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Use of High-Temperature Nuclear Reactors in Non-Electrical Technologies

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Abstract. The article considers the possibilities of using high-temperature gas-cooled reactors in multi-purpose installations that produce both electrical energy and, first of all, provide high-potential thermal energy for the conversion of fossil fuels, the production of hydrogen, synthesis gases, and reducing gas for ferrous metallurgy. Problems of research of thermal circuits of multi-purpose power-technological complexes with a nuclear source of heat are formulated. Schematic diagrams of such installations are given.

Keywords: high-temperature reactor, energy technology, energy analysis, temperature potential

1 Introduction

Research on the use of heat from nuclear reactors in non-electrical technologies has been conducted in the USA, Germany, Japan, China and other countries.

The implementation of such technologies requires a temperature potential of 700-1000°C. This condition is met by high-temperature gas-cooled nuclear reactors (HTGR), the temperature of the coolant - helium at the outlet can reach 1000-1100°C, and in some cases even higher.

The following are the most promising directions for using HTGR:

— ferrous metallurgy. Ferrous metallurgy is one of the largest consumers of fuel and energy resources. It consumes about 12% of all produced electricity and about 11% of produced fuel;

— creation of large-scale production of hydrogen, one of the main possible energy carriers and raw components of chemical production;

— the creation of nuclear energy technological installations based on steam catalytic conversion of natural gas or gasification of solid organic fuel;

— creation of nuclear energy technology plants in the chemical and nitrogen industry, which are major consumers of thermal and electrical energy and organic fuel;

— the use of HTGR in the oil refining industry and petrochemical industry, since petrochemical production at this stage uses a fairly significant part of oil as fuel.

Installations with HTGR that implement such technologies are multi-purpose and are called energy technology. High-potential heat (700-1000°C) is used for technological purposes – coal gasification, natural gas conversion, production of hydrogen and reduction gas in metallurgy, etc., and medium-potential heat (350-700°C) – for electricity generation.

Research devoted to the creation of large multi-purpose power-technological installations with an atomic heat source has been carried out since the 80s [1–3]. At the same time, considerable attention is paid to the atomic heat source – a high-temperature gas-cooled reactor, issues of nuclear fuel technology in such reactors, fuel element designs, hydrodynamics and heat transfer in the core, and the accumulation of operating experience. The issues of heat transfer from the reactor to the technological circuit, alternative possibilities of using the heat of a high-temperature reactor in various technologies, the choice of initial technological raw materials, analysis of the structure and technological principles of product development are considered [4–7]. In this case, various circuit solutions are assumed that make it possible to more or less successfully combine the temperature potential of the nuclear reactor coolant with the parameters of technological processes. At the same time, the creation of new, specific technologies, including both energy transformation processes (energy processes) and material transformation (technological processes), requires the development of new rational schemes, cycles and methods of analysis. Traditional analysis methods used for schemes of nuclear and thermal power plants, combined heat and power plants running on organic or nuclear fuel in this case are insufficient. This is determined by the significant variety of thermal schemes of such installations and the presence of qualitatively different types of products. In addition, in each scheme there are a large number of interrelated energy and technological parameters: temperature and pressure levels of heat carriers and working agents; temperature, pressure, initial composition and phase state of the reactants, utilization of the heat of technological processes in various parts of the installation, the use of working fluids (for example, water vapor) to provide technological processes, etc. At the same time, an approach to determining rational thermal schemes has not been created, cycles and operating parameters of such installations.

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2 Statement of the Research Problem

Nuclear power and technological installations as an object of research include inextricably linked energy and technological processes. Existing methods of energy analysis of both purely electric power plants and technological processes – the conversion of fuels, the recovery of metals from ores, the production of gas synthesis, etc. in their present form cannot be applied, firstly, due to the lack of the necessary thermodynamic functions for many elements and chemical compounds and, secondly, due to the presence of a specific source of heat – a high-temperature nuclear reactor.

