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ARTICLE

Development of Models for Estimating the Cost of Power Equipment Based on Supercritical Carbon Dioxide

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ABSTRACT

Power consumption increases annually, wherefore the air emissions during its production occasionally increase. One of the most promising trends of environmentally safe generation of electricity is the transition to oxygen-fuel power complexes operating on a carbon dioxide working medium, with a share of its capture up to 99%. It is worth noting that the breadth of application of power technologies is determined not only on the basis of criteria of thermal efficiency and environmental safety. The most important criterion is the indicator of economic accessibility, the failure of which does not yet allow for a large-scale transition to the use of electric power technologies with the capture and disposal of greenhouse gases. In this study, a set of multifactorial models for estimating the cost of the main generating equipment operating on supercritical carbon dioxide has been developed. it is found that an increase in the initial temperature and pressure will increase the cost of the main generating equipment operating on supercritical carbon dioxide.

Keywords: Supercritical Carbon Dioxide; Thermodynamic Cycle; Waste Heat Exchanger; Turbine; Combustion Chamber; Efficiency

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1. Introduction

Currently, methods of controlling such atmospheric pollutants as nitrogen and sulfur oxides are successfully applied at thermal power plants. However, the prevention of carbon dioxide emissions, which are formed in large quantities during the combustion of fossil fuels, still causes difficulties [1]. According to one research, if the population of a province rises 1%, their emissions may increase by 0.327 Mt on average [2]. Main reason could be increase in demeand of energy. The introduction of well-known carbon dioxide capturing technologies will lead to significant increase in the cost of power produced by 1.5–2 times [3]. In this regard, the issue of creating environmentally friendly and economically feasible high-capacity power sources remains unresolved [4]. The urgency of this problem is confirmed by the implementation of a number of international treaties, in particular, the Paris Agreement, to which about 200 countries, including Russia, are parties.

An oxygen-fuel technology for power production may be a promising solution to the problem [5–7]. Unlike conventional power units, oxygen-fuel power complexes (OFPC) almost do not pollute the atmosphere with emissions due to the Brayton closed cycle, the use of oxygen as a fuel oxidizer, and the disposal of carbon dioxide removed from the cycle. The high efficiency of oxygen-fuel cycles is due to the thermodynamic method of separation of a two-component working medium, which makes it possible to separate carbon dioxide from water vapor with minimal power consumption by condensing the latter in a separator feed cooler.

The Allam cycle is currently one of the most promising among the oxy-fuel power plants of the new generation. The technology, patented in 2010 by the inventor Rodney John Allam, allows achieving a record net efficiency of 58.9% for natural gas and of 51.44% for gasified coal, taking into account the costs of CO_2 disposal. The technology developers also highlight CAPEX of installed capacity. For the Allam cycle on natural gas, it may be \$800–1000/kW, on gasified coal e \$1500–1800/kW [8–10]. A big advantage of the Allam cycle technology is low atmospheric emissions. The traditional post-combustion carbon capture technology allows preventing 80–89% of carbon dioxide emissions and the Allam cycle 98.9%. It means that the mass of the produced CO_2 emissions for the Allam cycle is three to six times lower than for combined cycle with post-combustion carbon capture. The operating points for the Allam cycle are shown on a pressure-enthalpy diagram for pure carbon dioxide. CO_2 is compressed in a multistage compressor with intercooler up to 80 bar and then pumped to the maximum pressure in the cycle, ranging from 200 to 400 bar. After being pumped, CO_2 is sent to the regenerator where it is heated up to 700–750 °C due to the turbine exhaust heat and the internal low-grade heat from the air separation unit (ASU). After the regenerator, most of the CO_2 stream is directed to the combustion chamber in order to limit the maximum temperature, and a smaller part is used for gas turbine cooling. The rest of CO_2 is mixed with a compressed oxygen stream and is also directed to the combustion chamber. The working fluid temperature increases in the combustion chamber up to 1100–1200 °C due to the oxy-fuel combustion. The CO_2 recycle flow is used to limit the turbine inlet temperature. The turbine outlet pressure is in the range from 20 to 40 bar, which is less than the CO_2 critical pressure. After the turbine, the working fluid is sent to the regenerator. The high performance of the Allam cycle, as well as the unconventional chemical composition of the working fluid, make it necessary to develop a framework for power equipment, among which a supercritical CO_2 gas turbine deserves a special mention. When designing the CO_2 turbine, it is rational to use the existing practices in developing of steam and gas turbine technologies [11, 12]. The temperatures in the Allam cycle are lower than in modern gas turbine units and combined cycles, but much higher than in steam turbine units. At the same time, the maximum pressure in the Allam cycle does not exceed the maximum pressure in the newest steam turbine units but exceeds the maximum pressure in gas turbine units.

