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Utilization of organic Rankine cycles in a cogeneration system with a high-temperature gas-cooled nuclear reactor – thermodynamic analysis

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Abstract The paper presents results of a parametric analysis of a high-temperature nuclear-reactor cogeneration system. The aim was to investigate the power efficiency of the system generating heat for a high-temperature technological process and electricity in a Brayton cycle and additionally in organic Rankine cycles using R236ea and R1234ze as working fluids. The results of the analyses indicate that it is possible to combine a 100 MW high-temperature gas-cooled nuclear reactor with a technological process with the demand for heat ranging from 5 to 25 MW, where the required temperature of the process heat carrier is at the level of 650°C. Calculations were performed for various pressures of R236ea at the turbine inlet. The cogeneration system maximum power efficiency in the analysed cases ranges from ~35.5% to ~45.7% and the maximum share of the organic Rankine cycle systems in electric power totals from ~26.9% to ~30.8%. If such a system is used to produce electricity instead of conventional plants, carbon dioxide emissions can be reduced by about 216.03–147.42 kt/year depending on the demand for process heat, including the reduction achieved in the organic Rankine cycle systems by about 58.01–45.39 kt/year (in Poland).

Keywords: ORC; HTGR; Cogeneration system; Reduction in CO_2 emissions

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Nomenclature

N_{elG}	–	net electric power generated in the helium cycle, MW
$N_{el\mathrm{ORC}i}$	–	net electric power of the i-ORC system, MW
$\dot{Q}_{\mathrm{ORC}i}$	–	heat transferred to the i-ORC system, MW
$\dot{Q}_{tech}$	–	demand for process heat, MW,
$\dot{Q}_R$	–	thermal power of the nuclear reactor, MW

Greek symbols

η_{CS}	–	energy efficiency of the heat and power plant
η_{ORCi}	–	energy efficiency of the i-ORC system
η_{el}	–	partial power efficiency of electricity production

1 Introduction

In recent years there has been an increased interest in high-temperature gas-cooled nuclear reactors (HTGRs) to produce electricity and heat for technological processes requiring high temperatures. The results of studies on cogeneration systems using a high-temperature reactor can be found e.g. in [1–8]. Although in the past the design power of HTGR systems was generally at the level of about 600 MWe [1], attention is now focused on reactors characterized by smaller power capacities [1,2]. Such reactors could be the heat source for industrial plants requiring a high-temperature heat carrier and located relatively close to a nuclear power unit.

One potential area where high-temperature heat obtained from a nuclear reactor could be utilized is the thermochemical cycle of hydrogen production [3–5]. The possibilities of using a 600 MWt reactor for electricity generation, seawater desalination and hydrogen production in the iodine-sulphur (I-S) cycle, as well as for preparing steam for the soda-making process, are presented in [3]. In [4], the results are presented of a multivariate thermodynamic analysis of HTGR systems where electrical energy is generated in the helium cycle, the steam cycle and in the organic Rankine cycle (ORC) system with different working fluids. In this case, heat is supplied to heat exchangers of the iodine-sulphur (I-S) cycle subsequent stages. The results of analyses of a cogeneration system generating electricity in gas and steam cycles and supplying heat for the thermochemical cycle of hydrogen production (iodine-sulphur or sulphur-copper) are presented in [5]. Issues related to the possibility of utilizing heat generated in small pebble-bed modular reactors (PBMRs) in refineries are discussed in [6]. Investigations of the possibility of using waste energy in a cogeneration system producing electricity and process heat for the I-S cycle are presented in [7]. An ORC system with alkane or benzene as the working fluid is used for this purpose. In the cogeneration system electricity is also generated using a gas turbine system. The authors of [8] propose a system using a high-temperature reactor and a modified ammonia-water cycle. The system generates electrical energy and cold. The results made it possible to determine the optimal concentration of ammonia and estimate savings in chemical energy and the reduction in carbon dioxide (CO_2) emissions by a comparison with conventional systems generating electricity and cold. The paper [9] presents the results of multivariate energy analyses of a system generating high temperature process heat, electricity in Bryton and steam cycles. The system is also equipped with a high temperature argon heat pump.