The presence in the power plant of even two types of homogeneous energy products – electricity and heat, which is typical for combined heat and power plants, makes it difficult to analyze the efficiency of installations. Currently, there are several methods for analyzing the energy efficiency of thermal power plants [8–10], which evaluate the efficiency of their work in different ways. Moreover, the analysis carried out by different methods can lead to opposite conclusions. For power engineering installations, the task is much more difficult. Such an installation produces not only energy products in various forms, but also technological products of both an energy type: hydrogen, synthetic gaseous or liquid fuel, and a non-energy type: iron, reducing gas, ammonia, mineral fertilizers, and others. In addition, it is necessary to take into account the presence in energy technological installations of at least several types of initial energy and technological raw materials: nuclear fuel, organic fuel (coal or natural gas), which is used as technological raw materials, metal oxides, etc.

The analysis methods currently used in metallurgy, chemical and other industries are based on the laws of conservation of matter and energy balance and do not affect the issues of energy conversion in the system [11, 12]. Modern methods of analysis in the energy sector, of course, are based on the first and second law of thermodynamics. The emergence of a new object of study - a multipurpose power-technological installation, requires, along with other tasks, a thermal engineering study of thermal circuits of installations, matching of technological parameters, parts and devices of circuits.

The tasks of thermotechnical research of such installations are:

— development of analysis methods for multi-purpose power-technological installations;

— study of thermal circuits, processes and cycles, selection and recommendation of the most rational circuits operating in the region of optimal parameters.

The thermotechnical study of schemes of power technological installations with a nuclear heat source includes, firstly, the choice of chemical and technological processes implemented in the corresponding schemes, such as gasification of solid fuel with water vapor or carbon dioxide, conversion of natural gas, reduction of iron from ore according to various schemes, pre-conversion carbon monoxide in synthesis gas and others; secondly, the definition of relationships between the technological and energy characteristics of processes; thirdly, the development of criteria that evaluate the efficiency of installations and, on their basis, the choice of rational technological processes; the most advantageous parameters of schemes and optimal technological and energy parameters of processes; optimal design and overall characteristics of the equipment.