There are several ways to reduce the amount of CO_2 emissions by the energy industry. First of all, it is possible to make a qualitative step forward by increasing the energy efficiency of existing fossil fuel power plants [13]. This approach could slow down somewhat the growing CO_2 concentration in the atmosphere, but not stabilize it since combustion products consisting mainly of greenhouse gases will still be discharged into the air [14]. But CO_2 extraction from nitrogen-rich low-temperature waste gases is associated with high capital costs for special equipment, lower cycle efficiency and, ultimately, leads to an increase in the electricity cost by 1.5–2 times. The second promising growth area is renewable energy sources. The growth of solar cell energy efficiency and wind turbine capacity led to a significant reduction in the payback period for this type of units. Currently, the proportion of the world's renewable energy sources in the total power structure is less than 5% (excluding hydropower industry). That is due to the complexity of power loading control and the high cost of energy storage. An efficient way to reduce CO_2 emissions into the atmosphere, which implies maintaining economic growth, is the creation of closed thermodynamic cycles with oxy-fuel combustion [15, 16]. The energy efficiency of power generation and the absence of pollutant emissions in the air are the main advantages of these technologies. The following closed thermodynamic cycles have become widely known: semi-closed oxy-fuel combustion combined cycle (SCOC-CC), MATIANT cycles, NET Power oxy-combustion cycle, Graz cycles as well as supercritical CO_2 Brayton cycles [17–21]. The first modifications of these cycles appeared at the end of the last century. Today the USA, Japan, and European countries invest heavily in this area.

Despite the importance of improving power efficiency and environmental safety of power production, for the introduction of promising power complexes, it is necessary to achieve acceptable financial and economic indicators, the values of which largely depend on external economic factors. In order to form a valid conclusion on the potential for the development of new environmentally safe high-temperature power plants, it is necessary to conduct a feasibility study under various scenario conditions, which will form the path for sustainable development of the electric power industry in the medium and long term.

The purpose of this study is to develop multifactorial models for estimating the cost of the main power equipment: a cooled gas turbine on supercritical carbon dioxide, a combustion chamber and a set of waste heat exchangers of exhaust gases all these component are mostly complex and costly which could consider a major portion of cost of supercritical carbon dioxide power plant.

2. Methodology for Developing Models for Estimating the Cost of Equipment

The principle for model construction is to establish direct functional relationships between the initial parameters of the cycle, which have the greatest impact on the efficiency of the power plant and the cost items associated with the manufacture and sale of equipment. The algorithm for calculating costs for the production of new equipment includes an assessment of the weight and dimensional characteristics of its main components and parts through the execution of design calculations. The information obtained is used to select steel grades suitable for the manufacture of equipment parts, determine the size and total mass of blanks, the complexity of manufacturing all composite structural elements that can significantly affect the total costs of equipment production. Costs that do not directly depend on the values of the initial temperature, pressure, and flow of the working medium taken for calculation, in particular, shop costs, are accepted normatively in accordance with existing recommendations as a share of direct production costs.

Each of the presented models allows to predict the main items of the cost calculation of the main power equipment, the total cost of which largely determines the cost of the entire complex: the cost of purchasing materials and components, the payment for production personnel and contributions to social funds, the cost for maintaining process equipment in operating condition, the cost for the purchase of tools and the manufacture of devices. At the same time, each model allows to generate a forecast of the cost of equipment for any combination of the initial parameters of the cycle.

2.1. Development of a Cost Estimation Model for a Methane-Oxygen Combustion Chamber Using Supercritical Carbon Dioxide

To estimate the cost of the oxygen-fuel combustion chamber, a tubular combustion chamber design was adopted, which includes the main elements - an outer casing, a flame tube consisting of a diffuser, a cylindrical part and a gas collector [22]. In order to develop a functional cost model, a structural division and geometric simplification of the parts of the methane-oxygen combustion chamber were performed for the subsequent receipt of dependencies of the mass-dimensional characteristics of the equipment on the key parameters of the power plant.