This paper presents calculation results of a cogeneration system using a high-temperature nuclear reactor cooled with helium. The authors propose the structure of a system producing electricity in a Brayton and organic Rankine cycles as well as heat for a technological process requiring high temperature. The analysis takes account of two-stage helium compression with interstage cooling and a regenerative heat exchanger between the system of compressors and the nuclear reactor. The working fluids in the ORC are R236ea and R1234ze; among others they make use of waste energy. Multivariate analyses are performed assuming various R236ea pressures at the turbine inlet and values of the demand for process heat. The aim was to investigate the impact of the demand for process heat and of R236ea pressure on the total electric power of the system, the electric power and power efficiency of the ORC and the cogeneration system power efficiency. The calculation results also show the impact of thermal load on possibilities of ORC utilization in the cogeneration system. The reduction in emissions of harmful pollutants into the environment, achieved due to electricity generation in a system with a nuclear reactor instead of conventional combustion systems, is calculated for the Polish conditions.

2 Cogeneration system and mathematical model description

The proposed cogeneration system diagram is presented in Fig. 1. The system under analysis is composed of a nuclear reactor (R), two gas turbines (T1, T2) driving compressors (C-1, C-2), a heat exchanger (HX-tech), where heat is supplied to satisfy the needs of the technological process, and two heat exchangers (HX-1, HX-2) cooling the gas to the set temperature upstream the compressors. The system includes a regenerative heat exchanger (HX-reg) ensuring constant temperature of the gas at the nuclear reactor inlet. As mentioned above, the reactor is cooled with helium. Heat is supplied to ORC1 and ORC2 systems using intermediate cycles with Dowtherm A as the heat carrier. In the proposed structure of the system, the heat obtained from helium cooling in the interstage heat exchanger HX-1 is utilized in the heat exchangers (HX-41, HX-42, HX-43) of ORC2 system. Heat exchangers HX-31 and HX-32 in the ORC1 cycle are fed with helium heat using an intermediate cycle with heat exchanger HXX and Dowtherm A as the heat carrier. Exchangers HX-31 and HX-41 heat up the liquids, whereas in exchangers HX-32 and HX-42 the liquids evaporate. The dry saturated vapour of R1234ze obtained at the outlet of exchanger HX-42 (cf. 3g in Fig. 1) is then superheated in heat exchanger HX-43. In heat exchanger HX-11, Dowtherm A is cooled by water, ensuring constant temperature at the HX-1 inlet. The heat collected from helium in exchanger HX-2 upstream compressor C-1 and the heat taken by water in exchanger HX-11 are treated as waste heat. Water is also used as coolant in the condensers, namely

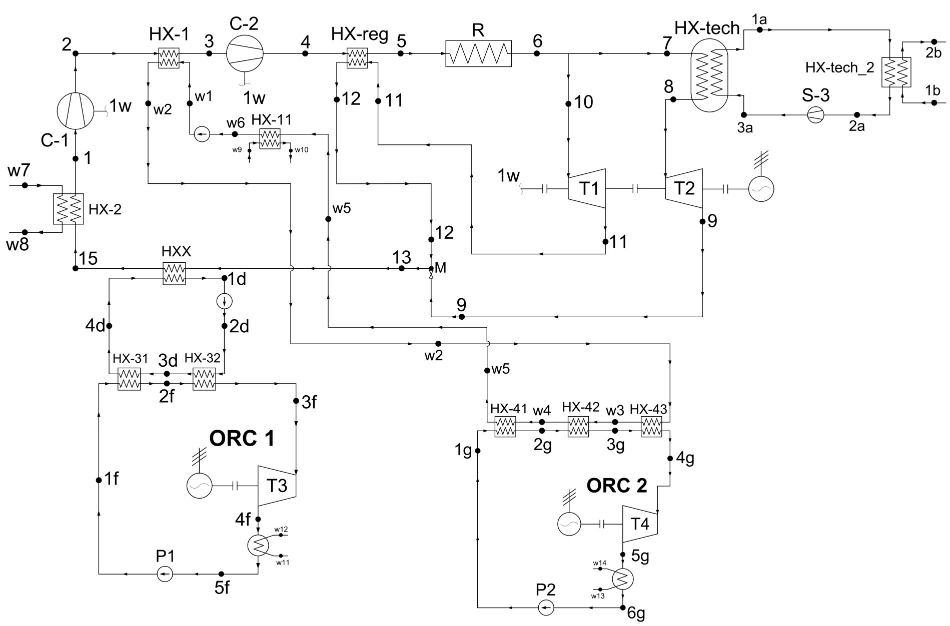

Figure 1: Diagram of the cogeneration system (Variant I).

