Open Access Journal

Journal of Power Technologies 95 (Polish Energy Mix) (2015) 32–41

journal homepage:papers.itc.pw.edu.pl

Thermodynamic analysis of a co-generation system with a high-temperature gas cooled nuclear reactor

Małgorzata Hanuszkiewicz-Drapała*, Julian Jędrzejewski

Silesian University of Technology, Institute of Thermal Technology
Konarskiego 22, 44-100 Gliwice, Poland

Abstract

This paper presents a proposal for a power system with a helium-cooled high-temperature nuclear reactor (V/HTR) used to generate heat and electricity. Heat is supplied to the technical system completing a sulfur-iodine cycle for hydrogen production. The amounts of heat and the values of the carrier temperature required at individual stages of the cycle are known. Helium energy is additionally used for electricity generation: directly—using a gas turbine and indirectly—in two steam systems. One system uses water vapor as the working medium, the other (the ORC system)—a low-boiling fluid. The paper presents the results of the system multivariate thermodynamic analyses performed using the EBSILON software package. The aim of the calculations is to investigate the impact of selected characteristic parameters of fluids and the ORC system fluid types on the power efficiency of the heat and power plant system and on the total power efficiency of the system, taking into account the hydrogen chemical energy.

Keywords: High-temperature gas cooled nuclear reactor, sulfur-iodine cycle, power efficiency

1. Introduction

The current policy of the European Union on reducing CO_2 emissions into the atmosphere creates favorable conditions for the development of unconventional technologies of heat and electricity generation. One possibility is to use renewable energy sources, e.g. wind, geothermal or solar energy. However, these solutions impose certain limitations related for example to the type of energy produced (electricity or heat), the energy characteristic parameters and the continuity of energy generation. In the case of heat generation, the parameter that determines the heat usefulness is temperature. The requirements of ensuring very high temperatures necessary for some technical processes combined with the need for a continuous supply of high-temperature heat practically eliminate the use of renewable energy sources. The gas-cooled nuclear reactor (HTR) is an alternative to the zero-emission technology of heat generation. In recent years there has been increased interest in high-temperature nuclear reactors—analyses have been performed of the feasibility and profitability of implementing this technology [1–3], also in view of the large market of process heat in Europe [4]. In future, such reactors could find application in glass making, cement production, coal gasification processes and electricity generation for example. One possibility of the reactors usage are the processes of producing the hydrogen needed in refineries and in the chemical industry. The most common process of hydrogen production is methane reforming. Another method is splitting water in thermochemical processes, e.g. in the sulfur-iodine cycle. This makes it possible to save natural gas.

Many works are available in literature on the analysis and modelling of the sulfur-iodine cycle, also taking account of the high-temperature nuclear reactor as the heat source [5–9]. Studies are also conducted on the use of solar energy in the process [10, 11].

*Corresponding author

Email address: Malgorzata.Hanuszkiewicz-Drapala@polsl.pl (Małgorzata Hanuszkiewicz-Drapała*)

This paper presents a proposal for an energy cogeneration system with a high-temperature nuclear reactor. In this case, the reactor is used to produce heat for the sulfur-iodine cycle and generate electricity. The production of hydrogen in the sulfur-iodine cycle is characterized by a different demand for heat and different levels of temperature required at the process individual stages [10]. The system structure is configured to satisfy such requirements and additionally generate electricity.

2. Description of the energy cogeneration system with a HTGR and of the system mathematical model

The paper presents results of thermodynamic analyses conducted for two systems of cogeneration with a high-temperature reactor. The diagrams of the systems are shown on Fig. 1 (Variant I) and on Fig. 2 (Variant II). The high-temperature nuclear reactor R is cooled with helium. The systems under analysis include electricity generation sub-systems and systems for the process heat transfer to the hydrogen production sulfur-iodine cycle. The main difference between the two variants is the regenerative heat exchanger after the helium compressor which makes it possible to maintain constant parameters of the gas at the nuclear reactor inlet with a possibility of reducing its temperature at the compressor inlet. However, due to the values of the helium temperature at characteristic points of the cycle, this solution also involves a need to change the system structure compared to Variant II.

The amounts of heat and the temperature levels required at individual stages of the hydrogen production process are known [10]. Heat exchangers W2-1, W3-1, W3-2, W3-3, W3-4 and W3-5 are characterized by a varied demand for the process heat and different levels of the heat carrier temperature. The medium transferring heat from the main gas cycle to the exchangers is helium.

The sulfur-iodine cycle may be described in a simplified manner using the following chemical reaction formulae (1)–(4):

$$H_2SO_4 \rightarrow H_2O + SO_3 \tag{1}$$

$$SO_3 = SO_2 + 0,5\, O_2 \tag{2}$$

$$SO_2 + I_2 + 2H_2O \rightarrow H_2SO_4 + 2HI \tag{3}$$

$$2HI \rightarrow H_2 + I_2 \tag{4}$$

Due to different values of temperature required at individual stages of the sulfur-iodine cycle, the process heat is extracted at different points of the helium main cycle, both in Variant I and Variant II. In the analyzed systems, the energy of the medium is used for electricity generation in systems of gas turbines T1 and T2 directly and, indirectly, in the water vapor cycle (T3, T4) and in the cycle with the low-boiling fluid (T5).