The cost of manufacturing combustion chambers, taking into account their number, consists of the sum of the costs of purchasing materials and the costs of its manufacture. Also, when assessing the cost of an oxygen-fuel combustion chamber, it is necessary to take into account the cost of manufacturing the burner device, which, although it has a small share in the structure of the metal content of the combustion chamber, but due to the high complexity of the design and, as a result, the labor intensity of manufacture, affects its cost of the combustion chamber. Burner device is usually 32% of the cost of materials required to manufacture the combustion chamber.

The total cost of manufacturing the elements of the oxygen-fuel combustion chamber (CC) is determined by formula (1):

$$P_{cc} = P_b + P_{ft} + P_d, \quad (1)$$

Where:

P_{cc} is the cost of manufacturing the combustion chamber body,

P_{ft}—cost of manufacturing a flame tube,

P_d—cost of the burner device.

In addition to the above costs, it is also necessary to take into account the company's profit, workshop and overhead costs of the enterprise, which make up 20%, 5% and 20%, respectively, of the total costs of manufacturing the combustion chamber[23]. Thus, the cost of manufacturing the elements (P_{elm}) of the oxygen-fuel combustion chamber is determined by formula (2).

$$P_{elm} = P_{mat} + P_{wp} + P_{mech} + P_{cp} + P_{shop} + P_{oc}, \quad (2)$$

Where:

P_{mat} is the cost of purchasing materials,

P_{wp}—cost of manufacturing the workpiece,

P_{mech}—cost of mechanical processing,

P_{cp}—company profit,

P_{shop}—shop costs,

P_{oc}—overhead costs.

The costs of purchasing materials are determined by the mass and size parameters of the combustion chamber determined by formula (3).

$$P_{mati} = M_{zi} S_{gi} \quad (3)$$

Where:

S_{gi} is the cost of 1 kg of alloy required to manufacture the i-th element of the combustion chamber, RUB/kg;

M_{zi}—mass of the i-th element of the combustion chamber, kg.

2.2. Development of a Cost Estimation Model for a Cooled Axial Turbomachine Using Supercritical Carbon Dioxide

The model for assessing the cost of manufacturing a cooled turbine on supercritical carbon dioxide is compiled for a gas turbine. It includes the main units and assemblies: a casing with diaphragms and nozzle blades installed in it, a rotor with a working blade apparatus, a combustion chamber, bearings and supports. The gas turbine has seven stages, four of which are made with cooling. The coolant, taken behind the compressor, is directed into the cooling system channels, after which it enters the flow part through a gap in the output edge and holes distributed along the blade feather.

To reduce the pressure on the casing wall, a two-casing design is implemented. The first four stages of the turbine, operating at maximum pressures and temperatures, are located in the inner casing of the turbine. The diaphragms of the fifth, sixth and seventh stages are installed in a cage that rests on the outer casing. This design solution allows for a hydraulic connection between the inter-casing space and the compartment behind the fourth stage of the turbine, which reduces the thickness of the casing walls, which require expensive nickel alloys for production.

A cost approach was used to develop the model, which consists of adding up the main cost items for the equipment elements that must be incurred for the manufacture and delivery of the equipment. To determine the total cost of a high-temperature cooled gas turbine, the costs of manufacturing its main parts were estimated. Particular attention was paid to the parts that form the flow path: the inner casing, outer casing, shaft, nozzle and rotor blades, disks, and diaphragms. The model also includes an estimate of the cost of manufacturing auxiliary structures and components: control systems, fuel and lubricating oil supply systems, bearings, supports, and parts built into the foundation.

The total costs of manufacturing a gas turbine P_{GT} are determined by formula (4):

$$P_{GT} = P_{blades} + P_{disk} + P_{shaft} + P_{diaphragm} + P_{ic} + P_{oc} + P_{bp} + P_{ors} + P_{ms}, \quad (4)$$

Where:

P_{blades} is the cost of manufacturing blades,

P_{disk}—cost of manufacturing disks.

The design of the gas turbine became the basis for drawing up a diagram of the relationship of parameters that determine the mass and size characteristics of the main turbine units and the cost of the high-temperature cooled gas turbine.

P_{shaft}—cost of shaft manufacturing,

$P_{diaphragm}$—cost of manufacturing diaphragms,

P_{ic}—cost of manufacturing the inner casing,

P_{oc}—cost of manufacturing the outer casing,

P_{bp}—cost of bearing production,

P_{ors}—cost of manufacturing the oil regulation and supply system,

P_{ms}—cost of manufacturing supports.

