективность установки увеличивается до 46 %.

Ключевые слова: возобновляемые источники энергии, энергетическая установка, аккумулятор энергии, роторно-поршневой двигатель, сжатый воздух, температура подогрева.

I. INTRODUCTION

The extensive advance in technological and industrial development gives rise to intense extraction and use of the underground resources, as well as to a high power generation (thermal, electrical, and mechanical). The intense burning of hydrocarbon fuel increases the greenhouse gas concentration in the atmosphere, particularly, that of CO_2 [1]. The growth in the greenhouse gas concentration elevates the average temperature over the planet, which, in its turn, leads to the global climatological disturbances [2, 3]. The deceleration in the increase in the average temperature on the planet can be reached by an abrupt decrease in CO_2 emission into the atmosphere. The reduction in the greenhouse gas concentration can be ensured by lowering the utilization of the underground resources' fuels and using the renewable energy sources. The latter, as well as the energy efficiency enhancement, are the most promising directions in the policy of the European countries [4]. The most extensively used types of the renewable energy sources include wind- and hydroenergy, solar energy, biomass energy and that of convertible domestic wastes, as well as the geothermal energy. Most part of these renewable types of energy sources are found to generate the electrical energy. The convenience of the electrical energy generation consists, first of all, of easy transportation and application. However, the impossibility of the direct storage is the electrical energy significant disadvantage. In addition, the generation of the electrical energy by means of the renewable sources is non-constant and heavily predictable (e.g., the absence of wind, cloudiness), etc.). Thus, a necessity arises to ensure the agreement between the generated and consumable energies. This can be realized using various accumulating systems, which make it possible to convert the surplus energy into other forms, accumulate it or store, or when necessary bring into balance generation and consumption [5–7]. One most essential feature of the energy accumulation system is its capacity for a longterm storage of the accumulated energy and continuity of the return generation [8, 9]. A scheme, composition and, hence, the cost of the accumulation system depend directly on the accumulation energy principle and modes of exploitation. According to the principle of the energy accumulation, the facilities can be divided into mechanical (flywheels, hydraulic and pneumatic accumulators) electrochemical (various kinds of banks of accumulators, hydrogen accumulators, super condensers), electromagnetic (semiconductor inductive energy storage units) and combined devices. Among the above methods for the accumulation of the surplus energy the most promising are: the storage of energy in the form of the compressed air, the CAES (Compressed Air Energy Storage) [9–12]; in the form of the cryogenic liquid, the LAES (Liquid Air Energy Storage) or the CES (Cryogenic Energy Storage) [13–17]; or their combinations at the supercritical air compression – the SC-CAES (Supercritical Compressed Air Energy Storage) [18]. The method for the energy storage in the form of the compressed air is the simplest in realization, it is reliable and safe, however, the EFC of it is lower compared to the LAES and SC-CAES. In [19], a principal scheme of an electrical station is presented, which operates using the compressed air. The technical and economic analyses of its realization have also been performed. A more complicated scheme of a combined wind electrostation, with surplus electrical energy being accumulated in the form of compressed air, and with the use of a biomass gasification energy is described in [20]. The prospects for the use of the compressed air as the surplus electric energy accumulator have been supported by two projects of electrostations, one of which is implemented in Germany (Huntorf) with a nominal power of 110 MW and the other in the USA (McIntosh Alabama) for 290 MW.

In [21, 22], as well as in other works mentioned above aimed at a generation of the electrical energy of the compressed air, the expansion dynamic machines (turbines) are proposed to be used. The application of turbines in the power devices of energy accumulation in the form of the compressed air is conditioned by the necessity to ensure the consumption of high amounts of air and the accumulator discharge almost to zero values. The compressed air expansion in the turbine can cause a substantial temperature decrease (to subzero), which may lead to freezing-up the piece of turbine with flowing water and the air lines. To ensure normal operation of the power device the compressed air heating is necessary to perform prior to the expansion. The air heating is carried out by burning the natural gas, which is also most convenient in the case of the turbine being used. The natural gas used for the heating up of the air in the turbine, decreases substantially the efficiency of the total facility. Thus, for instance, in [23], for the efficiency increase, the thermal energy generated from compression is offered to be utilized for heating the rooms and water. However, the accumulation of the heat that was released from the air compression is most promising to be used for the subsequent compressed air heating before its expansion in the turbine. These schemes of accumulation of the compressed air allow a substantial increase in the efficiency coefficient (EFC) of the power system and are referred to as adiabatic ADELE (der Adiabate Druckluftspeicherfürdie Elektrizitätsversorgung) or ACAES [24–30]. In the works presented, the analysis is absent of a possible use of other simpler types of expansion machines (e.g. those of a volumetric action) in the composition of the power devices for the energy accumulation in the compressed air form.

Our work differs from the above mentioned earlier western works in that it proposes to use a rotary piston engine as an expansion machine, which requires no additional heating of the compressed air prior to its expansion. This makes it possible to simplify the device and cheapen its manufacturing, as well as to refuse the use of a natural gas for the air heating before expansion. Thus, the estimation of the efficiency of the use of the expansion machines of a volumetric type in the energy accumulation schemes is urgent and highly promising.