As was mentioned above, the high-temperature nuclear reactor is cooled with helium, which—among others—supplies heat to exchanger W1. In the exchanger heat is absorbed by the medium—helium—and supplied to the process heat exchanger W2-1 (Fig. 1, Fig. 2), where the temperature of 850°C is required. One of the sulfur-iodine cycle stages takes place there—SO_3 decomposition to SO_2 and O_2 [10]. A part of the hot helium leaving the reactor is used in turbine T1 to generate electricity. The proportion of the division of the helium flow leaving the nuclear reactor between turbine T1 and heat exchanger W1 depends on the volume of hydrogen production, i.e. on the demand for high-temperature process heat. Expanding in turbine T1, the medium indirectly supplies heat to the process heat exchanger W-3.1 (Fig. 1, Fig. 2), where the sulfuric acid solution is heated, vaporized and decomposed to SO_3 and H_2O at the temperature of about 520°C. In Variant I, helium cooled in exchanger W1 expands in the turbine and then flows into exchanger W3 in the supply system of the process heat exchangers W3-2 and W3-3. The heat given up in the system is used in the process of hydrogen iodide HI decomposition (W3-3) and in the process of H_2SO_4 concentration (W-3.2). In Variant II, heat exchanger W3 is divided into two exchangers: W3a and W3b. Exchanger W3b is supplied with helium from turbine T2; the other exchanger W3a is fed with helium flowing from the exchangers of the steam power plant system. In both cases under consideration, the process heat exchanger W-3.4, which is also involved in the process of H_2SO_4 concentration, and exchanger W-3.5, where the process of SO_2 and H_2O separation takes place, are fed with the medium preheated in heat exchanger W4. The last link on the helium flow path before compressor S is the ORC system with a low-boiling fluid.

The proposed cogeneration systems are modelled using the EBSILON software. The mathematical models are based on several fundamental assumptions which are usually adopted in this type of analysis. Among others, the following is assumed: steady-state operation of the system, no heat losses to the environment in individual elements of the cycle and no losses of the working mediums. The pressure losses in pipelines, heat exchangers and in the nuclear reactor are taken into account and—using available options of the EBSILON program—so are the characteristics of the heat exchangers.

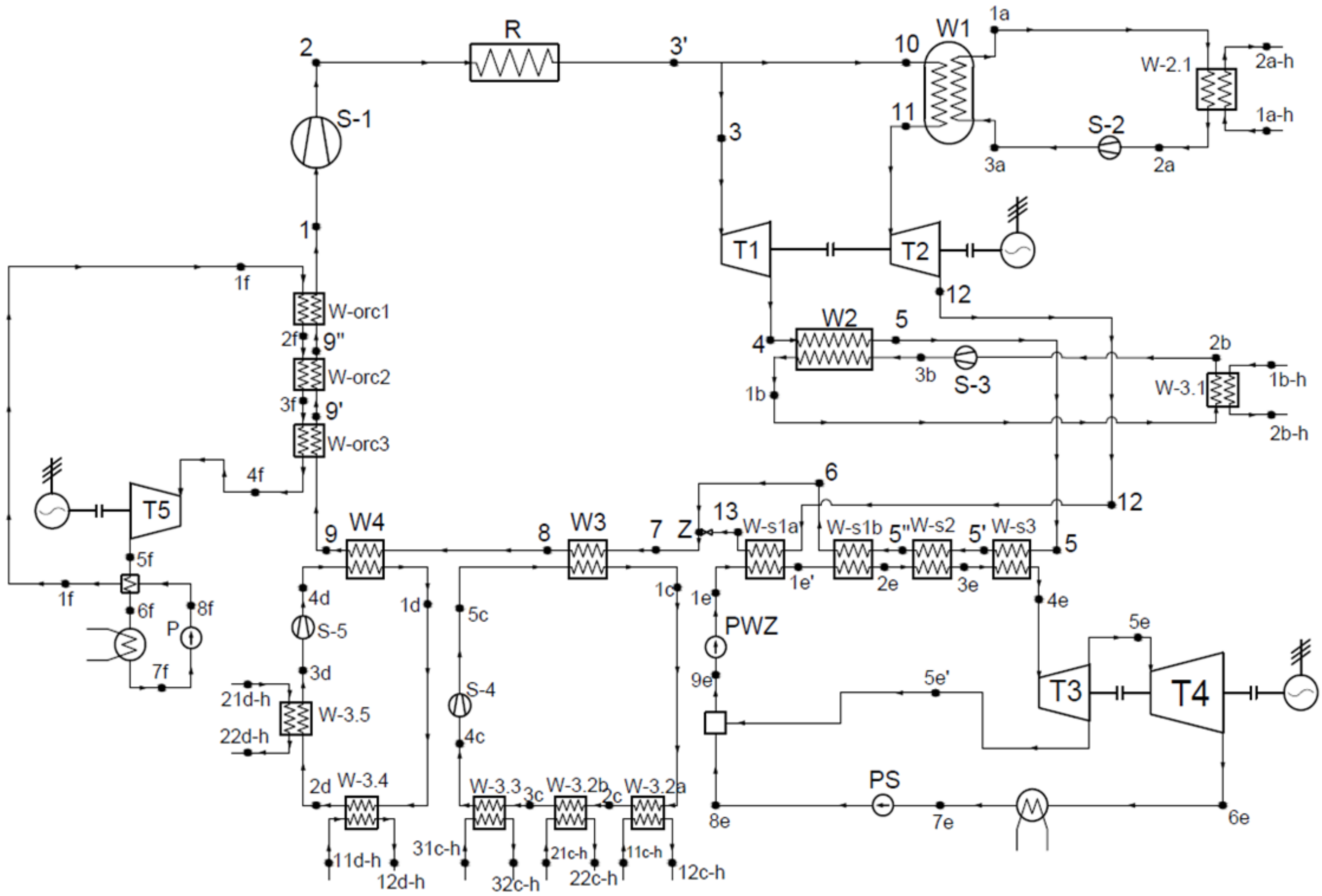

Figure 1: Diagram of the energy cogeneration system with the high-temperature nuclear reactor—Variant I