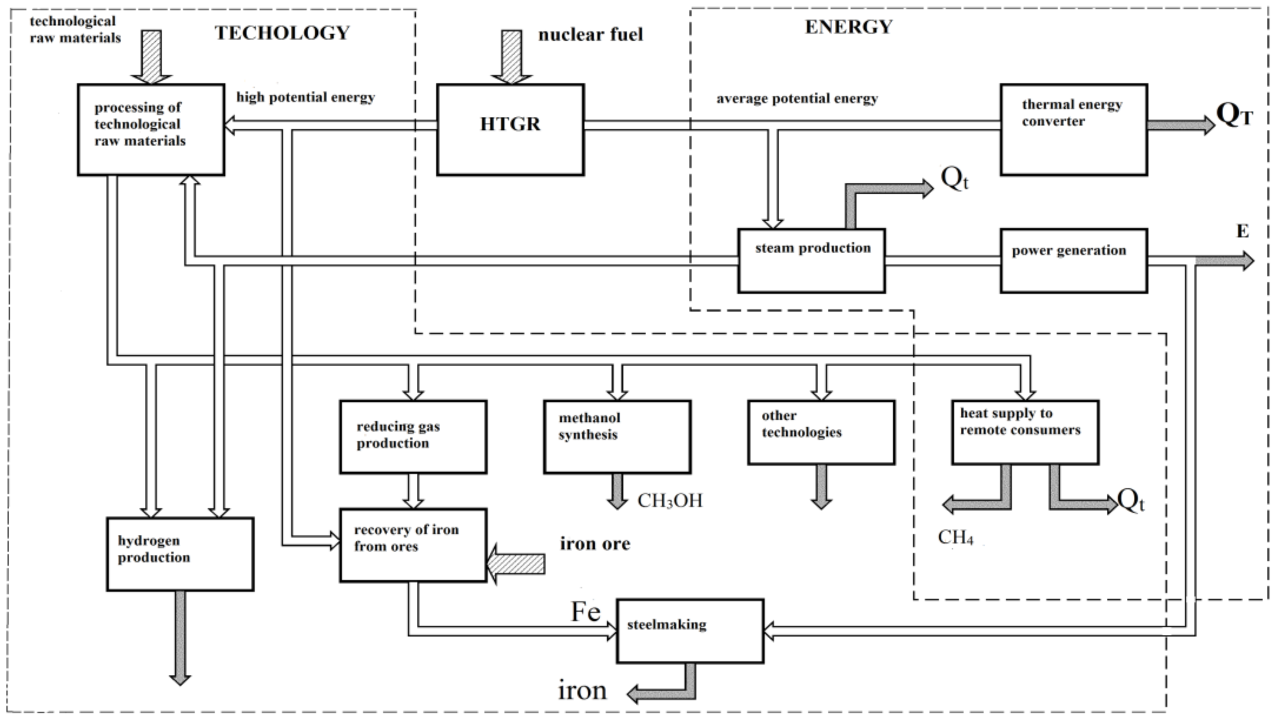

Figure 1. Formalized scheme of the energy technological installation.

In the general case, the object of study is an extensive class of installations, despite the specifically chosen source of heat and the initial technological raw material. Therefore, it is necessary to present a formalized scheme of the energy technological installation. This makes it possible to identify the essential elements, processes and relationships in the installation and to develop research methods.

Figure 1 shows such a formalized scheme of the nuclear power plant (NETI) – the object of study. The scheme defines the main flows of feedstock, process agents, working fluids and coolants. The atomic heat source provides technological and energy processes with thermal energy; processing of technological raw materials (conversion of natural gas, gasification of solid fossil fuels), recovery processes (they can be varied), production of water vapor for energy and technological purposes. The generated synthesis gas is a secondary raw material for various technological processes: the production of gaseous (hydrogen) and liquid (methanol) energy carriers, the production of reducing gas, etc. Technological production requires heat of high potential – 700–1000°C. The nuclear reactor also provides thermal energy and energy processes: the generation of steam for the production of electricity and for the provision of technological processes, the production of heat of various potentials for third-party industrial and domestic heat consumers. The required temperature level in this part of the installation is 300–700°C. Different potential, and consequently, the value of the heat of a nuclear reactor used in different parts of the installation; transfer of thermal energy into chemically bound energy of process agents; distribution of the thermal power of the reactor between different parts of the facility; the presence of transformation of both energy and matter; the connection between technological and energy processes and parameters makes it impossible to use traditional research methods used in the energy and technological industries.

In a number of works [8–11, 13–15], it is proposed to use thermodynamic methods to analyze technological processes in ferrous and nonferrous metallurgy, the chemical industry, and some other sectors of the national economy. Thermodynamic methods of technological processes have some differences in approaches to the analysis of technological processes, accepted reference levels of thermodynamic functions, proposed efficiency criteria, but they are all based on the fundamental laws of thermodynamics.

Nuclear energy technology installations as an object of study include inextricably linked energy and technological processes. Existing methods of thermodynamic analysis of both purely power plants and technological processes in their present form cannot be applied, firstly, due to the lack of necessary thermodynamic functions for many elements and chemical compounds [11, 16] and, secondly, due to the presence of a specific source of heat – a high-temperature nuclear reactor.

The method of thermodynamic analysis of nuclear energy technological installations will make it possible to study technological processes, the energy of which is provided by the heat of a nuclear reactor, to obtain rational schemes for organizing technological processes and their optimal parameters. In other words, the thermodynamic method of analysis will not only help to "look inside" the technological process, but will also indicate ways to create new, specific technologies, which are based on energy-saving principles.

