

Design of Thermoelectric Generators for Oil and Gas Production Systems

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Abstract

The article focuses on the ways to reduce energy costs at oil and gas production facilities. The ways for efficient conversion of compressed gas energy into thermal energy are studied. Authors focus on R&D efforts in respect of thermoelectric generators for hydrocarbons production and processing systems. Creation of new environmentally friendly technologies requires designing new special equipment, which will be more sophisticated in production and operation, and have less weight and lower cost. Generation of thermal energy from the compressed gas energy is broken down into several phases. At the beginning of the cycle, the potential energy of gas is converted into kinetic energy. The gas is channeled to the turbine where the kinetic energy of the gas is converted into mechanical energy. The mechanical energy is transmitted through the turbine shaft to the rotor of the hydraulic machine. A pump performs the role of the hydraulic machine; such a hydraulic machine converts the mechanical energy into the hydraulic energy, generating a fluid flow, which serves as the coolant. When the fluid circulates in a closed circuit, the hydraulic energy is converted into the thermal energy, which is accompanied by the coolant's heating. The energy conversion chain includes elements of an electromagnetic system; the efficiency of this approach is confirmed by relevant estimations and laboratory tests. A new concept of a thermoelectric generator for oil and gas production systems is suggested.

Keywords: Electromagnetic System, Energy Conversion, Engineering, Gas, Hydrocarbon Production, Oil, Research, Rotating Object, Thermoelectric Generator

1. Introduction

Reduction in energy costs at production facilities is a relevant issue for the oil and gas industry. The existing technological achievements provide obvious opportunities for efficient conversion of compressed gas energy into electricity and thermal energy. Prospective R&D efforts focus on the design of thermoelectric generators for hydrocarbons production and processing systems. Such equipment allows reducing the consumption of electricity and fuel gas, simultaneously eliminating air pollution. Discussing the disadvantages of the existing equipment, most experts point out to the heavy weight, and, respectively, high cost of the equipment used to develop environmentally friendly technologies. It is obvious that the approach to this problem that involves the search for additional funding for the purchase of expensive equipment (with an uncertain payback period) is not

efficient. Therefore, we may conclude that the development of new environmentally friendly technologies requires designing new special equipment, which will be more sophisticated in production and operation, and have less weight and lower cost.

Generation of thermal energy from the compressed gas energy is broken down into several phases. At the beginning of the cycle, the potential energy of gas is converted into kinetic energy. The gas is channeled to the turbine where the kinetic energy of the gas is converted into mechanical energy. The mechanical energy is transmitted through the turbine shaft to the rotor of the hydraulic machine. A pump performs the role of the hydraulic machine; such a hydraulic machine converts the mechanical energy into the hydraulic energy, generating a fluid flow, which serves as the coolant. When the fluid circulates in a closed circuit, the hydraulic energy is converted into the thermal energy, which is accompanied

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by the coolant's heating. The coolant flow circuit includes a technological device, which uses thermal energy. The coolant's temperature decreases after it passes through such a device, which consumes thermal energy. The cooled coolant flows back to the hydraulic machine in order to be reheated, and the cycle is repeated many times when the coolant circulates in a closed circuit.

The task of developing a new thermal generator is interdisciplinary, and the choice of the research direction must take into account the following aspects: the type of the machine used, the level of efficiency of machines, the scale of production of developed products and technologies for manufacturing parts and components, environmental safety issues, the level of innovation in product manufacturing and available technological solutions. In order to develop a cost-effective thermoelectric generator, relevant studies should focus on designing a technical system, which should be based on high-speed machines with average efficiency; small-scale production using low-cost stamping and welding technologies, in compliance with relevant environmental requirements; and the widespread use of innovations and available open technologies. Computer simulation showed the prospects for studies of impulse turbines for thermal generators, where the use of temperature differences (transforming into kinetic energy in the turbine nozzle) allows designing compact and low-cost equipment for thermal energy generation. Part of the power of recirculating fluids in the thermoelectric generator is converted into useful work—generation of a fluid flow in a closed circuit, and part of the power is dissipated in a vortex and converted into thermal energy. When considering the efficiency of pumps, we should take into account at least two options for solving the problem of the hydraulic and volumetric efficiency estimation. Disc friction loss should be considered as part of hydraulic losses, since in the general case, energy is also supplied to the recirculation loop at the rotor outlet due to the friction on the outer surface of the disc wheel. The energy conversion chain (starting from the compressed gas energy and ending with the thermal energy of the coolant flow) includes elements of an electromagnetic system. The efficiency of this approach is confirmed by relevant estimations and laboratory tests.

2. Literature Review

When choosing the research direction, we need to take into account the type of the machine used, the level of efficiency of machines, the scale of production of the

developed products and technologies for manufacturing of parts and components, environmental safety issues, the level of innovation in the product manufacturing, and available technological solutions.