The manufacturing costs of each unit consist of the costs of materials, the costs of mechanical processing, which include costs associated with the payment of labor to workers, the purchase of equipment, tools, maintaining the technological equipment in working order, as well as administrative (20%), shop (5%) and overhead costs (20%) of the enterprise.

The total cost of manufacturing a turbine part of the $P_{el.GT}$ turbine was calculated using formula (5).

$$P_{el.GT} = P_{mat} + P_{mech} + P_{cp} + P_{shop} + P_{oc}, \quad (5)$$

Where:

P_{mat} is the cost of purchasing materials,

P_{mech}—cost of mechanical processing,

P_{cp}—company profit,

P_{shop}—shop costs,

P_{oc}—overhead costs.

The costs of purchasing materials are determined by the sizes of the blanks required to manufacture parts and assemblies. The sizes of the main parts of the turbine are determined based on the design calculation using the method shown in figure. Taking into account the coefficient of the material used, the value of which depends on the manufacturing technology.

The costs of purchasing the material required for the manufacture of parts are determined by formula (6).

$$P_{mat} = \frac{M_{el.GT}}{K_m} C_{Alloy}, \quad (6)$$

Where:

$M_{el.GT}$ is the mass of the gas turbine part, kg;

K_m—coefficient of the material used;

C_{Alloy}—cost of alloy, RUB/kg.

The main component of the cost price of a gas turbine is the cost of performing technological operations (50%), which includes wages for workers, the purchase of tooling for machines and the maintenance of technological equipment in working order. In turn, the share of costs for materials is 19%.

2.3. Development of a Cost Assessment Model for a Recuperative System of a Power Plant Based on the Allama Cycle

The last of the key elements, the cost characteristics of which must be studied for the development of a functional-cost model of the main power equipment of the oxygen-fuel power complex on carbon dioxide, is the recuperative heat exchange system, consisting of five plate heat exchangers. The total thermal power of the multi-flow recuperator is 2.3 times greater than the power of the supplied electric energy of the Allam cycle, which, together with the need to maintain a minimum temperature difference at the pinch point, predetermines a significant heat exchange surface area. In turn, the use of high-temperature gases at the exhaust of the gas turbine as a heating medium necessitates the use of heat-resistant alloys in the manufacture of heat exchangers. The significant area of the heat exchange surface, made of expensive alloys, is the most important reason for the high cost of this element of the thermal scheme of the Allam cycle.

For a correct analysis of the influence of the Allam cycle parameters on the cost characteristics of a multi-flow recuperator, it is sufficient to develop a model for assessing the cost of heat exchangers operating on turbine exhaust gases. The significant total thermal power of heat exchangers exceeding 90% of the power of the entire heat exchange system, as well as the high temperatures of the coolants, determine the fact that their share will prevail in the cost structure of a multi-flow recuperator. The main component of the heating and heated environment of this heat exchanger is carbon dioxide, the proportion of which varies depending on the flow from 93 to 98%.

In order to determine the total cost of a recuperative heater, it is necessary to determine the costs of manufacturing its main elements. The main elements of a plate heat exchanger are plates with installed heat exchange intensifiers, a housing, and inlet/outlet pipes.

The total costs for manufacturing the recuperative heat exchanger P_{TO5} are determined by formula (7).

$$P_{TOS}=P_{plast}+P_{case}+P_{mp}+P_r, \quad (7)$$

Where:

P_{plate} is the cost of manufacturing plates, rubles;

P_{case}—cost of manufacturing the case, rub.;

P_{mp}—cost of manufacturing manifold pipes, rub.;

P_r—cost of assembling the recuperator, RUB.

The heat exchanger plates are flat wide metal products with applied intensifier ribs shows in **Figure 1**. Thus, intensification by ribs provides the greatest increase in N_u/N_{u0}. The manifold pipes are made in the form of rectangular channels. Two body plates provide reliable fastening of the plates and installation of external pipes to the heat exchanger.