The purpose of this research is to analyze the characteristics of the power devices for the accumulation of the surplus electrical energy in the form of the compressed air that are manufactured using the rotary piston expansion machines.

II. RESEARCH METHODS

The principle schemes of energy accumulation were plotted by the common methods of analysis and generalization using the rotary piston expansion machines. System analysis of the existing methods and schemes of accumulation of the surplus electrical energy made it possible to reveal and generalize the major advantages and disadvantages, as well as the most promising directions of improvement their efficiency.

The estimation of efficiency of using the rotary piston expansion machines in the schemes of energy accumulation was performed by the method of a mathematical modeling with the use of fundamental equations of thermodynamics, gas dynamics, heat- and mass exchange.

The mathematical model is based on the equation of the first law of thermodynamics for the open thermodynamic system

$$dQ \pm \sum_{1}^{n} i_j dM_j = d(Mu) + pdV, \qquad (1)$$

where dQ is the elementary heat amount supplied to the working body; $\sum_{1}^{n} i_j dM_j$ is the entalpy flux, brought in (+) or carried out (-) with the elementary masses dM_j out of volume V; M is the working body mass in the cylinder; u is the specific internal energy of the working body; p is the working body pressure in the cylinder. After certain formula (1) transformations, we shall obtain a differential equation of the rate change in the cylinder pressure of the rotary piston engine in a generalized form:

$$\frac{dp}{d\phi} = p\left(\frac{\frac{\sum_{1}^{n_1} dI_j}{d\phi}}{c_v TM} - k\frac{d\,lnV}{Vd\phi} - \frac{\sum_{1}^{n_2}\frac{dQ_{\text{ст}i}}{d\phi}}{c_v TM} \right), \qquad (2)$$

where $dQ_{\text{ст}i}$ is the heat exchange with the heat-reception wall surfaces; k is the adiabatic index; dI_j is the elementary entalpy of masses, that enter or leave the working cylinder.

The elementary entalpy of masses, which enter of leave the working cylinder of the rotary piston engine can be determined, using the following formula:

$$\sum_{1}^{n}\frac{dI_j}{d\phi} = \sum_{1}^{n} c_{pmj} T_j \frac{dM_j}{d\phi}, \qquad (3)$$

where c_{pmj} is the average isobaric heat capacity of the working body, entering or leaving the cylinder; T_j is the working body temperature.

The equation of heat exchange with the heat-reception wall surfaces in a general form can be determined according to the following formula:

$$\sum_{1}^{l}\frac{dQ_{\text{ст}i}}{d\phi} = \sum_{1}^{l}\alpha_i F_i \left(T - T_{\text{ст}i}\right)\frac{1}{6n}, \qquad (4)$$

where α_i is the coefficient of heat transfer from the working body to the i-th heat-reception surface; F_i is the area of the i-th surface; $T_{\text{ст}i}$ is the temperature of the i-th heat-reception wall; n is the rotation frequency of the rotor; φ is the variable value of the angle of rotation of the engine rotor.

During $dQ_{\text{ст}i}$ calculation, the coefficient of transfer from air to the heat-reception surfaces, α is determined using the dependence of A. I. Prilutskii [31—34] for the piston and rotary expansion machines:

$$\alpha = \frac{\lambda}{D} A \cdot \left(\frac{\rho \cdot w \cdot D}{\mu}\right)^{0,6} \qquad (5)$$

where λ is the coefficient of thermal conductivity; ρ is the air density; μ is the dynamic viscosity; D is the equivalent diameter of the cylinder; w is the conventional rate of air in the working cylinder; A is the density ratio $A = (\rho_{\text{н.у}} / \rho_{\text{н}})^{0,5}$.

The change in the cylinder volume with respect of the rotation angle of the rotor is determined using the following formula:

$$V(\phi) = V_s\Big(\frac{1}{\varepsilon - 1} + a_0 - [\,a_1 cos(2\phi) + a_2 cos(4\phi) - a_3 cos(6\phi) + a_4 cos(8\phi)]\Big), \qquad 6)$$

where V_s is the cylinder working volume; a_0, a_1, a_2, a_3, a_4 are the coefficients of the harmonic sequence; ε is the degree of compression.

Other components of the above differential equation of the pressure change rate are determined with the use of the commonly known dependences and expressions.

During realization of the mathematical model in the form of a calculation program, a well-known and widespread Weyler's method was used. We shall indicate the major admissions, as well as the initial and boundary conditions that were accepted in the mathematical modeling:

1. The processes in the working cylinder can be considered as quasi-stationary and quasi-equilibrium. This condition can be guaranteed by ensuring a definite ratio between the sizes of the working cylinder and the rotation frequency of

the central rotor. In addition, the parameters of the rotary piston expansion machine affect the admissible value of the selected gain of the angle of rotation of the central rotor $\Delta\varphi$ for each step of integration. Thus, the optimal value of the gain of the rotor angle of rotation is $\Delta\varphi = 1^o$.

