archives
of thermodynamics
Vol. **40**(2019), No. 4, 49–66
DOI: 10.24425/ather.2019.130007

Thermodynamic analysis of modular high-temperature nuclear reactor coupled with the steam cycle for power generation

MICHAŁ DUDEK*
MAREK JASZCZUR
ZYGMUNT KOLENDA

AGH University of Science and Technology, Faculty of Energy and Fuels,
Department of Fundamental Research in Energy Engineering,
Al. Mickiewicza 30, 30-059 Kraków, Poland

Abstract Consumption of energy is one of the important indicators in developing countries, but a lot of companies from the energy sector have to cope with three key challenges, namely how to reduce their impact on the environment, how to ensure the low cost of the energy production and how to improve the system overall performance? For Polish energy market, the number of challenges is greater. The growing demand for electricity and contemporary development of nuclear power technology allow today's design, implement new solutions for high energy conversion system low unit cost for energy and fuel production. In the present paper, numerical analysis of modular high-temperature nuclear reactor coupled with the steam cycle for electricity production has been presented. The analysed system consists of three independent cycles. The first two are high-temperature nuclear reactor cycles which are equipped with two high-temperature nuclear reactors, heat exchangers, blowers, steam generators. The third cycle is a Rankine cycle which is equipped with up to four steam turbines, that operate in the heat recovery system. The analysis of such a system shows that is possible to achieve significantly greater efficiency than offered by traditional nuclear reactor technology.

Keywords: Modular high-temperature nuclear reactor HTR; Rankine cycle; Steam turbine

---

*Corresponding Author. Email: michald@agh.edu.pl

Nomenclature

cp_{He} – helium specific heat, kJ/kgK
dp – pressure drop, Pa
dT_{LO} – lower terminal temperature difference, K
dT_{UP} – upper terminal temperature difference, K
F – correction factor
F_{AK} – correction factor
h_i – specific enthalpy, kJ/kg
$\dot{m}_i$ – mass flow rate, kg/s
K_{AN} – heat transfer coefficient area
$lmTd$ – mean log temperature difference, K
p_i – pressure, Pa
P_{HP} – high pressure steam turbine power, MW
P_{MP} – medium pressure steam turbine power, MW
P_{LP} – low pressure steam turbine power, MW
U – heat transfer coefficient, $\mathrm{W/(m^2K)}$
q_N – heat given to cold side of heat exchanger
T – temperature, K
W_{comp} – compressor work, MW
W_{pumpi} – pump work, MW
x – inlet steam content

Greek symbols

Σ_f – macroscopic and microscopic cross section, 1/cm
φ – average neutron flux, $\mathrm{1/m^2}$
η_{gen} – electric efficiency of generator
η_{mech} – mechanical efficiency
η_{isent} – isotropic efficiency of steam turbine
η_{TH2} – cycle total thermal efficiency

Subscripts

i – location in thermodynamic cycle

1 Introduction

In view of the recent European Union decarbonisation strategy [1], nuclear cogeneration is perceived as a carbon-free option of combined heat and power (CHP) generation. It will also contribute to the reduction of primary energy consumption because its overall efficiency is expected to be greater than the electrical efficiency of a condensing nuclear power plant (NPP), which is usually 33% [2]. In a nuclear power unit, extraction of steam and its use for district heating is possible by turbine system modification. The concept of using NPP to district heat (DH) production was investigated in the 1970s and the 1980s. Advanced studies were conducted in

Central and Eastern Europe, where either Russian water-water thermal reactors (VVER) or light water-cooled graphite-moderated reactor (LWGR) were operated [3,4]. In addition, Bruce A NPP with Canada Deuterium Uranium (CANDU) reactor, generated electricity, district heat, and process heat. Another example is NPP with pressurized water reactor (PWR) which supplies electric power as well as heat at 393 K to Beznau, Switzerland. There were also concept projects, e.g., Loviisa Unit 3 (Finland) which was supposed to supply heat to the Helsinki metropolitan area, located 80 km from the plant. However, this option has not been pursued [5].

Renewed interest was recently expressed by Nuclear Energy Agency (NEA) [5,6], who launched a project to assess the role and economics of nuclear cogeneration for a future low-carbon energy system [7-9]. Interesting analyses on nuclear cogeneration (considering also high temperature reactors) have been also done in Poland by Jedrzejewski and Hanuszkiewicz-Drapala [10]. In [11] impact of the nuclear power unit on decreasing emissions of greenhouse gases has been presented. The results show that in the case of nuclear power plants (the planned share of energy production in 2030) about 15% the greenhouse gasses burdening the energy mix will be as low as 171 kg CO_2/TJ in 2030. The neutronic analysis of the battery-type 20 MW high temperature reactors (HTR) using Monte Carlo method was done in [12]. Authors developed reactor model based on the publicly available data. The analysed system core was a small modular prismatic, graphite-moderated nuclear reactor, uranium fuelled. As a coolant helium gas was used.