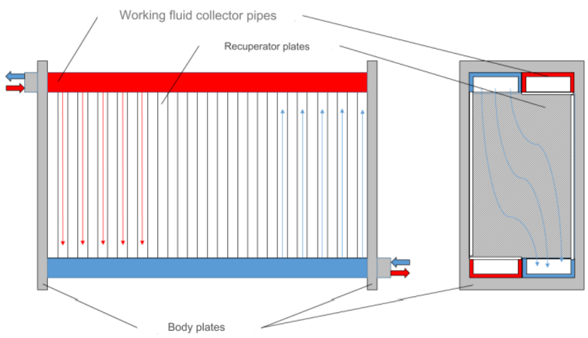

Figure 1. Shows the proposed design of the heat exchanger.

Manufacturing costs are made up of the costs of materials used to create its basic elements, the costs of mechanical processing and assembly. In addition to the above costs, it is also necessary to take into account the company's profit, workshop and overhead costs of the enterprise, which make up 20%, 5% and 20% of the cost of the product, respectively [24].

Thus, the total cost of manufacturing the elements of the heat exchanger was calculated using formula (8).

$$P_{el.TO}= P_m+P_{mech}+P_{assembly}+P_{assembly}+P_{shop}+P_{oc}, \quad (8)$$

Where:

P_m—costs of materials for procurement,

P_{mech}—cost of mechanical processing,

$P_{assembly}$—cost of assembly operations,

P_{cp}—company profit,

P_{shop}—shop costs,

P_{oc}—overhead costs,

The material costs are determined based on the final mass-dimensional parameters of the heat exchanger element blanks obtained during the calculation.

3. Results

3.1. Development of a Cost Estimation Model for a High-Temperature Cooled Gas Turbine

Using the developed model for estimating the cost of a high-temperature cooled gas turbine, its cost and mass for the base calculation point were determined: P0 = 30 MPa, T0 = 1100 °C (TST ≤ 600 °C), Pz = 3 MPa, D0 = 200 kg/s. the maximum thermal efficiency of the Allam cycle is achieved using this combination of parameters.

Figure 2 shows the structure for the production cost of a high-temperature cooled gas turbine by cost items for the base calculation point. The main component of the production cost of a gas turbine is the cost of performing process operations (50%), which includes the wages of workers, the purchase of equipment and tools, and the maintenance of process equipment in working condition. In turn, the share of material costs is 19%. The total cost for the installation of gas turbine operating at the base point parameters was 393.6 million RUB (32.1 $/kW).

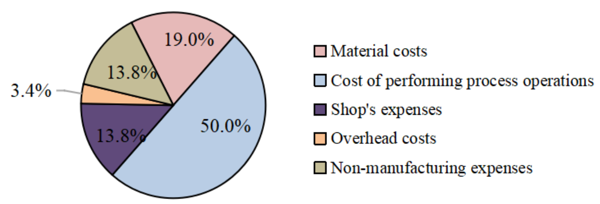

Figure 2. The structure for the production cost of a high-temperature cooled gas turbine for the base calculation point.

Figure 3 shows a graph of dependence of the gas turbine relative cost on the initial pressure and cycle and pressure temperature at the turbine outlet with a mass flow rate of the working medium equal to 200 kg/s. It can be observed that an increase in the parameters of carbon dioxide at the gas turbine inlet, in the temperature range from 1100 to 1300 °C (the temperature of the part walls is from 600 to 750 °C), leads to an increase in relative cost, and an increase in back pressure, on the contrary, is accompanied by a decrease in cost.

If the temperature of the working medium at the inlet is

1500 °C (the temperature of the part walls is 900 °C), there is a steep rise in the cost of a gas turbine by 1.34–1.76 times with an increase in the pressure at the turbine outlet from 3 to 4 MPa (P0 = 25–30 MPa) and from 4 to 5 MPa (P0 = 35 MPa).

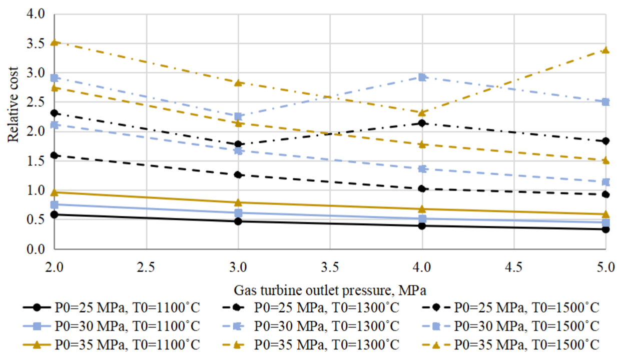

Figure 3. Dependence of relative cost of high-temperature cooled gas turbine on pressure and temperature variance.