2. The composition, uniformity, density, temperature, pressure of the working body before the engine (in the inlet receiver) are constant. This allows accurate initial data to be ensured in modeling.

3. Temperature, pressure and density of the working body (P_s, T_s, ρ_s) at the initial moment of time are relevant to the current value in the cylinder P_i, T_i, ρ_i.

4. When using the compressed air as the working body, the presence of an oil vapor and moisture is insignificant and does not affect the entalpy value and the change in the internal energy of the working body.

5. Pressure changes immediately upon opening inlet or outlet gas exchange apertures.

6. Heat transfer from the working body in the cylinder of the expansion machine occurs at a similar intensity of the process in all directions. Moreover, the possible local change in the heat transfer coefficients and local temperatures is not taken into account, but, rather, mean values are used. The heat transfer coefficient is determined with the use of the independence of A. I. Prilutskii.

7. The losses of the working body through the noncompactnesses of the working cylinder are fairly insignificant and are estimated using the empirical loss coefficient based on the experimental studies performed.

8. The central shaft of the rotary piston expansion machine rotates uniformly without vibrations.

9. Mechanical losses upon the definition of the efficient indices are estimated using the mechanical coefficient of efficiency.

II. THE RESEARCH RESULTS

The application of the system analysis during the development and estimation of the scheme of the power device for the accumulation of the surplus electrical energy in the form of the compressed air is justified by the fact that regardless of a substantial amount of the published sources, the existing systems are not yet sufficiently described. Thus, the information is insufficient or entirely absent on the characteristics of the device elements, as well as on the conditions and peculiarities of their exploitation in the composition of the whole device for the energy accumulation.

The major disadvantage of the power devices' functioning in the electrical energy accumulation based on the compressed air is a low EFC of the energy conversion. This is what creates the problem in practice. The simplest scheme of the energy accumulation in the form of the compressed air is the CAES diabatic scheme with the external heat supply for the air to be heated before its expansion in the turbine.

The main advantages of the system are a fairly high resource of operation, low production and maintenance costs (owing to simplicity), the possibility of the accumulator discharge almost up to zero values, as well as the possibility of accumulation of substantial volumes of energy (e.g., upon the use of the underground hermetically sealed cavities as the air storage reservoirs).

The essential fault of the CAES system is the reduction in the general EFC of the energy conversion caused by the use of air heating supplied by the external source (natural gas burning).

To enhance the efficiency and cheapen the production is possible using the elements of the accumulation system. The compressors and expansion machines are the main elements of the system. The most strict reliability requirements and demands for the efficiency of the energy conversion to ensure the wide range of exploitation, are claimed mostly to the expansion machines. The turbines were mentioned to be used as the expansion machines in the schemes of the energy accumulation. It is the turbines that require the additional external heat supply.

It is noteworthy that the turbine adiabatic EFC depends essentially on the productive capacity and pressure of air at the inlet. It is most urgent, in particular, for the minor-power accumulator devices. Partially, this problem can be solved by using several turbines, which substantially complicates and, accordingly, increases the cost of the power device.

The alternative solution can be the application of the rotary piston expansion engines (Fig. 1). The latter are characterized with the high efficient indicators in the wide range of the operational modes, since their construction includes the advantages both of rotary and piston expansion machines.

The major advantages of the rotary piston expansion engines are the following:

– simple, compact and reliable spool type construction for gas-exchange phase control;

– low relative mass;

– high equilibrium and absence of vibration due to a uniform distribution of cylinders and absence of a crankshaft;

– the ratio of the piston stroke to the cylinder diameter is less than unity (the engine is short stroke), which ensures low values of the piston rate (with the decrease in the piston rate, the inlet pressure losses are reduced, and so does the counter-pressure at the outlet);

– the absence of the dead volume;

– the possibility of control of the operational modes owing to the change in the degree of filling up, rather than in the inlet pressure;

– the engine start in any position;

– a better compression of the operational space compared to the rotary machines, which allows minimization of the compressed air losses at partial operational modes;

– reliable system of lubrication up to –50ºC.

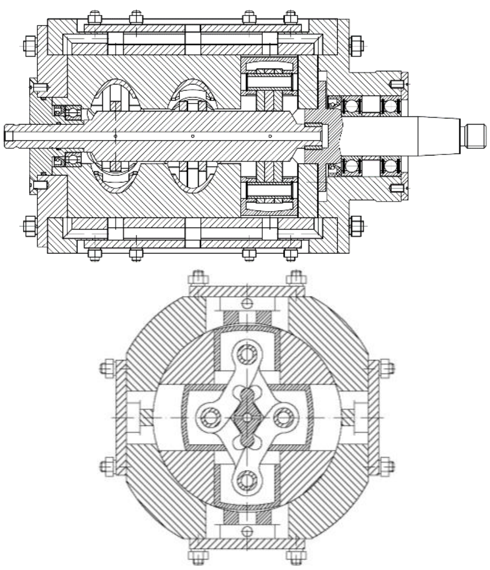


Fig. 1. General scheme of a rotary piston expansion machine.