in ORC1 and ORC2 systems. The water mass flow rate is calculated assuming constant values of water temperature at the condensers inlet and outlet. The pressure of the low-boiling fluids in the ORC cycles at the condenser inlet is determined as saturated pressure for the fluid temperature calculated assuming the minimum temperature difference in the condensers.

The low-boiling fluids are R236ea (ORC1) and R1234ze (ORC2). They were selected considering the level of toxicity and chemical stability, the flash point and environmental protection. R236ea is a low-toxic fluid, stable under high temperature and pressure. It has a high flash point and is environmentally friendly – the ODP (ozone depletion potential) equals zero and the GWP (global warming potential) is 20 [10].

Based on [11], the optimal working fluid should have the critical point 30–50 K below the temperature of the upper heat source. In the case of the ORC1 cycle, the temperature of the upper heat source ranges from 182°C to 238°C depending on the demand for process heat. The critical temperature of R236ea is 139.29°C, which means that R236ea fulfils this criterion. According to [12], the maximum power of ORC system is obtained if the critical temperature value totals about 80% of the temperature of the upper heat source. R236ea meets this criterion as well. According to [13], R236ea is a recommended fluid for use in ORC systems. In the considered case for the ORC2 cycle R1234ze was selected as the working fluid. R1234ze was examined in ORC systems [14]. It is a nontoxic fluid characterized by low flammability, and its negative impact on the environment is very low: ODP = 0 and GWP = 4 [15].

The calculations are performed using commercial Ebsilon Professional program, a highly flexible system for modelling thermodynamic cycles [16], which can be used to model thermodynamic processes occurring in cycles of conventional, nuclear and solar power plants. The cogeneration system is analysed assuming its steady-state operation and no heat losses to the environment in its elements. The mathematical model is made up of mass and energy balance equations for the system individual elements, equations of thermodynamic processes and relations used to calculate the specific enthalpy or entropy values of heat carriers. By solving this system of equations, it is possible to calculate the mass flow rate of low-boiling fluids, heat transferred to ORCs, mechanical power of the turbines, compressors mechanical driving power and finally the value of electric power generated in ORC1, ORC2 and in the gas system. Energy efficiencies of the heat and power plant, η_{CS}, and of the i-ORC system, η_{ORCi}, together with the partial power efficiency of electricity production, η_{el} can also be determined.

$$\eta_{CS} = \frac{\dot{Q}_{tech} + N_{elG} + \sum_{i=1}^{2} N_{el\,ORCi}}{\dot{Q}_R} \,, \tag{1}$$

$$\eta_{ORCi} = \frac{N_{el\,ORCi}}{\dot{Q}_{ORCi}} \,, \tag{2}$$

$$\eta_{el} = \frac{N_{elG} + \sum_{i=1}^{2} N_{el\,ORCi}}{\dot{Q}_R} \,. \tag{3}$$

3 Preliminary calculations – determination of parameters in the two-stage compression system

The thermodynamic analysis of Variant I was preceded by checking the impact of helium pressure in the two-stage compression system on the cogeneration system operation parameters. This was done by ranging thermodynamic calculations of the system Variant II with a simpler structure (cf. Fig. 2). The system mathematical model is based on the same assumptions and the calculations are performed using the Ebsilon Professional program. The main data for the calculations are listed in Table 1.