If we talk about the types of machines, we need to distinguish between two possible areas of operation: low-speed turbines and pumps or high-speed turbines and pumps. Experts note that an increase in the performance of turbines along with reduction in their weight, size, and cost are inextricably linked with the need to increase the rotor speed (Besedin²; Edel⁵; Kruchinina¹³; Nikiforov¹⁸; Smolenskii³¹; Spieldiener³²). However, increase in rotor speed rapidly leads to increased vibration level of rotors, which reduces the reliability and durability of machines and sealing devices. The sealing effect of non-contact seals limits (and does not eliminate) the fluid overflow between adjacent chambers and depends on the annular gap's flow resistance. Quite often, the functions of a bearing and a seal coincide. Studies of thermoelectric generators should focus on high-speed machines.

If we talk about the efficiency of machines, we should identify three possible areas of studies: machines with the highest efficiency; machines with medium efficiency; or machines with low efficiency. Equipment needs to be improved in terms of energy efficiency, technological and economic performance, to reduce significantly capital expenditures for alternative sources of thermal energy (Shishkin²⁹). Experts point out to the following important issues: creation of highly efficient alternative energy sources; development of relevant methodological fundamentals of optimal combination of several heat sources; development of evidence-based methods of estimation of the best options (Shishkin²⁸; Shishkin²⁹). When selecting the research area, it is important to consider the issue of efficiency of the equipment and system in general. The efficiency of thermal power plants is estimated typically based on the thermal efficiency and determines the necessary and sometimes apparent priorities (Il'in⁶). In particular, this parameter pushes alternative energy sources to the distant future. However, Il'in (Il'in⁶) and others point out to the long-pending need to develop a common methodology for the study of processes and plants, as well as justified indicators of their energy efficiency.

We should mention a well-known fact that the unilateral commitment to achieve the highest efficiency values is accompanied by a sharp increase in financial costs, which need to be incurred in order to achieve the objective. In such cases, the massive use of research

results becomes impossible because of the unacceptable increase in the final product's price. It turns out quite often that the target reduction of capital costs and the target improvement in the plant efficiency conflict with each other. Therefore, it is important to seek a compromise solution. In this regard, design of thermoelectric generators should be shifted towards the technology with the medium efficiency level (and in some cases with low efficiency).

If we talk about the technology used to ensure environmental safety, we can distinguish three possible directions of work in terms of the sealing technology. This work can either focus on the use of the contact sealing technology; or focus on the use of the non-contact sealing technology, or focus on the use of hermetically sealed systems, including the options with electromagnetic subsystems. A combination of such technologies is also considered. The range of sealing-related issues is extremely broad and requires a comprehensive approach to solving complex problems, which are at the crossroads of several sciences (Nabokikh¹⁷). First of all, these are the issues related to precision, manufacturing technology, and product assembly. Quite often, seals affect the quality performance of machines, as well as the acceptable areas of their application. A wrong choice of seals or their poor quality and improper use can lead to deviations in machine's performance, reduced reliability, and significant economic losses. Electromagnetic liquid seals represent a new class of sealing, known for the high level of tightness (Bolotov³; Krakov and Nikiforov⁸; Miu¹⁵; Perminov¹⁹; Saikin²²; Shets²⁷). With an increase in the speed of the sealed shaft, the critical differential pressure is reduced due to the significant effect of centrifugal forces. The study of flows and cooling conditions in the electromagnetic liquid volume showed that the exploitation of seals is possible at higher speeds than it had been assumed previously. Even very slow rotation of the shaft was found to lead to a homogeneous distribution of concentration of the magnetic nanoparticles in the gap. Various electromagnetic systems are being increasingly used in development of hermetically sealed equipment (Krasilnikov⁹; Krasilnikov¹⁰; Krasilnikov¹¹; Krasilnikov¹²). One of the directions of development of the country's energy sector includes creation of highly efficient compact power plants that convert (with minimal losses) energy from various sources into the thermal energy (Kalimullin⁷). They must comply with the most stringent air pollution requirements. According to experts, it is important to assess (correctly) the impact of climatic conditions on the

operation of the heat producing equipment. Other tasks include development of methods for estimation of the acceptable time for resumption of operation of the heat-producing equipment. Studies dedicated to designing thermoelectric generators should focus on the sealed systems technologies, using promising developments in the area of the electromagnetic technology.

A known device (Chernykh⁴), which relates to the gas industry (particularly, to devices for heating the coolant at gas distribution stations) may be selected as an analogue at the development of a new thermoelectric generator. The device (Chernykh⁴) comprises a gas turbine operating at differential gas pressure and connected in parallel to the gas pressure control unit of the main pipeline, and actuating the unit (pump or compressor) in order to accelerate and inject the coolant (liquid or gas) circulating in an external piping loop. The task of the utility model (Chernykh⁴) includes improvement in efficiency of the device, as well as improvement of its fire and explosion safety when used in gas distribution stations. Disadvantages of the known device include reduced efficiency of operation with changes in pressure and gas flow in the turbine, caused by the coolant heating device.