The study of thermal schemes of multi-purpose energy technological complexes with a nuclear source of heat, producing both energy and non-energy (technological) products has many different aspects. The main ones are the following:

1. Combination of the parameters of an atomic heat source with the parameters of energy and technological processes.
2. Structure and ratio of products produced by the plant.
3. Rational organization of technological processes.
4. Optimization of parameters of thermal schemes and processes.

Thermodynamic and thermoeconomic methods of analysis make it possible to solve these problems, as well as a number of other problems related to the development of energy-saving technologies, the rational use of raw materials and fuel and energy resources.

3 Thermal Schemes and Parameters of Power Technological Installations with HTGR

With all the variety of thermal schemes of power technological installations with HTGR, they have one common fundamental feature: the high-potential part of the heat of a nuclear reactor is used to provide technological processes: natural gas conversion, coal reforming, production of reducing gas in ferrous metallurgy, etc.; and due to the heat of medium and low potentials, electricity generation and heat supply to consumers are ensured.

A common part of the thermal schemes of nuclear energy technological schemes is the reactor circuit, which includes a high-temperature gas-cooled reactor with a helium coolant, a gas blower, pipelines, a complex of auxiliary systems and safety systems. To exclude the possibility of radioactivity penetrating into the power and technological parts of the installation, these circuits usually use an intermediate circuit that includes a helium-helium heat exchanger, a gas blower, and pipelines. The pressure of the coolant circulating in the intermediate circuit is higher than in the reactor circuit, which prevents the reactor coolant from penetrating into the intermediate circuit in case of leaks and ruptures of individual tubes of the heat transfer surface of the industrial circuit heat exchanger. Based on the experience of operating high-temperature gas-cooled reactors, the main parameters of the coolant were obtained. The helium temperature at the reactor

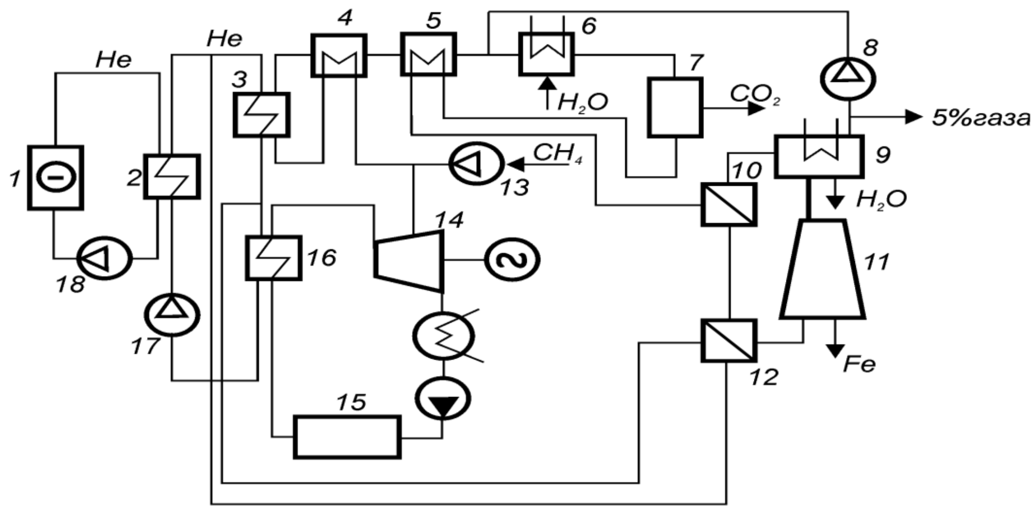

Figure 2. Scheme of the nuclear metallurgical complex on natural gas: 1 – HTGR; 2 – intermediate heat exchanger; 3 – converter; 4, 5, 10, 12 – heaters; 6, 9 – coolers; 7 – purification from CO_2; 8 – compressor; 11 – reduction furnace; 13 – compressor; 14- steam turbine; 15 – regenerative system; 16 – steam generator; 17,18 – gas blower.

outlet is 950–1000°C, the helium pressure at the reactor inlet is 5.0–5.5 MPa. The helium temperature in front of the blower is 350°C. The initial helium temperature of the intermediate circuit is 900-950°C, the helium pressure of the intermediate circuit after the blower is 5.5 MPa, the helium temperature before the blower of the intermediate circuit is 300°C. Technological processes are provided with high-potential heat of the reactor with a temperature level of 750–950°C. Heat of average potential 350-750°C is used for power generation, process steam production, domestic and industrial heat supply.