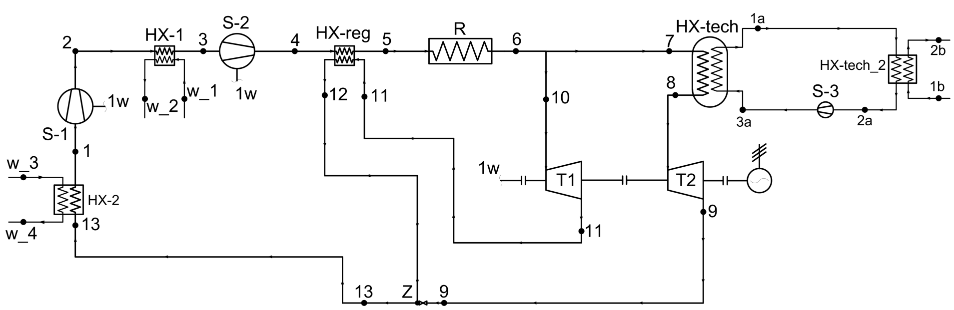

Figure 2: Diagram of the cogeneration system (Variant II).

The calculations are carried out assuming constant values of helium temperature at the inlet of compressors C-1 and C-2, *i.e.* $t_1 = 30°\mathrm{C}$ and $t_3 = 50°\mathrm{C}$ (cf. Fig. 2). The former value results from the possibility of heat being trans-

Table 1: Main data for the calculations – Variant II.

Quantity	Value	Unit
HTGR thermal power	100	MW
Process thermal load	15	MW
Helium temperature; t_5, t_6	250, 750	°C
Helium pressure; p_2	1.2–2.9	MPa
Helium pressure; p_4	3.0–6.0	MPa
Intermediate heat carrier temperature; t_{1a}, t_{3a}	650, 500	°C
Helium temperature in the compressor system; t_1, t_3	30, 50	°C
Mass flow rate; m_6, m_7	38.6, 19.3	kg/s
Inner efficiency of the gas turbine	90	%
Mechanical efficiency of the gas turbine	98	%
Efficiency of the electric generator	98.6	%
Helium pressure; p_9, p_{11}	1.0	MPa
Cooling water temperature; t_{w1}, t_{w2}	15, 25	°C
Cooling water temperature; t_{w3}, t_{w4}	15, 25	°C

ferred to the environment in exchanger HX-2, upstream compressor C-1. The aim of the calculations is to find the optimal values of helium pressure p_4 and p_2 at the reactor inlet and between the compression stages, respectively. Variant calculations are conducted for the p_4 values of 3–6 MPa assuming a constant thermal load of the process exchanger HX- tech (cf. Table 1).

The results of calculations are presented in Fig. 3 and 4. Line L_A in Fig. 3 illustrates the optimal values of interstage pressure (p_2) for assumed values of helium pressure at the reactor inlet (p_5). As indicated by the results of the analyses, the system electric power reaches the maximum value for interstage pressure $p_2 = 2.4$ MPa and helium pressure at the reactor inlet $p_5 = p_4 = 5$ MPa (cf. A in Fig. 3). The maximum value totals 18.233 MW. The power efficiency of the cogeneration system in Variant II is then equal to about 33.2%. The results of further numerical simulations show that a higher value of electrical power of about 18.27 MW can be achieved if temperature t_3 at the inlet of compressor S-2 is lowered to 40°C (cf. Fig. 4).

Figure 4 illustrates the calculation results for a wider range of helium temperature values ($t_3 = 40-100$°C). A rise in temperature t_3 involves a drop in the system net electric power, but also a decrease in the regeneration heat. For the maximum temperature assumed in the calculations

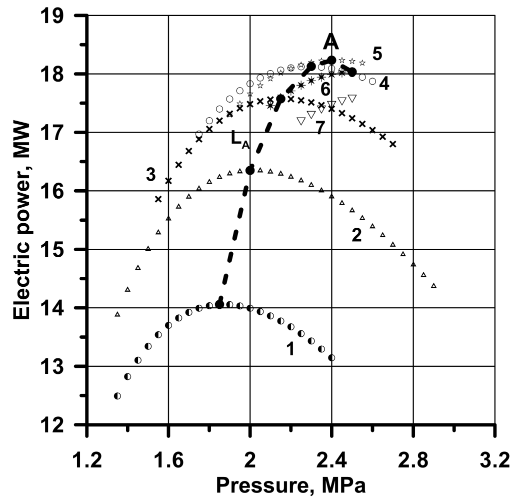

Figure 3: Net electric power depending on helium interstage pressure for assumed values of helium pressure at the reactor inlet: 1 – 3.0 MPa, 2 – 3.5 MPa, 3 – 4.0 MPa, 4 – 4.5 MPa, 5 – 5.0 MPa, 6 – 5.5 MPa, 7 – 6.0 MPa.