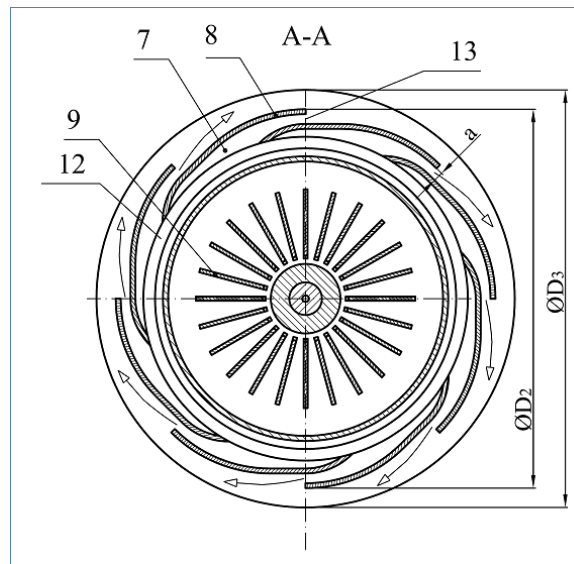


Figure 1. Turbine rotor (Sazonov and Zaiakin, 2005).

An important role in development of new technologies is assigned to the development of mathematical models and computer simulations in general (Mokhov¹⁶; Sazonov²³; Sazonov²⁴; Sazonov and Zaiakin²⁵). Analysis of the processes in the thermoelectric generator requires taking into account simultaneous rotor blade and vortex processes, as well as

turbine and pump processes (Sazonov²³). A turbine with radial movement of the actuator is considered as the main option. Gas is used as the actuator. However, we should take into account possible presence of solids and liquids in the flow. Figure 1 shows an analogue of the turbine for a thermoelectric generator (Sazonov and Zaiakin²⁵).

According to the description of the patent (Sazonov and Zaiakin²⁵), nozzles 8 are installed along the perimeter and inside the circle of D2 diameter with its center on the axis of rotation of the hollow shaft; the nozzles are arranged at least between the two discs with D3 diameter, concentric with D2 circle. Outlet 13 of each nozzle 8 may have the shape of a rectangle with the sides 'a' and 'c'. The length of the longest side of the rectangle ('c') is equal to the distance between the discs with D3 diameter.

The shape of the nozzle's outlet 8 may generate a flat jet (Sazonov and Zaiakin²⁵). Outlet 13 of each nozzle 8 has the shape of a rectangle with the sides 'a' and 'c'. The length of the longest side of the rectangle ('c') is equal to the distance between the discs with D3 diameter. The flat jet may wrap around curved surfaces without separation from the said surface, due to the Coanda effect. With unseparated flat jet on the curved upper wall of nozzle 8, the jet changes its flow direction. Such rotation is accompanied by a decrease in pressure over the curved top wall of nozzle 8, which contributes to the force acting on the outer wall of nozzle 8. In turn, the effect of this additional force increases the torque on the shaft and enhances the efficiency of the entire system (Sazonov and Zaiakin²⁵).

Theoretical studies covered impulse turbines and reaction turbines (Edel²⁵; Shlakhin³⁰; Smolenskii³¹). In the turbine's impulse stage, gas is expanded only in nozzles. The stage's temperature difference is entirely converted into kinetic energy in the nozzles. Rotor blades only convert the kinetic energy into mechanical work. The flow expands at the reaction stage with overpressure in the nozzles and channels of rotor blades. Modern turbines are known for wide use of stages with varying degrees of reaction, which occupy an intermediate position between purely impulse and purely reaction stages.

Studies suggest to consider the options with directed and distributed energy supply in the thermoelectric generator elements using serial and parallel connection of individual elements. As regards the hydraulic part of the thermoelectric generator, it is important to consider both the hydraulic pressure drop because of friction along the channels, and the hydraulic pressure drop because of the impact of the local hydraulic resistance. Hydraulic

resistance may be either fixed or variable, taking into account the development of hydrodynamic processes in separate areas of the process chamber. The physical properties of the actuator (liquid or gas) may change over time, taking into account steady or pulse modes. The energy conversion chain (starting from the compressed gas energy and ending with the thermal energy of the coolant flow) includes elements of an electromagnetic system. Experience with electromagnetic systems (when using individual components in the form of rotating objects) showed that such electromagnetic systems are promising.

Combination of electromagnetic systems and hydrodynamic systems can solve many environmental problems. In particular, electromagnetic clutches for pumping equipment are widely known. Electromagnetic brake systems allow efficiently converting mechanical energy into thermal energy (Baermann¹; Lee¹⁴; Pribonic²⁰; Pribonic²¹; Schultz²⁶; Spieldiener³²).

But there is a wider range of technical problems, where electromagnetic systems are not widely used because of the poor knowledge of specific issues. Development of mathematical models in order to describe the electromagnetic systems, in which at least one element is a rotating object, is a very relevant issue. Such a rotating object may contact with the separating screen. Such an approach to the design of an electromagnetic system is promising with regard to the significant expansion in the application of electromagnetic systems in general.