The change in efficient power N_e and that in rotation torque M_k depending on revolutions n of the rotary piston engine during the operation according to the external characteristic is shown in Fig 2.

The values of the engine parameters are presented in relative units, i.e., with respect to their nominal values.

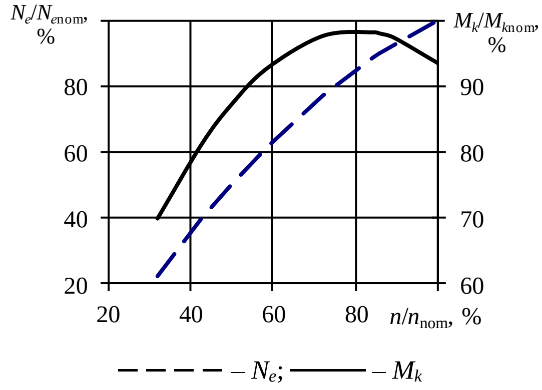


Fig. 2. Change in the relative efficient power N_e and the relative torque M_k of a rotary piston engine when operating on an external characteristic.

In addition, according to the carried out and generalized (by the authors of this work) experiments of the rotary piston engines using different parameters and operational modes, this type of engines under the positive value of the compressed air storage requires no additional preheating prior to expansion (Fig. 3). Moreover, the rotary piston engine system of lubrication can ensure a normal stable work of the engine up to –50ºC. Thus, in accordance with the testing data, the minimum temperature is in the range of –7…–25ºC and depends, in the first place, on the revolutions of the rotary piston engine (the air stream rate).

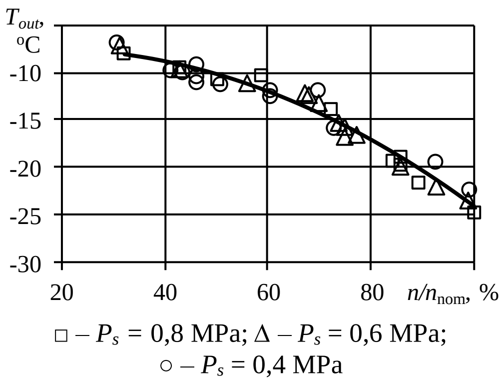
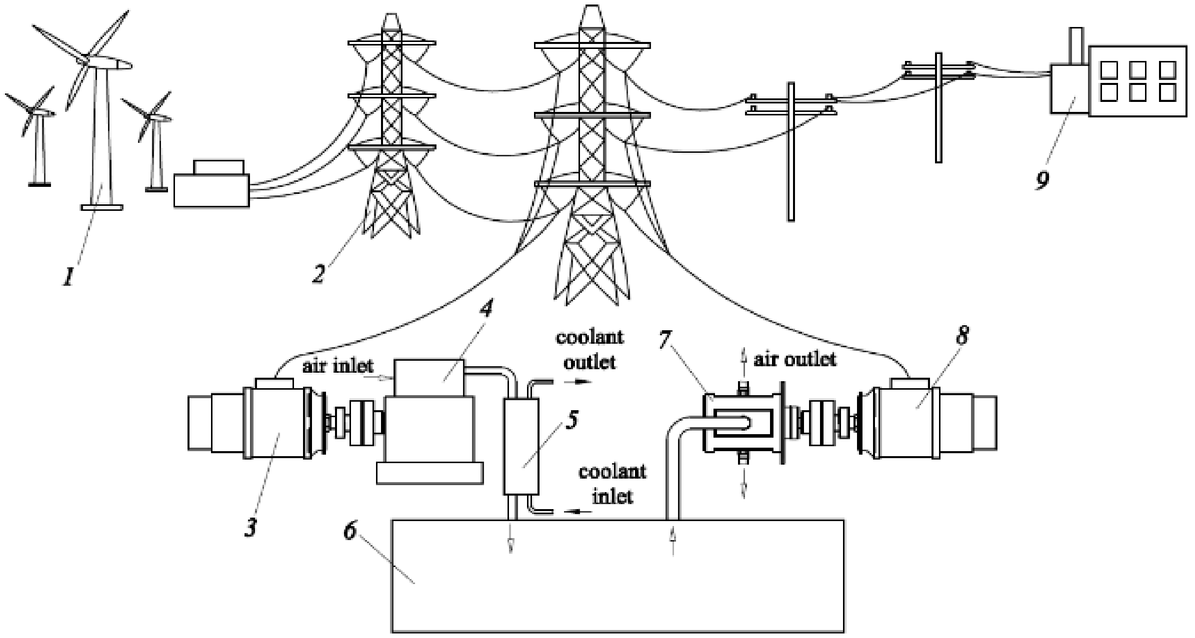


Fig. 3. Change in the temperature of the exhaust air out of a rotary piston engine according to the rate characteristic for different values of the working pressure Ps.