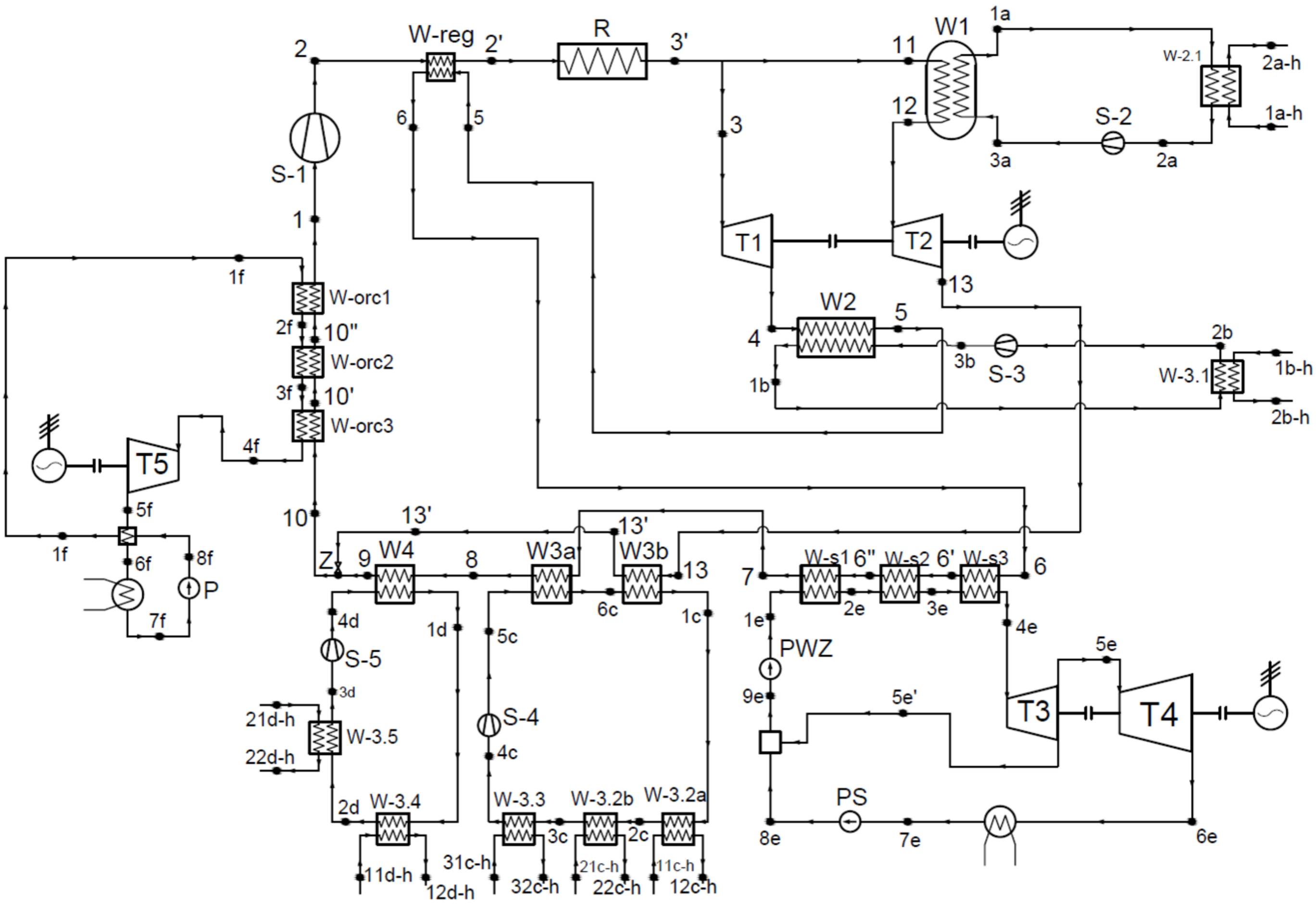

Figure 2: Diagram of the energy cogeneration system with the high-temperature nuclear reactor—Variant II

The mathematical model of the analyzed system is based on steady-state equations of the balance of energy and substance. In the EBSILON software, the system of equations is generated indirectly by constructing the system flowchart of its individual elements and then defining the connections between them and putting in characteristic data. The model is supplemented with equations of state of thermodynamic mediums, characteristics of devices and equations of adiabatic irreversible changes in the expansion and compression of the mediums.