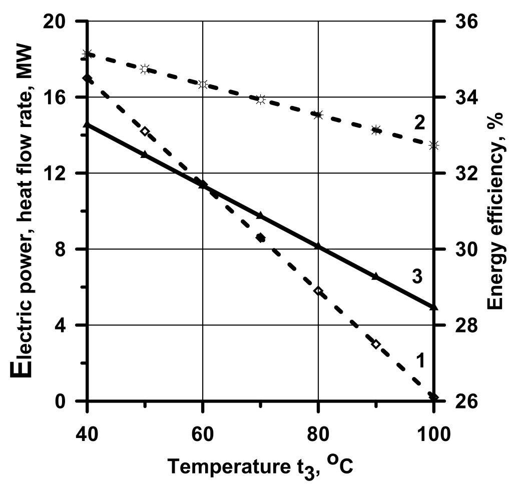

Figure 4: Thermal power of heat exchanger HX-reg (1), net electric power (2) and power efficiency of cogeneration system Variant II (3) depending on helium temperature t_3 at compressor S-2 inlet ($p_4 = 5$ MPa).

($t_3 = 100°$C), the heat transferred in exchanger W-reg reaches the lowest value of about 199 kW, and the cogeneration system electric power and power efficiency take the minimum values of 13.46 MW and 28.46%, respectively (cf. Fig. 4). The efficiency is determined assuming that the heat obtained from helium cooling in the compression system is not utilized energy-wise. In the assumed range of temperature t_3, it takes values ranging from about 33.3% to about 28.5%. Partial power efficiency of electricity production achieves values from 18.3% to 13.3%.

4 Results of thermodynamic calculations of cogeneration system Variant I

The basic data for thermal calculations of cogeneration system Variant I (cf. Fig. 1) are listed in Table 2. As mentioned before, mathematical model of the system allows to determine finally values of mechanical power of the turbines, the compressors mechanical driving power and the value of electric power produced in the gas and the ORC systems, the power efficiencies of the heat and power plant and of the ORC systems.

Multivariate calculations were performed for the following assumed process heat parameters: 5 MW (A), 10 MW (B), 15 MW (C), 20 MW (D), 25 MW (E) and for R236ea pressure values p_{3f} in the ORC1 system ranging from 1 MPa to 3.2 MPa (cf. Table 2). Assumed maximal value of this pressure is lower than critical pressure equalling 3.5 MPa. The main results of the numerical simulations are presented in Figs. 5–9. Net electric power

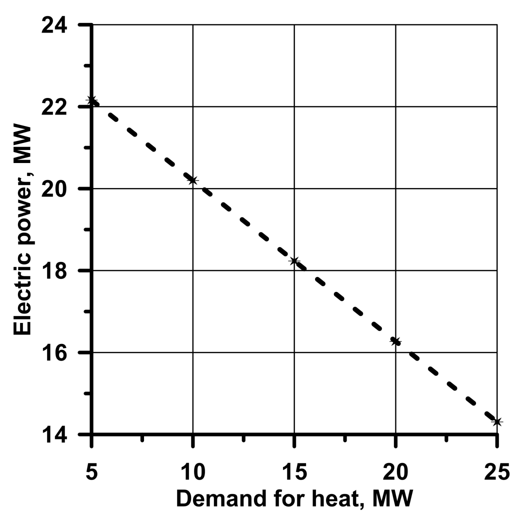

Figure 5: Net electric power generated in the helium system depending on the demand for process heat.

Table 2: Main data for the calculations – Variant I.