Based on the reviewed scientific information, we selected and justified research areas in respect of thermal energy generated by the compressed gas energy at gathering facilities in hydrocarbons fields. In the general case, the following three main subsystems of the thermoelectric generator should be considered: a gas turbine, transmission, and a hydraulic machine. Development of a new thermoelectric generator is an interdisciplinary task, because we need to consider (jointly and within a single system) the issues related to the technology of extraction, collection and preparation of oil and gas, creation of machines and equipment for the oil and gas industry, and mechanical engineering issues. Besides, such a list should include certain issues related to the design of turbomachines, pumps, heat engines, as well as theoretical issues of hydrodynamics and gas dynamics.

In order to select the line of research, we identified the main problem, without solution of which we cannot talk about the practical use of alternative sources of thermal energy. The main problem is represented by high capital

expenditures for alternative sources of thermal energy. The selected direction of research should focus on a solution to this major problem.

3. Methods

Applied research is based on experimental and analytical research methods using mathematical models and relevant software.

When choosing the research direction, the following aspects were taken into account: the type of the used machine, the level of efficiency of the machine, the scale of production of developed products and technologies for manufacturing parts and components, environmental safety issues, the level of innovation in product manufacturing, and available technological solutions.

Figure 2 shows the design of the thermoelectric generator. Gas turbine 1 is connected (through transmission 2) to heater 3, equipped with the electromagnetic system. The mechanical energy from turbine shaft 1 is transmitted to heater 3 with the electromagnetic system. Coolant removes heat from heater 3 through line 4. Our research plan includes development and study of the original designs of the gas turbine and heater with an electromagnetic system, using state-of-the-art technologies of production and operation of the equipment. The research also focuses on creation of cheap, simple, and reliable equipment for quick resolution of various technical problems.

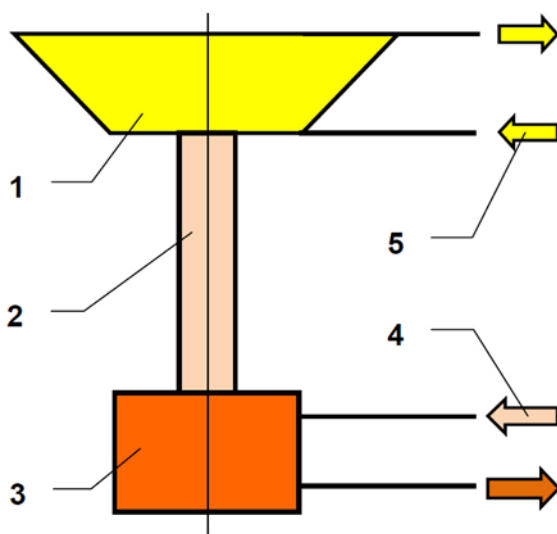


Figure 2. Design of the thermoelectric generator: 1- Gas turbine; 2- Transmission; 3- Heater with the electromagnetic system; 4- Coolant circuit; 5- Line of compressed gas.

Figure 3 shows the design of the developed device for heating the coolant (thermoelectric generator).

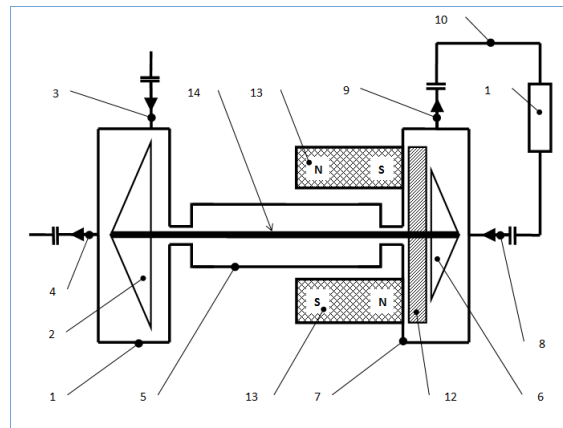


Figure 3. Design of the developed thermoelectric generator.

The device for heating coolant contains a source of mechanical energy in the form of a gas turbine, which comprises turbine housing 1 and turbine rotor 2. Turbine housing 1 is equipped with gas inlet 3 and gas outlet 4. The gas turbine is connected to the pump through transmission 5. The pump has impeller 6, housing 7 with fluid inlet 8 and fluid outlet 9. Impeller 6 may have various designs, including the design in the form of a vane impeller (as in vane pumps) or the design in the form of a disc impeller (as in disc pumps). Fluid conduits 8 and 9 are connected to external closed-loop pipeline 10, filled with liquid coolant. Consumer of thermal energy 11 is connected to external closed loop pipeline 10. Pump's impeller 6 comprises at least one disc 12, made of an electrical conductor. Two or more discs 12 (mounted together with impeller 6 on shaft 14) may be used. Pump housing 7 contains permanent magnets 13 (arranged circumferentially); the polarity of the magnets alternates in the circumferential direction, allowing to induce eddy currents in disk 12 made of electrical conductor. Common shaft 14 has turbine rotor 2, pump's impeller 6, and disc 12 made of electrical conductor. Aluminum, titanium, or copper alloys may be used as the electrical conductor. Disc 12 may be a one-piece monoblock wheel; moreover, disk 12 may include several parts, and such parts may have different geometrical dimensions and the type of material used. Transmission 5 may include bearing supports for the housing of shaft 14, and sealing devices to isolate the fluid chamber from the gas chamber with a liquid coolant (the sealing device is not shown in the figure).