The mathematical models developed for Variant I and Variant II of the system made it possible to conduct multivariate thermodynamic analyses. For example, a comparison is made in the paper of the impact of the use of a regenerative heat exchanger after the compressor for different values of the medium pressure in the ORC system. Moreover, analyses are performed of the effect of different kinds of the low-boiling fluid and of the impact of the degree of helium thermal regeneration after the compressor on the system power efficiency (Variant II). The calculations are performed assuming, among others, the following quantities: the nuclear reactor thermal power, the thermal parameters of helium before and after the reactor and before the compressor, the heat flux required at individual stages of the sulfur-iodine cycle and the mass flows of mediums. It is assumed that in subsequent exchangers of the steam system and of the ORC system the following processes occur one by one: the liquid is heated to the saturation state, vaporized and then superheated at a selected difference between the temperature of superheated steam and helium. It is further assumed that in Point 9e after the deaerator the condensate is in the saturation state and the pressure drops in pipelines and heat exchangers are taken into consideration. The model does not take account of the heat produced in the Bunsen reactor. The values of internal and mechanical efficiencies of turbines, compressors and pumps are also selected.

The main results of the calculations are the values of electric power generated in the gas (helium) system, the ORC system and the H_2O cycle, as well as the values of driving power of the compressors and pumps. Based on the results, the cogeneration system efficiency (5), the power generation efficiency of the entire system taking account of the chemical energy of hydrogen produced (6) and the partial efficiency of electricity generation in the ORC system (7) are determined.

The efficiencies are defined as follows:

- cogeneration system efficiency:

$$\eta_{EC} = \frac{\dot{Q} + N_{elG} + N_{elH2O} + N_{elORC} - N_{elI-S}}{\dot{Q}_R} \tag{5}$$

- power generation efficiency:

$$\eta_E = \frac{\dot{E}_{ch} + N_{elG} + N_{elH2O} + N_{elORC} - N_{elI-S}}{\dot{Q}_R} \tag{6}$$

- partial efficiency of the ORC system:

$$\eta_{ORC} = \frac{N_{elORC}}{\dot{Q}_{ORC}} \tag{7}$$

where: $\dot{E}_{ch}$—produced hydrogen chemical energy flux, N_{elG}—net electric power generated in the helium cycle, N_{elH2O}—net electric power of the steam cycle, N_{elORC}—net electric power of the ORC system, N_{elI-S}—net electric power used in the sulfur-iodine cycle, $\dot{Q}$—demand for process heat, $\dot{Q}_R$—thermal power of the nuclear reactor, $\dot{Q}_{ORC}$—flux of heat supplying the ORC system.

3. Calculation results and conclusions

As was mentioned above, the developed model of the energy cogeneration system with a high-temperature nuclear reactor was used to conduct multivariate analyses. The values of the basic data assumed for the calculations are as follows: Q_R = 30 MW, $t_{2'}$ = 425°C, $t_{3'}$ = 890°C, p_2 = 40 bar, $p_{3'}$ = 35 bar, p_{5f} = 0.1 bar, p_5 = 8 bar, p_{6e} = 0.1 bar. The mass flows of mediums in both the steam and the fluid vapor cycles are determined. Their values result from the assumptions made for the heat exchangers in the systems. The following values of the heat flux required in the process heat exchangers are assumed [6]: $Q_{W-2.1}$ = 1420 kW, $Q_{W\ 3.1}$ = 2075 kW, $Q_{W-3.2a}$ = 1318 kW, $Q_{W-3.2b}$ = 1065 kW, $Q_{W-3.3}$ = 1450 kW, $Q_{W-3.4}$ = 140 kW, $Q_{W-3.5}$ = 273 kW; the assumed total demand for electric energy in the sulfur-iodine cycle is N_{elI-S} = 480 kW. These values correspond to the hydrogen production of 10 mol/s. The working fluid assumed for the ORC system is ethanol.
The impact of selected thermodynamic parameters of the mediums and of the type of the low-boiling fluid on the system efficiency is also analyzed.
The calculations were performed for assumed values of the temperature of helium before compressor S (150°C—Variant I, 110°C–140°C—Variant II), at different values of the low-boiling fluid pressure at the turbine inlet. Selected results of the analyses are presented on Fig. 3– 13. In the second case under analysis (Variant II) the calculations were also

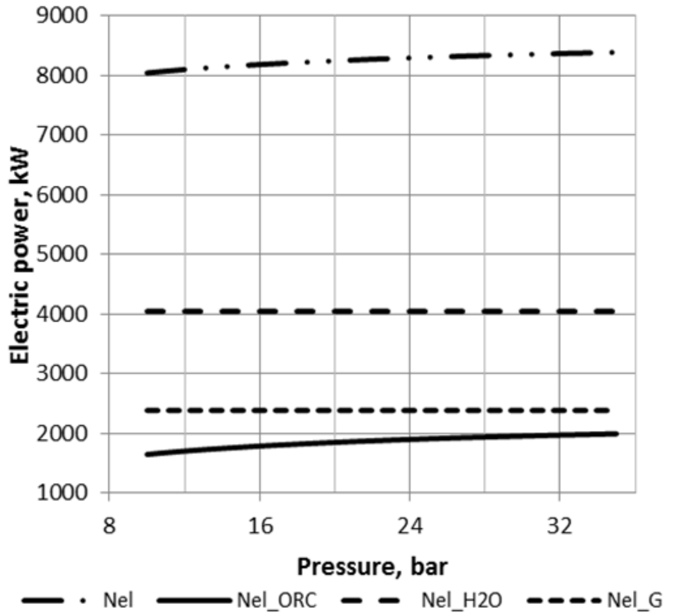

Figure 3: Total net electric power generated in the cogeneration system, electric power of the OCR system, electric power of the vapor cycle for assumed values of the low-boiling fluid vapor pressure (ethanol, p_{4e} = 80 bar, t_1 = 150°C)—Variant I