The choice of a steam power plant for the power part of nuclear power technological installations is based on meeting the specific requirements for steam parameters under the operating conditions of the technological parts of the installations, as well as the potential of HTGR heat used to generate electricity. The helium temperature at the inlet to the steam generator is in the range of 700-750°C. The required amount of steam for technological needs can be obtained from a condensing turbine with controlled steam extractions, or from the exhaust of a cogeneration turbine. Consideration of the possibility of using these two types of steam turbines showed the preference for a condensing turbine with controlled steam extractions. This is explained, firstly, by a relatively small share of steam extractions for technological needs from the total steam consumption for the turbine (10–15%) and, secondly, by the need to have steam extractions of various parameters in some cases (for example, when producing hydrogen). At the same time, condensing turbines with controlled

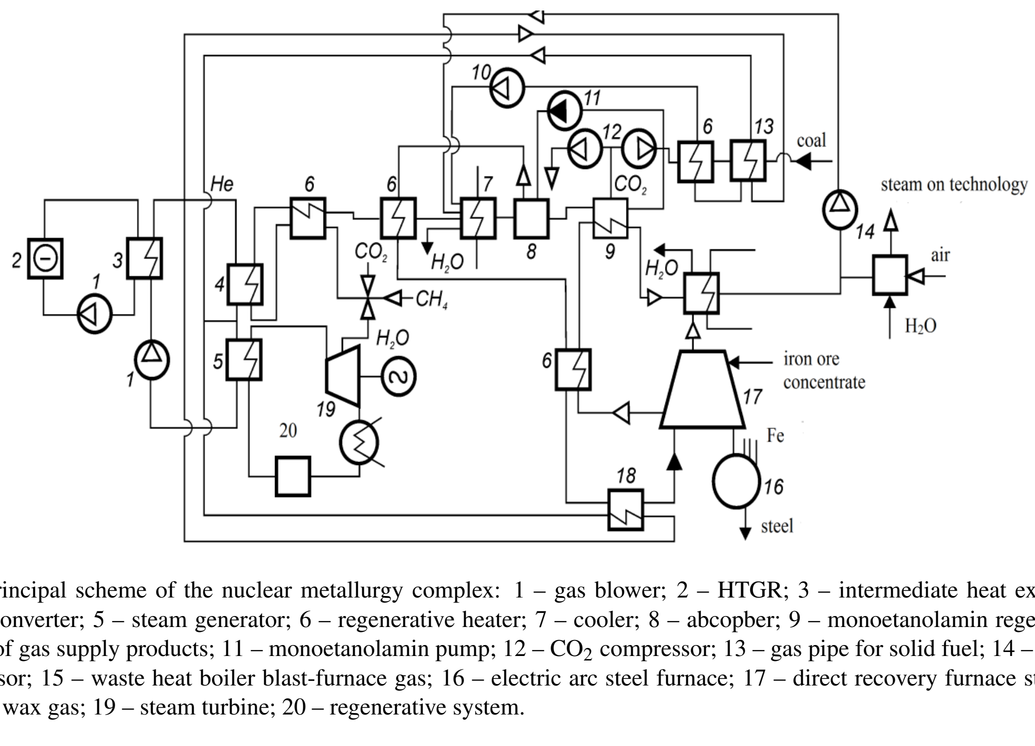

Figure 3. Principal scheme of the nuclear metallurgy complex: 1 – gas blower; 2 – HTGR; 3 – intermediate heat exchanger; 4 – natural gas converter; 5 – steam generator; 6 – regenerative heater; 7 – cooler; 8 – abcopber; 9 – monoetanolamin regenerator; 10 – compressor of gas supply products; 11 – monoetanolamin pump; 12 – CO_2 compressor; 13 – gas pipe for solid fuel; 14 – blast furnace gas compressor; 15 – waste heat boiler blast-furnace gas; 16 – electric arc steel furnace; 17 – direct recovery furnace steel; 18 – gel heater of the wax gas; 19 – steam turbine; 20 – regenerative system.