The device for heating the coolant works as follows. The device for heating the coolant contains a source of mechanical energy in the form of the gas turbine, which comprises turbine housing 1 and turbine rotor 2. Turbine housing 1 is equipped with gas inlet 3 and gas outlet 4. Compressed gas is fed into inlet duct 3. In turbine housing 1, the potential energy of gas is converted into kinetic energy; the high-speed gas flow exerts force on turbine rotor 2, causing its rotation. The kinetic energy of gas is converted into mechanical energy. The mechanical energy is transmitted to the pump's impeller 6 through shaft 14 and transmission 5. Common shaft 14 has turbine rotor 2, pump's impeller 6, and disc 12 made of an electrical conductor. The pump has impeller 6, housing 7 with fluid inlet 8 and fluid outlet 9. Fluid conduits 8 and 9 are connected to external closed-loop pipeline 10, filled with liquid coolant. Water, oil or other fluids, which are used in heat supply systems and heat exchangers, may be used as the liquid coolant. Pump's impeller 6 exerts force on the liquid coolant and generates its flow. Rotating disc 12 also exerts force on the liquid coolant due to friction, as in the disc pumps. Therefore, part of the mechanical energy is converted into hydraulic energy to maintain circulation of the liquid coolant. The flow is directed from the center of impeller 6 to the fluid's outlet 9, which is caused by centrifugal forces during the fluid's rotation inside the pump's housing 7. From the fluid's outlet 9, the flow is withdrawn into external closed loop pipeline 10, to which consumer of thermal energy 11 is connected. The flow is then recycled to fluid inlet 8, and the coolant circulation cycle repeats. With such movement of the coolant, the hydraulic energy is converted into thermal energy, which is caused by losses of the hydraulic energy for local hydraulic resistance and frictions when the coolant moves inside closed loop pipeline 10.

Pump's impeller 6 contains disc 12, made of an electrical conductor. Pump housing 7 contains permanent magnets 13 (arranged circumferentially); the polarity of the magnets alternates in the circumferential direction, allowing to induce eddy currents in disc 12 of the conductor. As we know, movement of an electrical conductor through electromagnetic field induces eddy currents in the electrical conductor. Eddy currents heat up disc 12, which is made of an electrical conductor. The electromagnetic system may also contain rotating parts, cylindrical or spherical elements. Since disc 12 is positioned inside pump's housing 7, which is filled with liquid coolant, thermal energy is transferred from disc 12 to the coolant circulating in closed loop pipeline 10.

Therefore, part of the mechanical energy is converted into thermal energy due to eddy currents in disc 12. This part of the process does not depend on the coolant circulation mode. Therefore, this part of the flow may be adjusted independently, particularly by changing the quantity of permanent magnets 13, or by changing the gap between magnet 13 and disc 12, as in conventional electromagnetic systems for eddy current brake within the framework of the well-known method of dynamic braking. As you know, when the problem of passage of an electrical conductor along the electromagnetic system is solved, the main element of machine braking (chain of permanent magnets with alternating polarity) is selected. When choosing the type of permanent magnets, the electromagnetic system is adjusted with account of possible changes in the quantity of magnets in the system and changes in the gaps when installing the magnets. Electromagnetic systems may be used for converting mechanical energy into thermal energy, with electromagnetic coupling used as a decelerator. When gas pressure and flow in the turbine are changed, the rotation speed of shaft 14 and the torque on shaft 14 change as well. In this case, in order to maintain optimal operation of the gas turbine, the pump and electromagnetic system's operation modes are also changed using the above controls.

The proposed engineering solution uses two methods to convert mechanical energy into thermal energy—the hydraulic method and the method based on eddy currents (the dynamic method). Use of two different processes allows to optimize the design of the coolant-heating device, enhance the device control options and increase, respectively, the efficiency when changing the pressure and gas flow in the turbine. More control opportunities contribute to the expansion of options of the device's efficient use for coolant heating. The proposed technical solution allows to reduce the weight and dimensions of the coolant-heating device, including reduction in the pump's weight and the closed circuit pipeline. Thus, the technical result (improved design of the coolant-heating device, which improves efficiency when the pressure and gas flow in the turbine change) is achieved.