The increase in the cost of the turbine is associated with the increase in the cost of manufacturing the outer casing. As mentioned earlier, in order to reduce the maximum pressure drop on the casing walls behind the fourth stage, the hydraulic connection of the inter-casing space and the section behind the fourth stage was carried out. Consequently, the choice of material will depend on the temperature of the working medium at the entrance to the fifth stage, therefore, an increase in pressure at the outlet will be accompanied by a decrease in the available heat drop of each grid and an increase in the temperature of the working medium in the inter-casing space. Thus, a sharp increase in the relative cost of the turbine is caused by a change in the alloy used for the outer casing from 15H12VNMF to HN35VT.

3.2. Development of a Model for Estimating the Cost of a Waste Heat Exchanger System

Using the developed model for estimating the cost of a waste heat exchange system, its cost is determined for the basic combination of four parameters of the Allam cycle (for the base calculation point): GTO4 = 600 kg/s, P0 = 30 MPa, tGT = 700 °C (gas temperature at the gas turbine outlet), PGT = 3 MPa.

Figure 4 shows the structure for the production cost of a waste heat exchanger by cost items for the base calculation point. The main component of the production cost of the heat exchanger is the cost of materials (50.5%). In turn, the share of the cost of performing process operations, which includes the wages of workers, the purchase of equipment and tools, and the maintenance of process equipment in working condition, is 13.8%. The total cost for the waste heat exchangers at the base point parameters was 790.2 million RUB (64.5 $/kW).

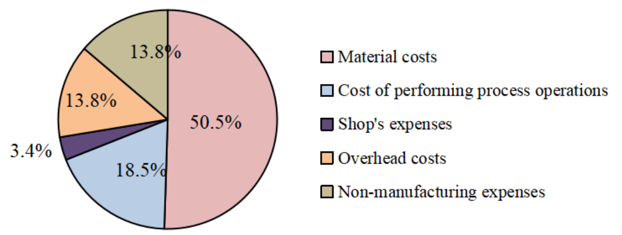

Figure 4. The structure for the production cost of a waste heat exchanger for the base calculation point.

Figure 5 shows the influence on the change in the cost of the waste heat exchanger is the steel grade change by an increase in the temperature at the outlet of the gas turbine. The factor having the least influence is the change in the pressure of the heating coolant. The minimum cost values are shown by a curve constructed for a gas turbine outlet temperature of 500 °C and a coolant pressure of 25 MPa (54–56% of the base value). The maximum cost values are shown by a curve constructed for a gas turbine outlet temperature of 700 °C and a coolant pressure of 35 MPa (117–123% of the base value).

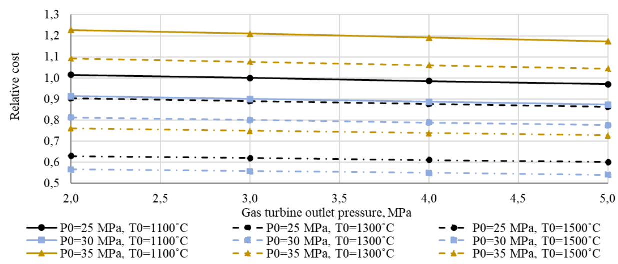

Figure 5. Dependence of relative cost of waste heat exchanger on pressure and temperature variance.

3.3. Development of a Model for Estimating the Cost of an Oxygen-Fuel Combustion Chamber

Using the developed model for estimating the cost of an oxygen-fuel combustion chamber, its cost is determined for the basic combination of three basic parameters of the Allam cycle (for the base calculation point): G0 = 600 kg/s, P0 = 30 MPa, T0 = 1100 °C [25].

Figure 6 shows the structure for the production cost of an oxygen-fuel combustion chamber by cost items for the base calculation point. The main component of the production cost of the combustion chamber is the cost of materials (38.5%). In turn, the share of the cost of performing process operations, which includes the wages of workers, the purchase of equipment and tools, and the maintenance of process equipment in working condition, is 30.6%. The total cost for the installation of combustion chamber operating at the base point parameters was 706.4 million RUB (57.7 $/kW).