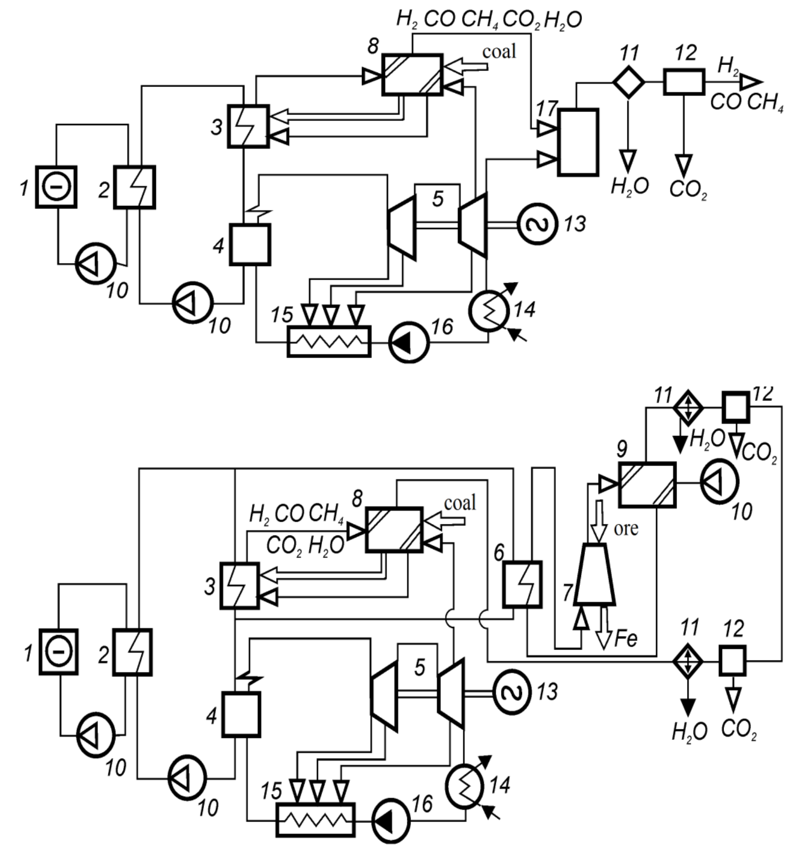

Figure 4. Schemes of installations for obtaining hydrogen (a) and sponge iron (b) with steam gasification of solid fuel: 1 – HTGR; 2 – heat exchanger of the intermediate circuit 3 – gas pipe for solid fuel; 4 – steam generator; 5 – steam turbine; 6 – heater for reducing gases; 7 – recovery furnace; 8 – regenerator of the gas supply circuit; 9 – recovery circuit regenerator; 10 – gas blower; 11 – coolers; 12 – purification of gases from CO_2; 13 – electric generator; 14 – turbine condenser; 15 – regenerative system; 16 – feed pump; 17 – preconvector CO.

steam extractions, operating at rated power and with a full load of extractions, in terms of their performance indicators, are very close to cogeneration turbines.

Gaseous (natural gas) or solid (coal) fossil fuels can serve as technological raw materials for power technological installations with HTGR. Depending on this, schemes of such installations on natural gas or coal are distinguished.

Figure 2 shows a diagram of a nuclear metallurgical complex running on natural gas. The heat carrier is helium of the primary circuit, heated in a high-temperature reactor 1 through the heat exchanger of the industrial circuit 2, transfers heat to the natural gas convector 3 and the steam generator 16. The steam-methane mixture is supplied to the converter, preheated in the heater 4. The converted gas ($CO + H_2$) after cooling is purified from carbon dioxide (monoethanolamine cleaning) and water vapor (7 and 6), then heated again (10 and 12) and sent to the reduction furnace 11, where it is used as a top gas for the reduction of iron from oxides.