We suggest to consider the options with directed and distributed energy supply in the thermoelectric generator elements using serial and parallel connection of individual elements. As regards the hydraulic part of the thermoelectric generator, it is important to consider both the hydraulic pressure drop because of friction along the channels, and hydraulic pressure drop because

of the impact of the local hydraulic resistance. Hydraulic resistance may be either fixed or variable, taking into account the development of hydrodynamic processes in separate areas of the process chamber. The physical properties of the actuator may change over time, taking into account steady or pulse modes. The energy conversion chain (starting from the compressed gas energy and ending with thermal energy of the coolant flow) includes elements of an electromagnetic system. Experience with electromagnetic systems (when using individual components in the form of rotating objects) showed that such magnetic systems are promising. Combination of electromagnetic systems and hydrodynamic systems can solve many environmental problems; in particular, electromagnetic clutches for pumping equipment are widely known. But there is a wider range of technical problems, where electromagnetic systems are not widely used because of the poor knowledge of specific issues. Development of mathematical models in order to describe the electromagnetic systems (in which at least one element is a rotating object) is a very relevant issue. Rotating objects (cylinder, sphere) are selected at the first phase of works. Such a rotating object may contact with the separating screen. Such an approach to the design of an electromagnetic system is promising with regard to the significant expansion in the application of electromagnetic systems in general.

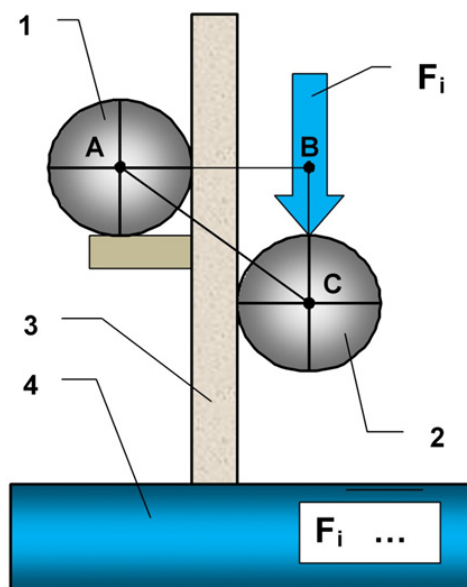


Figure 4. Laboratory setup for testing of electromagnetic systems.

Accurate assessment of a possible relationship between the attraction force and linear displacement in an operating couple (e.g., in the operating couple of two magnets) is important in terms of a separate electromagnetic system. In some cases, the properties and the actual technical condition of the magnets remain unknown. The magnet may be partially demagnetized. In such case, sophisticated calculation methods are useless, because input parameters are uncertain. In this case, the weight-based testing of the electromagnetic system (widely known for its simplicity) may be useful. Figure 4 shows the design of the laboratory setup.

Cylinder magnets 1 and 2 are separated by screen 3. The electromagnetic system is placed on scale 4. For the simplified model ignoring the losses from rolling resistance, we may argue that when external force F_i is applied to magnet 2 (leading link), the scale will show the value of this particular force F_i (when setting the scale to measure the additional weight). Initially, when $F_i = 0$, magnet 2 is located at point B. The distance between the magnets in this position is equal to L_{AB} — the length of segment AB. The force of attraction between the magnets in the initial state is denoted as F_0 . Displacement of magnet 2 along line BC describes parameter L_{BC} ; therefore, relative displacement y may be expressed as $y = L_{BC} / L_{AB}$. We may introduce another dimensionless parameter, force $F = F_i / F_0$. A mathematical model (partially represented by formulae 1 and 2) was developed for engineering and design operations. The exponent (n), taken from well-known theories, describes the force of attraction between the magnets, as measured along the line passing through the magnet's center ($n = 2$ or $n = 3$, depending on the source). But we should mention that this ratio needs to be adjusted depending on performance of the electromagnetic system (in the above example, $n = 3$).

$$F = y(1+y^2)^a \quad (1)$$

$$a = -0.5(n+1) \quad (2)$$

Figure 5 shows a picture of a laboratory setup made for the circuit shown in Figure 4. Experience shows that appropriate fine-tuning of the design of such a laboratory setup allows to test more sophisticated electromagnetic systems.



Figure 5. Laboratory setup for testing electromagnetic systems.

4. Results

Different versions of electromagnetic systems were prepared for laboratory studies; Figures 6-8 show examples of electromagnetic systems with 2 or 3 cylindrical elements.

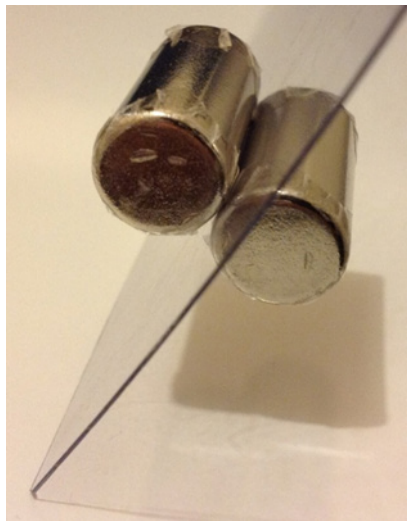


Figure 6. Electromagnetic system with two cylindrical elements.