Quantity	Value	Unit
HTGR thermal power	100	MW
Process thermal load	5–25	MW
Helium temperature; t_5, t_6	250, 750	°C
Helium pressure; p_5, p_2	5.0, 2.4	MPa
Intermediate heat carrier temperature; t_{1a}, t_{3a}	650, 500	°C
Helium temperature in the compression system; t_1, t_3	30, 50	°C
Helium pressure; p_9, p_{11}	1.0, 1.0	MPa
Mass flow rate; m_6, m_7	38.6, 19.3	kg/s
Inner efficiency of the gas turbine	90	%
Mechanical efficiency of the gas turbine	98	%
Efficiency of the electric generator	98,6	%
Cooling water temperature; t_{w7}, t_{w8}	15, 25	°C
Cooling water temperature; t_{w9}, t_{w10}	15, 25	°C
Heat carrier temperature; t_{w1}	30	°C
Heat carrier temperature; t_{w2}	165	°C
Heat carrier mass flow; m_{w1}	107.4	kg/s
Heat carrier pressure; p_{w1}	0.5	MPa
Temperature difference; $t_{13} - t_{1d}$	10	K
Heat carrier mass flow; m_{1d}	100	kg/s
Heat carrier pressure; p_{1d}	0.5	MPa
R236ea pressure; p_{3f}	1–3.2	MPa
R236ea subcooling in 2f point	2	K
R236ea steam quality; x_{3f}	1	–
R236ea pressure; p_{4f}	0.2444	MPa
Inner efficiency of the turbine T3	85	%
Inner efficiency of the pump P1	80	%
Temperature difference; $t_{4d} - t_{1f}$	10	K
Cooling water temperature; t_{w11}, t_{w12}	15, 25	°C
R1234ze pressure; p_{4g}	3.2	MPa
R1234ze subcooling in 2g point	2	K
R1234ze steam quality; x_{3g}	1	–
R1234ze superheating degree in 4g point	10	K
R1234ze pressure; p_{5g}	0.5784	MPa
Inner efficiency of the turbine T4	85	%
Inner efficiency of the pump P2	80	%
Temperature difference $t_{w5} - t_{1g}$	10	K
Cooling water temperature; t_{w13}, t_{w14}	15, 25	°C
Minimum temperature difference in the condensers	5	K

generated in the system of gas turbines T-1 and T-2 decreases with a rise in the demand for process heat and takes values ranging from about 22.2 MW to 14.3 MW (cf. Fig. 5). Turbine T-1 mechanical power is constant, while the T-2 gas turbine operation depends on the demand for process heat. At a rise in the thermal load, $\dot{Q}_{tech}$, the turbine power decreases due to the drop in the temperature of helium at the outlet of the process heat exchanger (HX-tech). The mechanical driving power of compressors calculated for the assumed pressures and temperatures of helium in the compression system is constant and totals about 57.5 MW. In the considered cases of the demand for heat, it ranges from about 71.9% (A) to about 79.8% (E) of the mechanical power of the gas turbines.

Having an indirect impact on the temperature of helium feeding exchanger HXX, the intake of heat in exchanger HX-tech determines the possibility of electricity generation in the ORC1 system. Figure 6 presents the ORC1 system net electric power depending on the demand for heat. As already mentioned, the variant calculations were conducted for the assumed values of R236ea pressure p_{3f} at the turbine inlet (cf. Table 2).

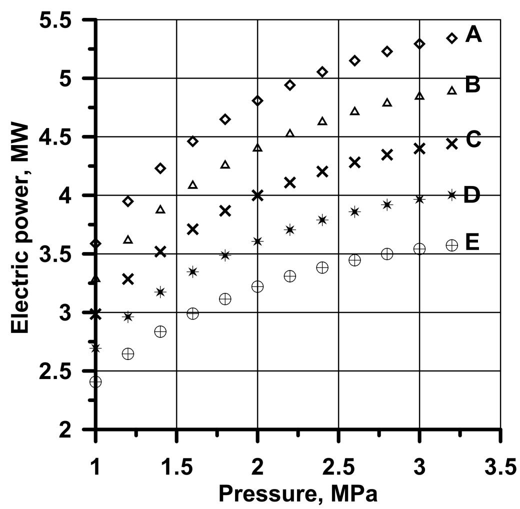

Figure 6: Net electric power of ORC1 system depending on R236ea pressure p_{3f} for assumed values of the demand for process heat: A – 5 MW, B – 10 MW, C – 15 MW, D – 20 MW, E – 25 MW.

As mentioned before, at a rise in the thermal load, helium temperature t_{13} decreases, which involves a decrease in temperature t_{2d} of the heat carrier supplying the ORC1. This has an impact on the ORC1 operation.