The experimental studies were carried out using the small-size rotary piston machines with a work volume from 116 cm^3 to 535 cm^3, the ratio of the piston stroke to the cylinder diameter of 0.39–0.44 and the relative mass of 1.6–3 kg/kW. The operating pressure in the inlet receiver was 0.4–2.0 MPa. The rotation frequency of the rotor varied in the range of 400–

2200 rot/min. The effective power of the tested engines was 1–20 kW.

Figure 4 shows the scheme of the power device for accumulation of the surplus electrical energy in the form of the compressed air. The electrostation scheme in (Fig. 4) is the simplest and cheapest scheme for manufacturing and accumulation of the electrical energy (CAES). It is noteworthy that this electrostation has the essential distinction from those existing, namely, it lacks the compressed air heating before expansion, which is reached by the use of the rotary piston engines.



1 – the source of electrical energy; 2 – the high-voltage power lines; 3 – the electric motor; 4 – the air compressor; 5 – the air cooler; 6 – the compressed air accumulator; 7 – the rotary piston engine; 8 – the electrical current generator; 9 – the consumer of electrical energy

Fig. 4. General scheme of a wind power station with a system of diabatic accumulation of surplus electrical energy.

According to the works [10, 11, 30], the efficiency of the CAES devices with the use of turbines and natural gas for the air heating prior to the expansion is up to 33.3–55.0 %. Moreover, the natural gas burning is accompanied by the release of CO_2 into the atmosphere. It is noteworthy that the presented EFC values are the efficiency of a complete cycle of the energy conversion. However, the works lack the information on the accounting treatment of the losses and the EFC calculation. In this context, the comparison and estimation of the efficiency of the energy conversion appears to be extremely problematic, and it can be performed just in the first approximation.

A preliminary estimation of the efficiency of the energy conversion for the proposed scheme can be performed by comparison of the energy consumptions for the generation of 1 kW of the electrical energy.

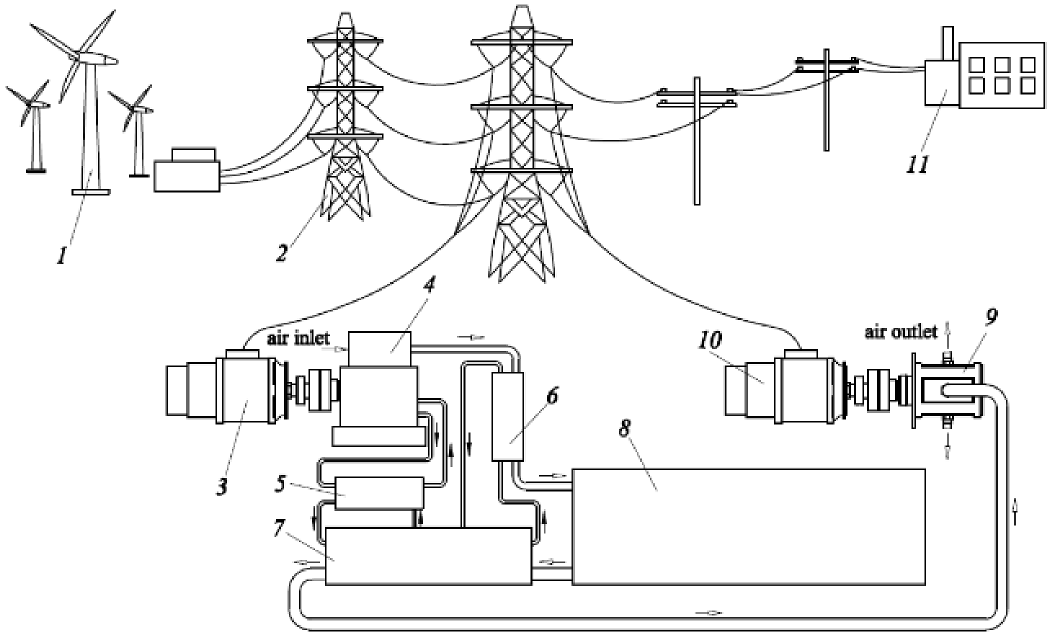
Thus, according to the known data for the finite generation of 1 kW of the electrical energy, at the electrostation with the power of 110 MW (Huntorf, Germany) [9], it is necessary to consume 0.8 kW of the electrical energy (needed for the compressed air) and 1.6 kW of thermal energy supplied with the natural gas (in terms of the lowest heating capacity). In this case, the electrostation coefficient of efficiency is 41.6 %.

According to the test data, in the absence of control of the degree of filling up and heating of the compressed air at the inlet (the most unfavourable conditions of exploitation), the effective EFC of the rotary piston engine is 0.41. Correspondingly, if the energy consumptions for the accumulation of the compressed air are accepted to be equal and the losses at the storage in both devices are assumed to be equal too, then the efficiency of the proposed device will almost be at the same level (41 %). Moreover, the absence of the natural gas burning will set to zero CO_2 release. The absence of the natural gas in the cycle of the electrical energy generation, reduces substantially the total power of the electrostation (by 66.7 %), at other conditions being equal in accumulation of the compressed air. The energy drop in the power device is compensated by the absence of the natural gas application and reaching the entire ecological compatibility of the device. Thus, a compromise is reached between the power, economic and ecological factors of the power device. Similar compromises are justifiable, and they are applied fairly often in the engine building [35, 36].