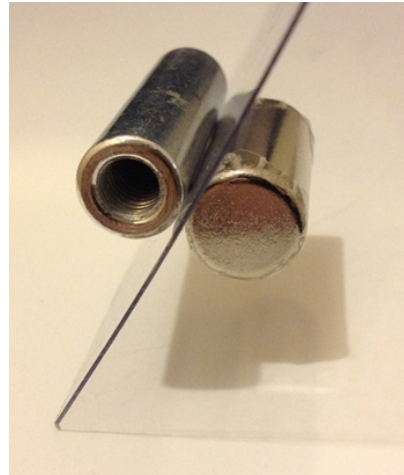


Figure 7. Electromagnetic system with two cylindrical elements. In this example, one of the cylindrical elements is made of carbon steel in the form of a hollow billet.

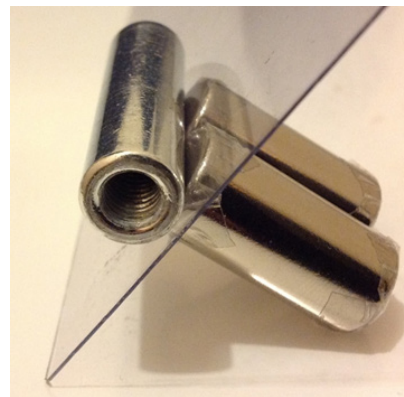


Figure 8. Electromagnetic system with three cylindrical elements. In this example, one of the cylindrical elements is made of carbon steel in the form of a hollow billet.

Results of the Physical Experiments (PE), which were conducted in a laboratory setting, are shown in Figures 9 and 10. The coordinate plane also presents the results of Numerical Experiments (NE), as well as the results of calculations using the developed mathematical models and formulas 1 and 2.

Cylindrical magnets (12 mm in diameter and 25 mm in length; the magnet's material: Nd-Fe-B) were used in laboratory tests. In the first case, the screen was made of a polytetrafluoroethylene (2.2 mm in thickness). Other options were also considered, including the screen made of titanium and stainless steel.

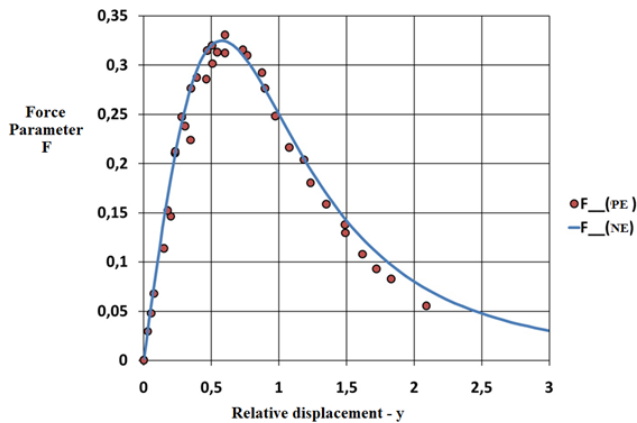


Figure 9. Dependence of the force parameter (F) on relative displacement (y). Physical Experiment (PE) and Numerical Experiment (NE). The screen was made of polytetrafluoroethylene. Screen thickness- 2.2 mm.

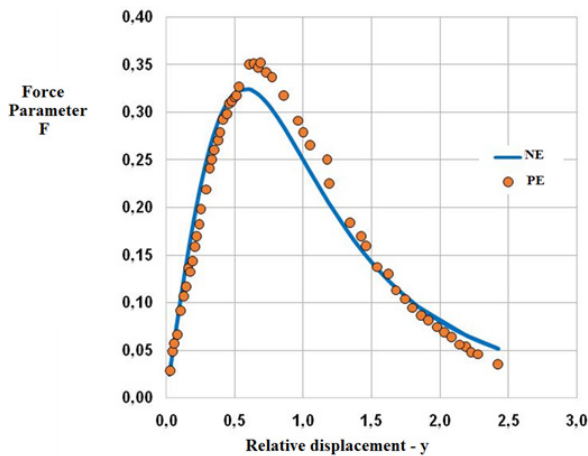


Figure 10. Dependence of the force parameter (F) on relative displacement (y). Physical Experiment (PE) and Numerical Experiment (NE). Material of the composite screen: The first screen layer is made of 12X18H10T stainless steel; The thickness of the first screen layer is 1 mm; the second layer of the screen is made of polytetrafluoroethylene; The thickness of the second screen layer is 2.2 mm.

The results of the physical and numerical experiments allow to conclude that the developed mathematical model reflects the physical processes occurring in the magnetic system. The research results may be used in design and calculation works related to the development of thermoelectric generators equipped with electromagnetic systems.

5. Discussion

Comparing various types of machines, two possible areas of work were distinguished: low-speed turbines and pumps or high-speed turbines and pumps. Since improved performance of turbines along with reduced weight, size, and cost is inextricably linked with the need to increase the rotor speed, the studies dedicated to designing thermoelectric generators should focus on high-speed machines.