For the lowest process thermal power (5 MW), at R236ea pressure in the range $p_{3f} = 1-3.2$ MPa, the calculated net electric power values of ORC1 system are the highest and total 3.59–5.34 MW (cf. A in Fig. 6). If the system thermal load is five times bigger (cf. E in Fig. 6), the electric power varies in the range of 2.40–3.57 MW. Figure 7 presents changes in the power efficiency of the ORC1 system depending on R236ea pressure p_{3f}. The efficiency of the ORC1 calculated according to Eq. (2) varies from 9.5% for the pressure of 1 MPa to 14.2% for 3.2 MPa.

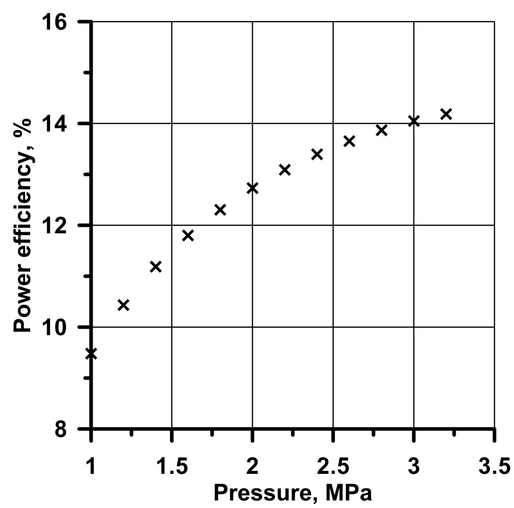

Figure 7: Power efficiency of ORC1 system depending on R236ea pressure p_{3f}.

The ORC2 working parameters are independent of thermal load values – temperature t_{w2} of the heat carrier Dowtherm A in the intermediate cycle is constant (Table 2). This means constant values of electric power and power efficiency. The electric power totals 2.79 MW and the power efficiency – 11.7%.

In variants A–E the cogeneration system electric power varies in the range of 30.30–19.50 MW. The maximum values for cases A and B total about 30.30 MW and 27.88 MW, respectively, and in cases C, D, and E – about 25.47 MW, 23.10 MW, and 20.67 MW. (cf. Fig. 8). Increased production of process heat involves a rise in the cogeneration system power efficiency – the maximum calculated efficiency value totals 45.67% (cf. E in Fig. 9). If the thermal load is smaller (cases A–D), the maximum efficiency is lower by about 10.4, 7.8, 5.2, and 2.6 percentage points, respectively, which means a drop by about 22.7%. 17.0%, 11.4%, and 5.7% compared

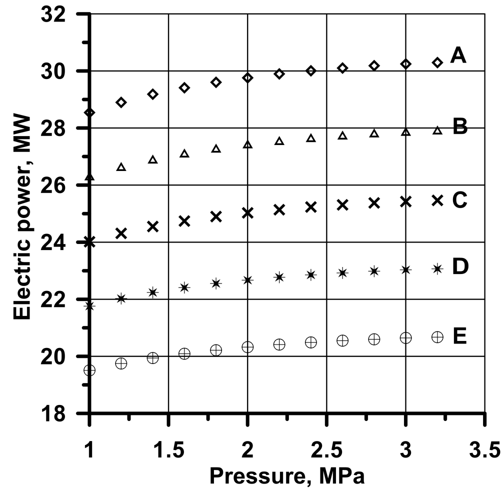

Figure 8: Total net electric power depending on R236ea pressure *p3f* for assumed values of the demand for process heat: A – 5 MW, B – 10 MW, C – 15 MW, D – 20 MW, E – 25 MW.

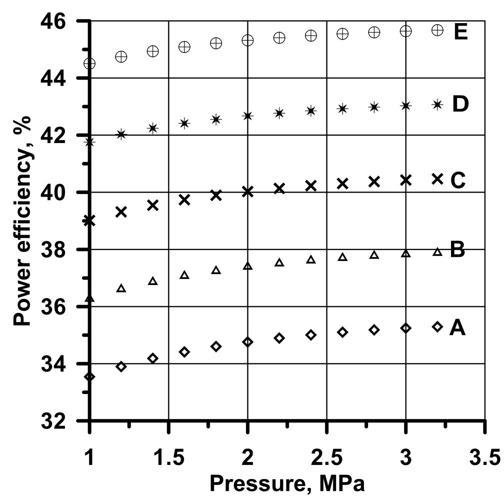

Figure 9: Power efficiency of the cogeneration system depending on R236ea pressure p_{3f} for assumed values of the demand for process heat: A – 5 MW, B – 10 MW, C – 15 MW, D – 20 MW, E – 25 MW.

to the maximum efficiency for the maximum demand for heat (E). Partial power efficiency of electricity production takes maximum values ranging from about 30.3% (A) to about 20.7% (E).