In order to ensure equal capacities and duration of electricity generation of a standard CAES and the proposed device, it is necessary to enlarge the reserve of the compressed air, as well as to increase the size of the expansion machine.

The use of the adiabatic systems with turbines allow increasing the efficiency of the energy conversion up to 70 % compared to that of the diabatic, which is confirmed by the energy devices' projects [24–30].

The application of the heat compression for heating the air before expansion will also make it possible to enhance the efficiency of the operation of the rotary piston expansion machine. Figure 5 shows the scheme of the power device for accumulation of the surplus electrical energy in the form of the compressed air of the adiabatic type. In the scheme presented, the heat released during the air compression is collected in a special thermal accumulator and at a discharge of the air accumulator, the heat is supplied to the compressed air prior to its expansion.



1 – the source of electrical energy; 2 – the high-voltage power lines; 3 – the electric motor; 4 – the air compressor; 5 – the compressor cooler; 6 – the air cooler; 7 – the heat accumulator; 8 – the compressed air accumulator; 9 – the rotary piston engine; 10 – the electric current generator; 11 – the consumer of electrical energy.

Fig. 5. General scheme of a wind power station with a system for adiabatic accumulation of excess electrical energy.

The increase in the compressed air temperature ensures increasing in the indicator indices of the rotary piston expansion machine.

The mean value of temperature of the compressed air heating in the modeling process was chosen to be 80°C. Figure 6 shows the change in the indicator diagram upon the increase in the compressed air temperature prior to the expansion in the working cylinder.

Also, the adiabatic scheme use makes it possible to decrease the volume of the compressed air accumulator itself or to increase the duration of the electrical energy generation, which is particularly urgent for the accumulator with a relatively low power.

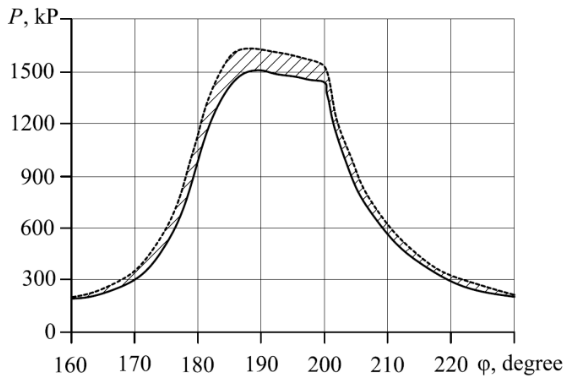


Fig. 6. Fragments of indicator diagrams of a rotary piston engine at different temperatures of compressed air at the working cylinder inlet.

However, it is noteworthy that in addition to the complication of the construction of the power device for the energy accumulation, there is another significant disadvantage in the adiabatic scheme, namely, the EFC drop in the energy conversion during the comparatively long and unstable cycles of charging and discharging of the accumulator. In the first place, this results from cooling of the thermal accumulator. Therefore, the application of the adiabatic scheme of accumulation is more urgent for the power devices with low energy, e.g., up to 500 kW.

IV. CONCLUSIONS

The performed research allowed defining the possible and promising use of the rotary piston expansion machine as a generator drive of the electrical current in the power devices for the accumulation of the compressed air. It was established that the operational characteristics of the rotary piston expansion machines (rate characteristics and minimum cycle temperature) are relevant to the parameters of the power devices for the air accumulation.

The use of the rotary piston expansion engines in the composition of the accumulation diabatic device made it possible to refuse the natural gas burning for the heating of air before its expansion on conserving the total power efficiency of the device at the level of 41 %. The absence of the supplied energy in the form of the burnt natural gas decreases the general energy of the power device by 66.7 %. The decrease in the total energy is compensated by the reduction of CO_2 release to zero, i.e., in fact, it makes this device ecologically pure, which is a certain compromise between the power, economic and ecological indicators. Under conditions of the proposed accumulation scheme, it is possible to substantially enhance the power of the electrical generation just by increasing the compressed air volumes.

The modeling of the operational process of the rotary piston expansion engine using the accumulation adiabatic scheme showed that in conditions of a fixed air reserve, the compressed air temperature increase prior to the expansion by 80oC increases the indicator indices by 11 %. In addition, the efficiency of the device for the accumulation of the compressed air increases to 46 %.

Promising is a further study of the characteristics of the adiabatic power devices for the electrical energy accumulation using the rotary piston expansion machines for different generated power, as well as the operational modes (charge and discharge cycles). The research of the possibility of application of the rotary piston expansion machines in the LAES, CES and SC-CAES devices is also of practical interest.

References

[1] Henderson R. M., Reinert S.A., Oseguera M. *Climate Change in 2020: Implications for Business.* Harvard business school, 2020, № 9-320-087, pp. 1-27.