Following the construction of the first nuclear power plants in the 1950s and 1960s, nuclear power enjoyed very rapid growth from the 1970s. The promise of low-cost nuclear power was bolstered by the oil crisis of the 1970s which led to concerns about the security of fossil fuel supply and high fuel prices [13]. Subsequent growth in the 1990s was checked by lower than expected electricity demand growth, reactions to the accidents at Three Mile Island and Chernobyl, and in some countries, moves to liberalize the power sector. Starting in the 2000s and driven by Asian economic development, an unexpected revival of nuclear took place. The advantages of nuclear power are being increasingly recognized: a reliable and secure source of power that in many countries is fully competitive, moreover, a technology that in normal operation is environmentally benign with zero carbon emissions. With the shift of economic gravity towards the rapidly growing countries, where existing forms of power generation are facing multiple limits to the role that they can play [14,15], nuclear power is seen by a number of governments as an important part of the generation mix. Around 11% of the world's electricity is generated by about 450 nuclear power reactors. About 60 more reactors are under construction, equivalent to 16% of existing capacity, while an additional 150–160 are planned, equivalent to nearly half of existing capacity.

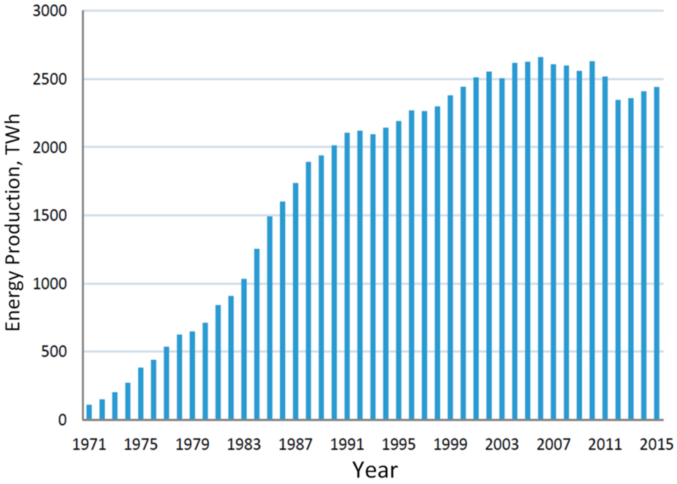

Figure 1: Nuclear Energy Production TWh [16].

In 2016 nuclear plants supplied 2476 TWh of electricity, up from 2441 TWh in 2015. This is the fourth consecutive year that global nuclear generation has risen, with output 130 TWh higher than in 2012. Two-thirds of the units under construction are located in three countries: China, India, and Russia. Projections indicate that nuclear power generation capacity will increase in the Far East (China, Japan, and the Republic of Korea), and downward shifts are set to occur in North America and Western Europe [1]. All of the nuclear power plants are thermal plants, similar to gas or coal-fired power plants.

The amount of energy released in this type of power plant is very large – 10 000 times larger than chemical processes such as the combustion of fossil fuel. This high energy density is, in fact, one of the great technical advantages of nuclear energy since it means that much lower amount of fuel is needed than fossil fuel, refuelling only needs to be carried out periodically, sitting of plants can be quite flexible and it is much easier to protect

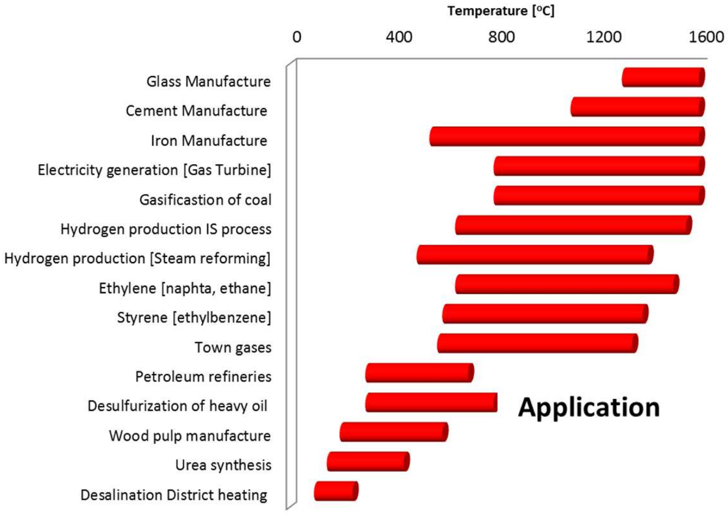

Figure 2: Potential application of new generation Nuclear Reactor Technology [17].

against disruptions to fuel supply. The other advantage is that there is no chemical burning going on [1]. Different type of nuclear reactor technology is presented in Tab. 1.