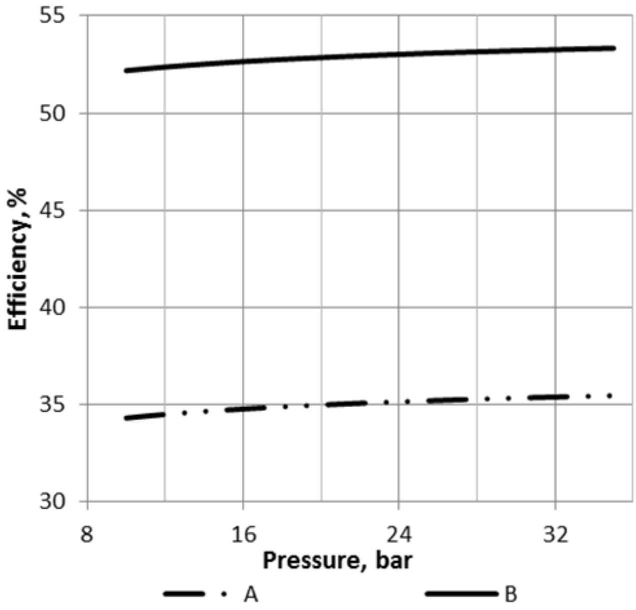

Figure 4: Efficiency of the cogeneration system (A) and the system total power efficiency (B) for assumed values of the low-boiling fluid vapor pressure (ethanol, p_{4e} = 80 bar, t_1 = 150°C)—Variant I

made for other low-boiling fluids—pentane, butane, R113 and R11 (Fig. 11, Fig. 13).

In the case of Variant I, the system electric power varies in the range of 8.05...8.40 MW, at the ethanol vapor pressure ranging from 10 to 32 bar. The increase is related to the rise in the ORC system power, at a practically constant value of electric power generated in the H_2O vapor cycle. The power efficiency of the cogeneration system in the considered range of pressure values varies only slightly—between 52.2% to 53.3%. Lower values are obtained for the power efficiency of the entire system, i.e. for efficiency calculated assuming that the products of the system operation are electricity and hydrogen. They are in the range of 34.3...35.7%.

Fig. 5 presents the dependence of the driving mechanical power of the compressor on the gas temperature at the device inlet. As was mentioned earlier, it is possible to reduce this temperature without changing the temperature of the helium before the reactor t_2 if a regenerative heat exchanger W-reg is installed (Fig. 2). In the proposed solution, considering the value of temperature t_2, the exchanger is supplied with helium leaving heat exchanger W2. The mass flow of the medium varies depending on the temperature of helium before the compressor (t_1) because a drop in the medium temperature at the compressor inlet requires a bigger flux of regeneration heat (Fig. 6).

The impact of the temperature of helium t_1 on the system operation parameters, including net electric power and power efficiency is illustrated on Fig. 7–11. The figures concern the temperature of helium included in the range of 110°C–140°C and the ethanol vapor pressure before the turbine—from 10 bar to 35 bar. In each analyzed variant, at the assumed value of ethanol pressure before turbine T5, a drop in the temperature of helium at the compressor inlet involves a rise in the net electric power of the entire system (Fig. 7). The total electric power of the system varies between ~7.86 MW and ~8.85 MW. The effective power generated in the gas part of the system is constant at about 20.6 MW; the electric power of the ORC system rises (Fig. 8) but the electric power of the water vapor system drops (Fig. 9). If the temperature of helium is lowered (at a constant value of ethanol vapor pressure), the rise in the ORC system power results from the increased flux of heat absorbed from helium before the compressor, and the decrease in the steam system electric power (Fig. 9) is related to the need to provide a bigger flux of heat to the regenerative heat exchanger W-reg (Fig. 6).

Consequently, the heat flux supplied to the steam system is smaller. However, the factor which is of decisive importance in terms of the total net electric power and efficiency of the cogeneration system is the impact of the temperature of helium at the compressor inlet on the device driving power (Fig. 6). A rise in the value of ethanol vapor pressure involves an increase in the electric power gener-

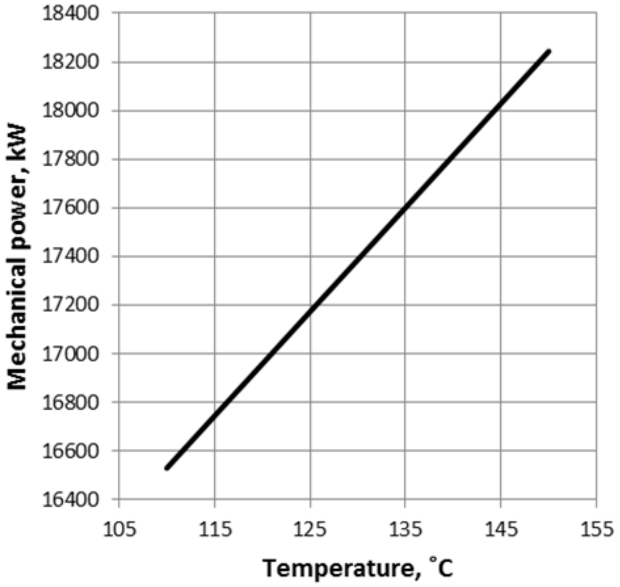

Figure 5: The compressor driving mechanical power depending on helium temperature at the device inlet—Variant II