[2] Burck Jan, Hagen Ursula, Höhne Niklas, Nascimento Leonardo, Bals Christoph. *Climate Change Performance Index.Results 2020.*Germany: Germanwatch, New Climate Institute & Climate Action Network, 2019. 32 p.

[3] Masson-Delmotte, V., P. Zhai, H.-O. Pцrtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Pйan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield (eds.). *Global Warming of 1.5°C.* Intergovernmental Panel on Climate Change, 2019. 616 p.

[4] Pathways to Sustainable Energy: Accelerating Energy Transition in the Economic Commission for Europe. 2019, ECE/ENERGY, 1.

[5] Zakeri, B., Syri, S. *Electrical energy storage systems: A comparative life cycle cost analysis*. Renew. Sustain. Energy Rev., 2015, 42, pp. 569-596.

[6] Geng X., Zhu Q., Guo H., Duan C., Cui H. *Energy storage technology and application in Power system*. Smart Grid, 2016, 4, pp. 54-59.

[7] Luo X., Wang J., Dooner M., Clarke J. *Overviewof current development on electrical energy*

storage technologies and application potential in power system operation. Appl. Energy 2015, 137, pp. 511-536.

[8] Sameer H., Johannes L. *A review of large-scale electrical energy storage*. Int. J. Energy Storage, 2015,39, pp. 1179-1195.

[9] Budt M., Wolf D., Span R., Yan, J. *A review on compressed air energy storage: Basic principles, past milestones and recent developments*. Applied Energy, 2016, 170, pp. 250-268. doi:10.1016/j.apenergy.2016.02.108.

[10] Wang Jidai, Lu Kunpeng, Ma Lan, Wang Jihong, Dooner Mark, Miao Shihong, Li Jian, Wang Dan, *Overview of compressed air energy storage and technology development*. *Energies*, 2017 10, 991, pp. 1-22. doi:10.3390/en10070991.

[11] Venkataramani G., Parankusam P., Ramalingam V., Wang J. *A review on compressed air energy storage – A pathway for smart grid and polygeneration.* Renew. Sustain. EnergyRev. 2016, 62, pp. 895-907.

[12] Yao E., Wang H., Wang L., Xi G., Marechal F. *Thermal-economic optimization of a combined cooling, heating and power system based on small-scale compressed air energy storage*. EnergyConvers. Manag. 2016, 118, pp. 377-386.

[13] Morgan R., Nelmes S., Gibson E., Brett G. *Liquid air energy – Analysis and first results from a pilot scale demonstration plant*. Appl. Energy, 2015, 137, pp. 845–853.

[14] Morgan R. *Liquid air energy storage – From theory to demonstration*. Int. J. Environ. Stud. 2016, 73, pp. 469-480.

[15] Kantharaj D., Garvey S., Pimm A. *Compressed air energy storage with liquid air energy capacity extension*. Appl. Energy 2015, 157, pp. 152-164.

[16] Pimm A.J., Garvey S.D., Kantharaj B. *Economic analysis of a hybrid energy storage system based on liquid air and compressed air*. J. EnergyStorages 2015, 4, pp. 24-35.

[17] Ameel B., TJoen C., Kerpel K., Jaeger P., Huisseune H., Belleghem M.V., Paepe M.D. *Thermodynamic analysis of energy storage with a liquid air Rankine cycle*. Appl. Ther. Eng. 2013, 52, pp. 130–140.

[18] Guo H., Xu Y., Chen H., Zhou X. *Thermodynamic characteristics of a novel supercritical compressed air energy storage system*. Energy Convers. Manag. 2016, 115, pp. 167–177.

[19] Liu C., Xu Y., Hu S., Chen H. *Techno-economic analysis of compressed air energy storage power plant*. EnergyStorageSci. Technol., 2015, 4, pp. 158-168.

[20] Diyoke Chidiebere, Aneke Mathew, Wang Meihong, Wu Chunfei *Techno-economic analysis of wind power integrated with both compressed air energy storage (CAES) and biomass gasification energy storage (BGES) for power generation*. The Royal Society of Chemistry *(RSC Adv.)*, 2018, 8, pp. 22004-22022. doi: 10.1039/c8ra03128b.

[21] Zhao P., Gao L., Wang J., Dai, Y. *Energy efficiency Analysis and Off-design Analysis of Two Different Discharge Modes for Compressed Air Energy Storage System Using Axial Turbines.Renew.* Energy, 2016, 85, 1164-1177.

[22] Y. Zhang, K. Yang, X. Li, J. Xu, *Thermodynamic analysis of energy conversion and transfer in hybrid system consisting of wind turbine and advanced adiabatic compressed air energy storage*, Energy, 2014, vol. 77, pp. 460-477.

[23] H. Safaei and M. J. Aziz, [Thermodynamic analysis of a compressed air energy storage facility exporting compression heat to an external heat load], *Proceedings of ASME 201412thBiennial Conference on Engineering Systems Design and Analysis*. Copenhagen, Denmark, 2014, pp. 1-10. doi:10.1115/ESDA2014-20412

[24] Sciacovelli A., Li Y., Chen H., Wu Y., Wang J., Garvey S., Ding, Y. *Dynamic simulation of Adiabatic Compressed Air Energy Storage (A-CAES) plant with integrated thermal storage – Link between components performance and plant performance.*AppliedEnergy, 2017, 185, pp. 16-28. doi:10.1016/j.apenergy.2016.10.058.