Practice shows that commitment to achieving the highest efficiency values is accompanied by a sharp increase in financial costs, which need to be incurred in order to achieve the objective. Massive use of research results becomes impossible because of the unacceptable increase in the final product's price. In such cases, the target reduction of capital costs and the target improvement in efficiency of the plant conflict with each other. Therefore, it is quite important to seek a compromise solution. In this regard, designing thermoelectric generators should be shifted towards the medium efficiency technology.

As regards the scale of manufacturing of the developed product, two directions are possible: large-scale production and small-scale production. Old technologies focus mainly on large-scale production; however, the ways goods are manufactured have changed, and the rapid change in the range of products already eliminates manufacturing of large batches over a long period. In this regard, designing thermoelectric generators should be shifted towards the technologies focusing on small-scale production. Studies should focus on relatively cheap technologies of construction materials processing, which use hermetically sealed systems, taking the advantage of promising developments in the area of electromagnetic technologies.

Development of a new thermoelectric generator is an interdisciplinary task, because we need to consider (within a single system) the issues related to the technology of extraction, collection and preparation of oil and gas, creation of machines and equipment for the oil and gas industry, and mechanical engineering issues. Besides, such a list should include certain issues related to the design of turbomachines, pumps, heat engines, as well as theoretical issues of hydrodynamics, gas dynamics, and magnetic systems.

In order to select the line of research, we identified the main problem, without solution of which we cannot talk about the practical use of alternative sources of thermal energy. The main problem is represented by high capital expenditures for alternative sources of thermal energy. The R&D efforts should focus on seeking solutions to this major problem.

6. Conclusion

Given the interdisciplinary nature of the scientific problem, the chosen direction of research may be described as follows: designing a cost-effective thermoelectric generator should focus on the use of high-speed medium efficiency machines. It is important to take into account the peculiarities of modern small-scale production. Particular attention should be paid to the issues of compliance with environmental requirements, and electromagnetic systems may be used here most efficiently.

A special thermoelectric generator is used for production of thermal energy out of the compressed gas energy at gathering facilities in hydrocarbons fields. The designed thermoelectric generator contains a source of mechanical energy in the form of a gas turbine with a gas inlet and outlet; the gas turbine is connected to a pump. The pump has an impeller, a housing with a fluid inlet and outlet, and fluid channels connected to the outer closed loop pipeline filled with liquid coolant. The impeller comprises a disc (made of electrical conductor). The pump housing contains permanent magnets (arranged circumferentially); the polarity of the magnets alternates in the circumferential direction, allowing inducing eddy currents in the conductor disc.

Generation of thermal energy from the compressed gas energy is broken down into several phases. At the beginning of the cycle, the potential energy of gas is converted into kinetic energy. The gas is channeled to the turbine where the kinetic energy of the gas is converted into the mechanical energy. The mechanical energy is transmitted through the turbine shaft to the rotor of the hydraulic machine. The turbine rotor and the rotor of the hydraulic machine are mounted on the same shaft. A pump performs the role of a hydraulic machine; such a hydraulic machine converts the mechanical energy into hydraulic energy, generating a stream of fluid, which serves as coolant. When the fluid circulates in a closed circuit, the hydraulic energy is converted into thermal energy, which is accompanied by the coolant heating.

The coolant flow circuit includes a technological device, which uses the thermal energy. The coolant temperature decreases after it passes through such a device, which consumes the thermal energy. The cooled coolant flows back to the hydraulic machine in order to be reheated, and such a cycle is repeated many times when the coolant circulates in a closed circuit.

Subsequent studies suggest to consider the options with directed and distributed energy supply in the thermoelectric generator elements using serial and parallel connection of individual elements. As regards the hydraulic part of the thermoelectric generator, it is important to consider both the hydraulic pressure drop because of friction along the channels, and the hydraulic pressure drop because of the impact of the local hydraulic resistance. Hydraulic resistance may be either fixed or variable, taking into account the development of hydrodynamic processes in separate areas of the process chamber. The physical properties of the coolant may change over time, taking into account steady or pulse modes. The energy conversion chain (starting from the compressed gas energy and ending with the thermal energy of the coolant flow) includes the elements of an electromagnetic system. Experience with magnetic systems (when using individual components in the form of rotating objects) showed that such magnetic systems are promising. A new mathematical model for the electromagnetic system with rolling elements, which allows to accelerate the design work and to specify the actual properties of specific magnets, was developed. Laboratory tests were conducted, and relevant calculations were verified. The results of the physical experiments (conducted in a laboratory) allow concluding that the developed calculation method accurately reflects the essence of the physical processes. Cylindrical magnets were used in the laboratory tests. Our research plan includes development and study of original designs of the gas turbine and heater with an electromagnetic system, using state-of-the-art technologies of production and operation of the equipment. The research focuses on creation of cheap, simple, and reliable equipment for quick resolution of various technical problems. The technical proposal and the results of numerical and physical experiments will be used for preparing the application materials when patenting new technical solutions within the framework of the research. The technical proposal and the results of numerical and physical experiments are used in various designs of thermoelectric generators as part of the ongoing research and development.

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