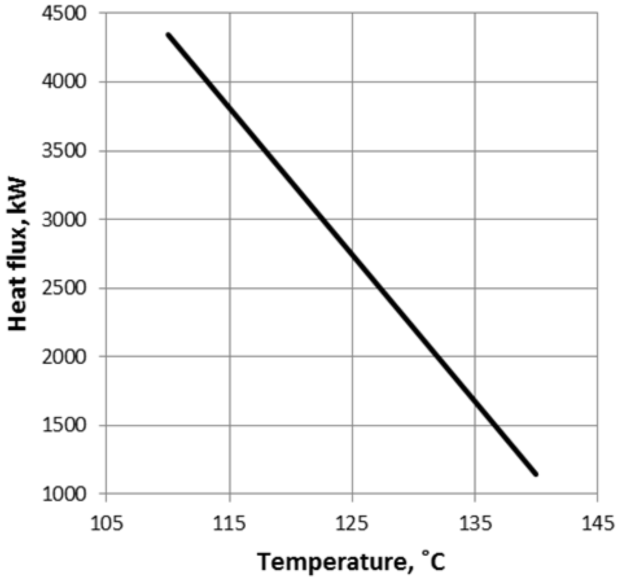

Figure 6: The regeneration heat flux depending on helium temperature at the inlet—Variant II

ated in the ORC system (Fig. 8), and—consequently—in electric power of the entire system (Fig. 7). The power efficiency of the cogeneration system in the variants under analysis varies from about 51.5% to about 54.7% (Fig. 10); the system total efficiency calculated according to (6) varies in the range of 35.6%–36.7% (Fig. 11).

The results of the analyses presented on Fig. 12–14 prove that the selection of a low-boiling fluid substantially affects the ORC system efficiency and, consequently, the efficiency of the cogeneration system and the total power efficiency of the system as a whole. In the case under consideration, for a constant temperature of helium at the compressor inlet (t_1=110°C), it is favorable to use the R113 fluid—at the pressure value of vapor at the turbine inlet of about 20 bar, the ORC system efficiency is about 25%, and the cogeneration system efficiency—about 55.5%. Slightly lower values (by about 0.75 percentage points) are characteristic of ethanol (Fig. 10) and the lowest efficiency values at the same pressure are obtained for butane—about 52.6% (Fig. 12).

4. Final comments

This paper presents a proposal for the structures of energy cogeneration systems with a high-temperature nuclear reactor used to generate process heat with specific parameters and thermal energy. The presented results of thermodynamic analyses indicate the direction of actions that should be taken to improve system efficiency. Lowering the temperature of helium at the compressor inlet—and the related bigger flux of regeneration heat involve a need to reconstruct the system structure. Reducing the helium temperature further may eliminate the use of steam as the working medium. The selection of the medium in the ORC system is also important. The results of analyses performed for the temperature of helium at the compressor inlet of 110°C indicate that using R113 is a favorable option. In this case, the power efficiency of the entire system reaches approximately 39.5%. A further increase in regeneration heat in the cogeneration system used for process heat and electricity generation would require thermodynamic analyses that take account of other thermodynamic mediums in vapor systems. In order to find the optimum solution in the future, it will be necessary to conduct both thermodynamic and economic analyses which additionally factor in the environmental impact.

Acknowledgements

This work was financed by the National Centre for Research and Development, Poland, under the strategic project “Technologies Supporting Development of Safe Nuclear Power Engineering”, Task 1: “Development of high-temperature reactors for industrial purposes (HTRPL)”, grant number—SP/J/1/166183/12

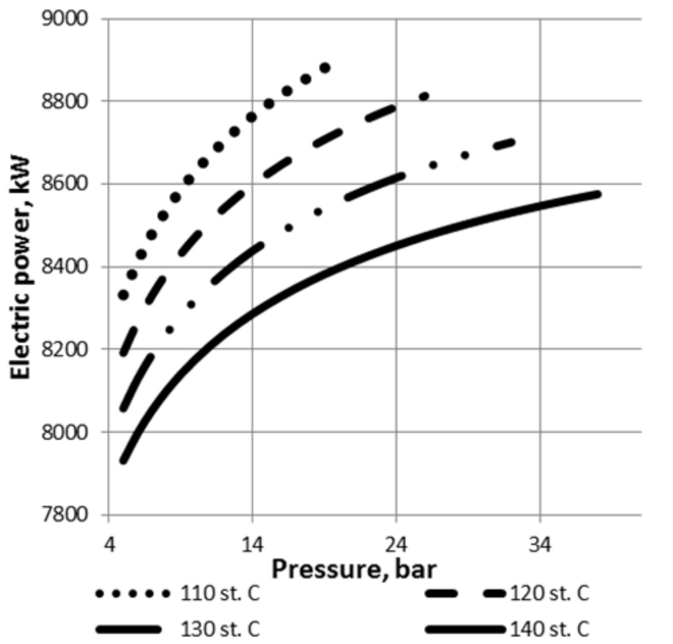

Figure 7: Total net electric power generated in the cogeneration system for assumed values of the temperature of helium before the compressor (ethanol, p_{4e} = 80 bar)—Variant II