5 Reduction in emissions of harmful substances

One of the ways to reduce the amount of substances emitted to the environment due to electricity generation is to replace conventional systems based on fuel combustion with nuclear power units. Assuming the cogeneration system continuous operation, the maximum annual production of electricity totals about 265–181 GWh depending on the demand for process heat. Table 3 presents the amounts of harmful substances released into the environment in the process of production of 1 MWh of electricity in fuel combustion plants in Poland [17]. The data were used to calculate the reduction in the emissions of the substances over a year that is achieved due to electricity production in the analysed cogeneration system with high-temperature, gas-cooled nuclear reactor (E1) and electricity generation in the ORC systems only (E2), Table 4. The calculation results show that in the variants under consideration CO_2 emissions are decreased by about 216.03–147.42 kt/year, including the drop in the ORC system by about 58.01–45.39 kt/year. Considering the ongoing degradation of the natural environment, it is essential that emissions of the other substances (cf. Table 4) should be reduced, too. Electricity prices are now also indirectly affected by the binding limits of CO_2 emissions, which is considered

Table 3: Emission intensity for electricity produced in a combustion plant in kg/MWh [17].

CO_2	SO_2	NO_x	CO	Total dust
814	0.762	0.775	0.277	0.046

Table 4: Annual electricity production and air pollution emissions: E1 – the cogeneration system with the high- temperature, gas-cooled nuclear reactor / E2 –ORC systems only.

Variant	Annual electricity production E1/E2, GWh	Annual emissions E1/E2				
		CO_2, kt/year	SO_2, t/year	NO_x, t/year	CO, t/year	Dust, t/year
A	265.39/71.27	216.030/58.012	202.2/54.3	205.7/55.2	73.5/19.7	12.2/3.3
B	244.21/67.28	198.786/54.767	186.1/51.3	189.3/52.1	67.6/18.6	11.2/3.1
C	223.10/63.37	181.602/51.582	170.0/48.3	172.9/49.1	61.8/17.6	10.3/2.9
D	202.06/59.53	164.479/48.458	154.0/45.4	156.6/46.1	56.0/16.5	9.3/2.7
E	181.10/55.77	147.417/45.394	138.0/42.5	140.4/43.2	55.1/15.4	8.3/2.6

as a greenhouse gas. This is also an important factor that creates the need for zero-emission heat sources to produce electricity.

6 Summary and conclusions

The aim of the computational simulations was to estimate the power efficiency of a cogeneration system with a high-temperature helium-cooled nuclear reactor generating heat for a technological process. The system includes organic Rankine cycles with R236ea and R1234ze as the working fluids. This solution made it possible to improve energy utilization in the entire system. The heat losses to the environment related to the helium cooling process in the compression system were reduced. The results of the multivariate analyses show that for the adopted assumptions and data, in the range of the demand for process heat of 5–25 MW, the ORC systems maximum electric power varies from about 8.13 MW to about 6.37 MW. In these variants, the maximum share of the ORC systems in the total electric power of the system ranges from 26.9% to 30.8%. The theoretical thermodynamic analysis results presented in the paper indicate that it is possible to use a high-temperature nuclear reactor in the analysed cogeneration process of heat and electricity production with the power efficiency included in the range from 33.5% to 45.7%. Replacing conventional electric power generation systems with the ones including nuclear reactors is one of the possibilities to reduce emissions of harmful substances into the environment and save chemical energy of fossil fuels. One advantage of the considered system is a relatively small thermal power of the reactor characterized by advantageous safety characteristics. This is extremely essential in terms of operational safety. The proposed system makes it possible to produce both process heat and electricity with a relatively high power efficiency.

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