When using energy-technological systems in ferrous metallurgy, the amount of iron formed, and, consequently, the performance of the installation, depends on the composition of the reducing gas. The analysis showed that the highest yield of iron is obtained at an approximately equal ratio of H_2 and CO in the reducing gas. Such a ratio can be achieved only by introducing an additional source of carbon monoxide into the circuit, the role of which can be played by a solid fuel gasifier. The latter is supplied with carbon dioxide taken from the mixture of converted and top gases. The corresponding installation diagram is shown in Figure 3.

Figure 4a shows a thermal diagram of an energy-technological installation for hydrogen production. The technological part of the scheme includes a solid fuel gasifier 3, a regenerative heater of coal and water vapor with gaseous products of gasification 5, a carbon monoxide do-converter 6, and a device for hydrogen purification after preconversion from carbon dioxide 7 and water vapor 8. Gasification of coal and preconversion of carbon monoxide is carried out by steam from turbines 10. The coal gasification process is endothermic. The required amount of heat is supplied from the intermediate circuit coolant. Hydrogen production from gaseous gasification products (synthetic gas) occurs by steam-water post-conversion of carbon monoxide. The process of carbon conversion proceeds with the release of energy, which makes it possible to organize its autothermal flow. Gas purification from carbon dioxide after conversion is carried out with a solution of monoethanolamine. There are well-developed methods and installations for industrial gas purification, the schemes of which are given, for example, in [17]. Vapors are removed by their condensation in a cooler.

Synthetic gas obtained during the gasification of solid fuel contains a significant amount of hydrogen and carbon monoxide, so it can be used as a reducing agent for the metallization of iron ore raw materials. Figure 4b shows a diagram for the recovery of sponge iron from ore. The gasification circuit is similar to the gasification circuit of the hydrogen production scheme. Useful components of coal gasification (hydrogen, carbon monoxide and methane) are sent to the circuit for recovering iron from ore. This circuit includes a reduction furnace 7, where the ore is heated and reduced to iron; heat exchanger 6, which transfers the required amount of heat to the reducing gas (CO, H_2, CH_4), regenerator 9, coolers for removing water vapor 11 and cleaning products from carbon dioxide 12. The amount of reducing gas is formed from the gas recycled in the reduction circuit and the gas coming from gasifier. Recirculation provides the necessary excess of reducing gas in the furnace. After the furnace, the gaseous reduction products enter the regenerator, the initial components of the reducing gas are heated, and, after passing through the cooler (with water vapor condensation) and purification from CO2, carbon monoxide and hydrogen recirculating in the reduction circuit merge with the purified gasification products. As a result of recycling, useful gasification products (CO, H_2, CH_4) are completely used to recover iron from ore.

The considered basic thermal diagrams and parameters of power technological installations are the initial information for research and optimization, the choice of rational ways of organizing and parameters of technological processes and their optimal combination with the parameters of a high-temperature nuclear reactor and installation cycles.

4 Conclusions

1. The directions of using high-temperature reactors in non-electrical technologies are analyzed: conversion of fossil fuels, ferrous metallurgy, hydrogen production, chemical and oil refining industries.

2. A formalized scheme of an energy-technological installation with HTGR is presented, which makes it possible to identify essential elements, processes and relationships in the installation and develop research methods.

3. The tasks of studying the thermal schemes of multipurpose energy technological complexes with an atomic heat source, which produce both energy and non-energy (technological) products, are formulated.

4. The basic technological schemes of power plants with HTGR, using natural gas and coal as technological raw materials, producing both energy-type products - electrical and thermal energy, and technological products - synthesis gas, hydrogen, reducing gas, ferrous metallurgy products are considered.

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