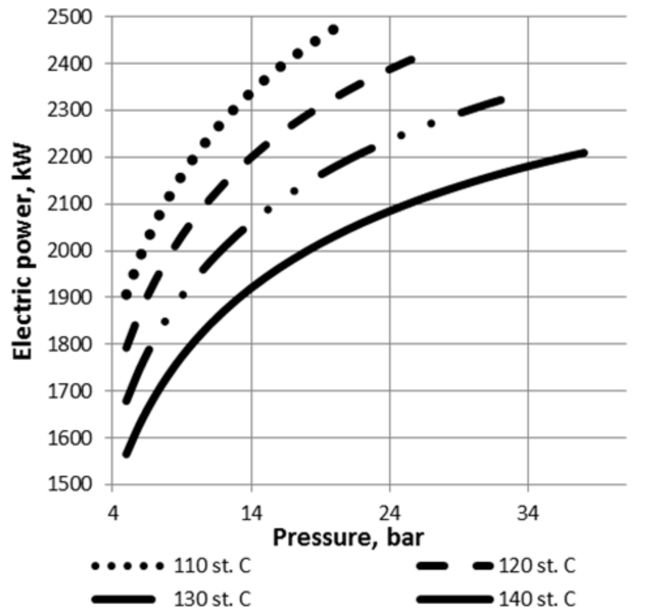

Figure 8: Net electric power generated in the ORC system for assumed values of the temperature of helium before the compressor (ethanol, p_{4e} = 80 bar)—Variant II

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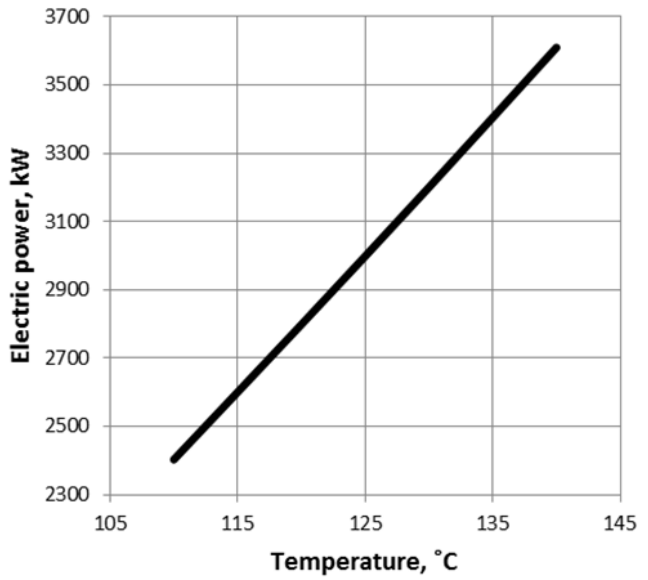

Figure 9: Net electric power generated in the water vapor system for assumed values of the temperature of helium before the compressor—Variant II

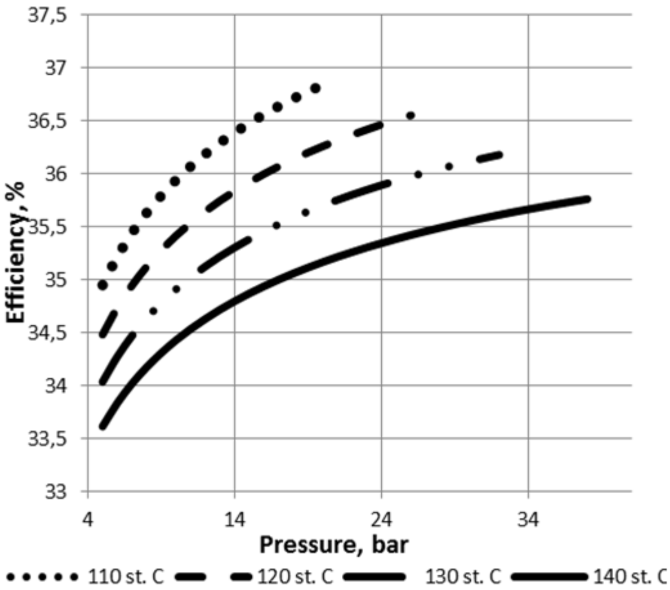

Figure 11: Power efficiency of the system for assumed values of the temperature of helium before the compressor (ethanol, p_{4e} = 80 bar)—Variant II