[25] Guo Z., Deng G., Fan Y., Chen G. Performance optimization of adiabatic compressed air energy storage with ejector technology. *Applied Thermal Engineering*, 2016, 94, pp. 193-197. doi:10.1016/j.applthermaleng.2015.10.047.

[26] Grazzini G., Milazzo A., *A thermodynamic analysis of multistage adiabatic CAES*, Proc. IEEE, 2012, vol. 100, no. 2, pp. 461-472.

[27] Hartmann N., Vöhringer O., Kruck C., Eltrop L., *Simulation and analysis of different adiabatic Compressed Air Energy Storage plant configurations*, Appl. Energy, 2012, vol. 93, pp. 541-548.

[28] Barbour E., Mignard D., Ding Y., Li Y., *Adiabatic Compressed Air Energy Storage with packed bed thermal energy storage*, Appl. Energy, 2015, vol. 155, pp. 804-815.

[29] Yang K., Zhang Y., Li X., Xu J., *Theoretical evaluation on the impact of heat exchanger in Advanced Adiabatic Compressed Air Energy Storage system*, Energy Convers. Manag., 2014, vol. 86, pp. 1031-1044.

[30] Mei S., Wang J., Tian F., Chen L., Xue X., Lu Q., Zhou Y., Zhou X. *Design and engineering implementation of non-supplementary fired compressed air energy storage system: TICC-500*. Sci. China. 2015, 58, pp. 600-611.

[31] Priluckij A.I. *Razvitieteorii, metodovraschetaioptimalnogoproektirovaniyaporshnevyhkompressornyhirasshiritelnyhmashin*. Diss. dokt. tehn. nauk [Development of theory, calculation methods and optimal design of reciprocating compressor and expansion machines.Dr. technical sci. diss.]. St. Petersburg, 2015. 278 p.

[32] Priluckij I.K., Priluckij A.I. Korotkaya I.P., Kornev V.V., Molodov M.A., Galyaev P.O., Snazin A.A. Analiz processov teploobmena v stupeni vysokooborotnogo porshnevogo detandera [Analysis of heat transfer processes in a high-speed piston expander stage]. *Nauchnyj zhurnal NIU ITMO. Seriya «Holodilnaya tehnika i kondicionirovanie» – Scientific journal of NRU ITMO. «Refrigeration and Air Conditioning Series»*, 2015, no.2, pp. 81-91. (InRussian).

[33] Priluckij A. I., Priluckij I. K., Ivanov D. N. Teploobmen v stupenyah mashin obyomnogo dejstviya. Sovremennyj podhod [Heat transfer in steps of positive displacement machines. Modern approach]. *Kompressornaya tehnika i pnevmatika – Compressor technology and pneumatics*, 2009, no. 2, pp. 16-23. (In Russian).

[34] Priluckij A.I., Priluckij I.K., Demakov A.S. Analiz processov teploobmena v stupeni porshnevogo kompressora na osnove raschetnyh ciklov v T-s i h-m koordinatah. [Analysis of heat transfer processes in a piston compressor stage based on calculation cycles in T-s and h-m coordinates].*Kompressornaya tehnika i pnevmatika – Compressor technology and pneumatics*, 2009, no. 1, pp. 14-18. (In Russian).

[35] Romanov V.A., Kukis V.S. Povyshenie moshnostnyh, ekonomicheskih i ekologicheskih pokazatelej porshnevyh DVS putem ispolzovaniya sistem akkumulirovaniya energii [Increasing the power, economic and environmental performance of reciprocating internal combustion engines by using energy storage systems]. *Dvigateli vnutrennego sgoraniya – Internal combustion engines*, 2007, no. 1, pp. 53-56.

[36] Romanov V.A., Kukis V.S. Ispolzovanie dvigatelya stirlinga dlya utilizacii "otbrosnoj" teploty silovyh i teplogeneriruyushih ustanovok [Using a Stirling Engine to Recycle Waste Heat from Power and Heat Generating Units]. Aviacionno-kosmicheskaya tehnika i tehnologiya – Aerospace engineering and technology, 2009, no. 8 (65), pp. 148-152.

Information about authors.

Mytrofanov Oleksandr Sergeyevich
PhD, Associate Professor of Department of Internal Combustion Engines, Plants and Operation
Research interests: engines of unconventional schemes, alternative fuels, waste energy utilization.
E-mail: Mitrofanov.al.ser@gmail.com
ORCID: 0000-0003-3460-5369

Proskurin Arkadii Yuryevich
PhD, Associate Professor of Department of Internal Combustion Engines, Plants and Operation
Research interests: engines of unconventional schemes, alternative fuels, waste energy utilization.
E-mail: arkadii.proskurin@nuos.edu.ua
ORCID: 0000-0002-5225-6767