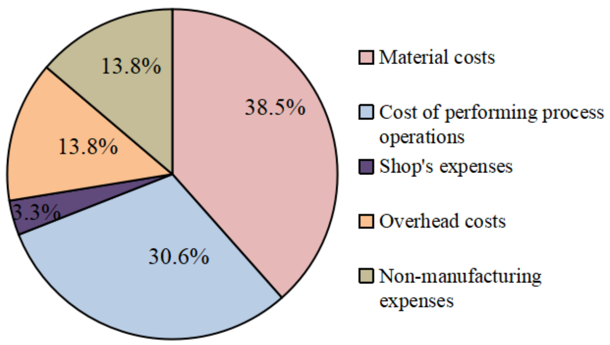

Figure 6. The structure for the production cost of an oxygen-fuel combustion chamber for the base calculation point.

Figure 7 shows a graph of dependence of the oxygen-fuel combustion chamber relative cost of the working media parameters. The factor that has the greatest impact on the change in the cost of the combustion chamber is the change in the flow rate of the working medium. The change in the pressure of the working medium at the outlet of the combustion chamber has the least impact.

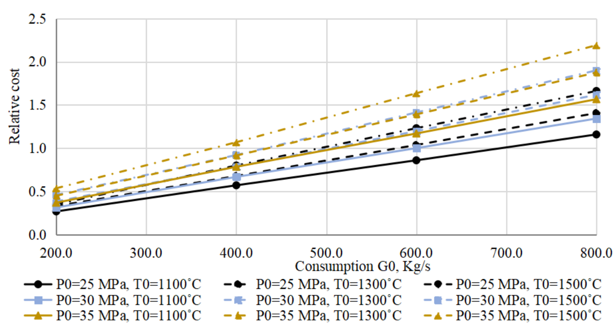

Figure 7. Dependence of relative cost of oxygen-fuel combustion chamber on pressure and temperature variance.

The minimum values of the combustion chamber cost were obtained for a curve constructed for a temperature of 1100 °C and a pressure of 25 MPa of the working medium (56–57% of the base value). The curve constructed for a temperature of 1500 °C and a pressure of 35 MPa of the working medium corresponds to the maximum values of the combustion chamber cost (118–119% of the base value).

4. Conclusions

1) A set of multifactor models has been developed for estimating the cost of a high-temperature cooled carbon dioxide gas turbine, a high-pressure oxygen-fuel combustion chamber and a high-temperature waste heat exchange system. On the basis of the developed models, the dependences of the cost of the oxygen-fuel power complex equipment on the thermodynamic parameters and the flow rate of the working medium are constructed. The cost of the oxygen-fuel power complex equipment operating according to the Allam cycle is determined at an initial temperature of 1100 °C, an initial pressure of 30 MPa, a pressure at the outlet of a carbon dioxide turbine of 3 MPa, including the cost of the turbine of 393.6 million RUB, the cost of the combustion chamber is 706.4 million rubles, the cost of the regenerative heat exchange system is 1520.0 million rubles.

2) The influence of the main thermodynamic parameters on the costs associated with the manufacture of oxygen-fuel power complex equipment has been established:

an increase in the initial temperature by 10% leads to an increase in the cost of the turbine by 76.4–91.3%, the combustion chamber - by 12%, the heat exchange system - by 7.6–21.7%;

- an increase in consumption by 10% is accompanied by an increase in the cost of the turbine by 6.5–7.9%, the combustion chamber - by 15%, the heat exchange system - by 4.6%;
- an increase in the initial pressure by 10% leads to an increase in the cost of the turbine by 10.5–15.9%, the combustion chamber - by 10.1%, the heat exchange system - by 10.7%;
- an increase in the pressure at the turbine outlet by 10% is accompanied by a decrease in the cost of turbine by 4.9–13.3%.

These cost estimation could be used for designing supercritical carbon dioxide power plants. It could be more cost effective if use for commercial implication based on certain recommended inlet pressure and temperature range.

Author Contributions

Conceptualization, M.V.O. and M.M.S.; methodology, M.M.S.; software, M.V.O.; validation, I.I.K., A.N.V. and I.A.M.; formal analysis, M.V.O. & I.A.M.; investigation, M.M.S.; resources, M.V.O.; data curation, A.N.V.; writing—original draft preparation, M.M.S.; writing—review and editing, M.V.O.; visualization, I.A.M.; supervision, I.I.K.; project administration, M.V.O.; funding acquisition, I.I.K. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Conflicts of Interest

The authors declare no conflict of interest.

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