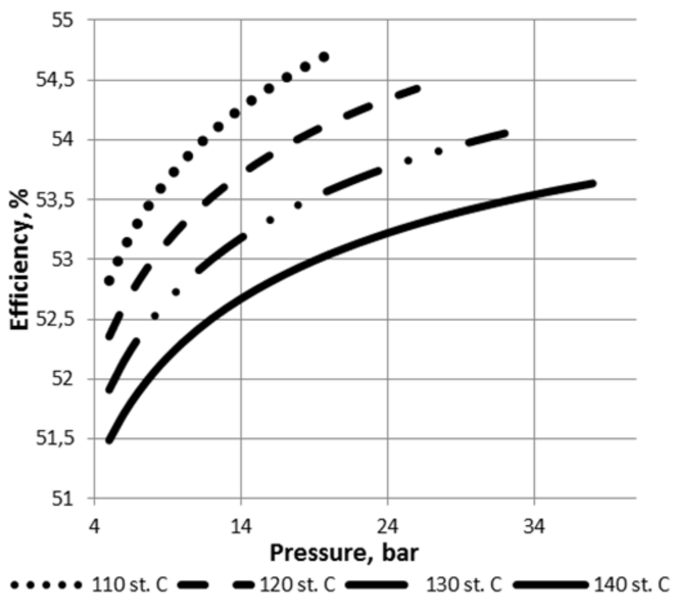

Figure 10: Efficiency of the cogeneration system for assumed values of the temperature of helium before the compressor (ethanol, p_{4e} = 80 bar)—Variant II

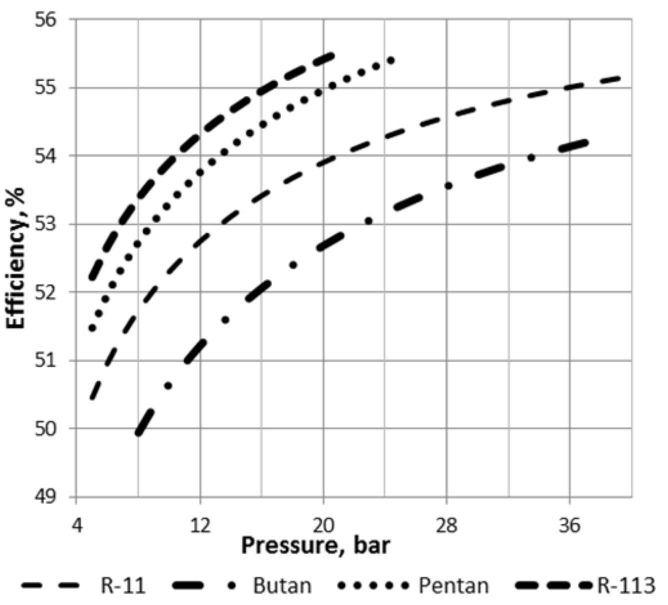

Figure 12: Power efficiency of the cogeneration system for selected low-boiling fluids (helium temperature before the compressor—110°C) (p_{4e} = 80 bar)—Variant II

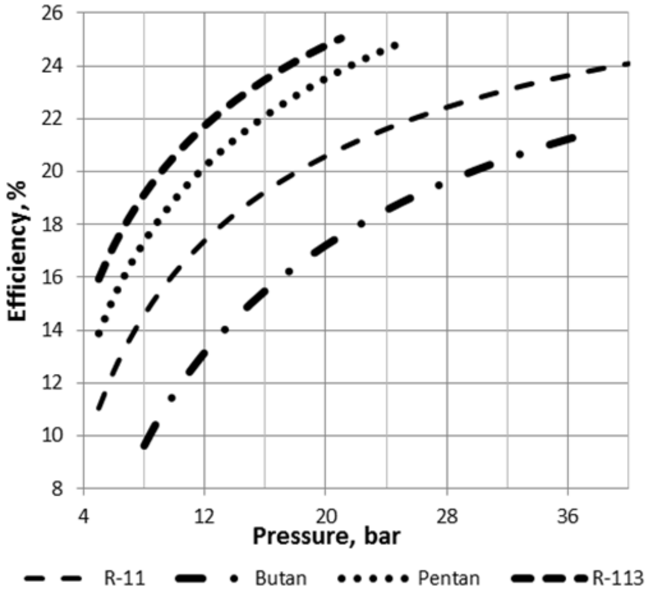

Figure 13: Power efficiency of the ORC system for selected low-boiling fluids (helium temperature before the compressor—110°C) (p_{4e} = 80 bar)—Variant II

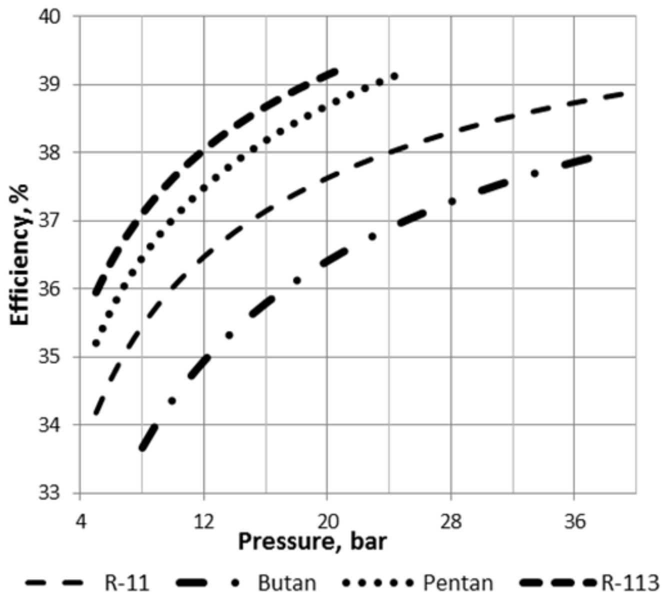

Figure 14: Total power efficiency of the system for selected low-boiling fluids (helium temperature before the compressor—110°C) (p_{4e} = 80 bar)—Variant II