Table 1: Different type of nuclear technology – general parameters [18].

Parameter	Units	Nuclear reactor types					
		PWR	BWR	AGR	CANDU	RMBK	HTR
Power	MW	1200	600	600	600	1200	1300
Dimensions of core	m	3 × 3.7	3.7 × 3.7	9.1 × 8.5	7.1 × 5.9	11.8 × 7	9.8 × 6
Pressure	MPa	15	7	4	8.6	4.7	4.8
Outlet temperature	K	597	561	923	578	557	993
Steam pressure	MPa	0.4–0.6	0.7	1.6	0.47	0.65	1.75
Superheated steam temperature	K	543-563	553	565	553	553	803
Thermal efficiency	%	35	34	42	30	31	40

The currently operating nuclear power plants which can be found in 30 countries around the world are mostly Generation II. Over 90% of these are light water reactors pressurized and boiling water reactors (PWR, BWR) [19,20]. The longevity of the Generation II reactors has turned out to be quite remarkable and the performance of these units has improved steadily with time. These days, most plants operate routinely with higher than 80% capacity factors and are expected to be capable of operating for 50–60 years [1]. Generation III reactors represent an evolutionary development of Generation II and all designs currently available are PWRs, BWRs or pressured heavy water reactors (PHWRs). They offer improved safety and economic performance [21].

There are many future reactor technologies which are in various stages of research and development status. One of them is small modular reactors (SMR), which promise real improvement in reactor flexibility and efficiency.

The high-temperature nuclear reactor is a very promising concept for using a high temperature for industrial applications, there is only one site in the world where such reactors are currently under construction. This is Shidao Bay NPP in China and the reactors are two HTR-PM (high-temperature reactors-pebble-bed module 250 MW_t). The construction has begun in 2012 and the operation was predicted for 2017. The outlet temperature of primary coolant, equal to 1023 K, is in the lower range of heat needed for efficient fuel production [22]. This type of reactor is designed to offer even higher temperature, up to 1273 K very high temperature reactor (VHTR) but the construction is still at the research stage. One project launched by the United States Department of Energy (DOE) is a next-generation nuclear power plant (NGNP) which assumes designing a VHTR similar to Areva's SC-HTGR (steam-cycle high-temperature gas-cooled reactor) with the aim of using up to 30% of process heat to produce hydrogen. The prototype of NGNP reactor is likely to be deployed by approximately 2030 [23]. Another program based on VHTR reactors was taken by Korean Atomic Energy Research Institute (KAERI). In cooperation with China and Japan, they plan to start operation of their first VHTR, coupled with hydrogen production in 2020 [24] with the outlet temperature of 1173–1273 K. In [25] authors performed thermal analysis of the power plant with high-temperature nuclear reactor and intermediate steam cycle. Presented analyses include three co-generation cycles with HTR reactor and intermediate water cycle used to transport heat from the power plant to external technological system located 1 km from power plant. Results show that temperature and pressure in pipes does not eliminate these solutions.

Many research studies have been conducted on the implementation of high-temperature nuclear reactors in the United States, Russia, Japan, and France [23,26]. At present on HTR's advanced research programs are in progress in many countries. Table 2 includes basic parameters of high-temperature nuclear reactors (HTR) which can be used with a gas turbine combined cycle (GTCC) or Rankine cycle [27].

Table 2: High-temperature nuclear reactors cycles world projects [27].

Parameter	HTR Cycle General Concepts			
	GTMHR	GTHTR300	ANTARES	VHTR NGTCC
Power [MW$_{th}$]	600	600	600	350
Thermodynamic cycle	Inter-cooled recuperated Brayton cycle	Recuperated Brayton cycle	Combined cycle	Combined cycle
Power conversion working fluid	He	He	He/N$_2$	He
Reactor inlet/ outlet temperature [K]	764/1073	860/1073	628/1073	673/1173
Thermal efficiency [%]	47.6	45.6	47.0	51.5
Turbine inlet temperature [K]	1123	1123	1073	1223
Reactor gas pressure [MPa]	0.71	0.7	0.55	0.71
Compression ratio	2.86	2	2	1.94
Plant net power [MW$_e$]	286	274	270 (80T, 200T)	180 (50T, 130ST)

The aim of the present work is to analyse the possibility of efficient power generation using the modular high-temperature nuclear systems that will be introduced to the industry in the near future.

2 Model description

In the paper, numerical analysis of modular high-temperature nuclear reactor coupled with the steam cycle for power generation is presented. The analysed system consists of three independent cycles. The first two are high-temperature nuclear reactor cycles which consist of two modules of

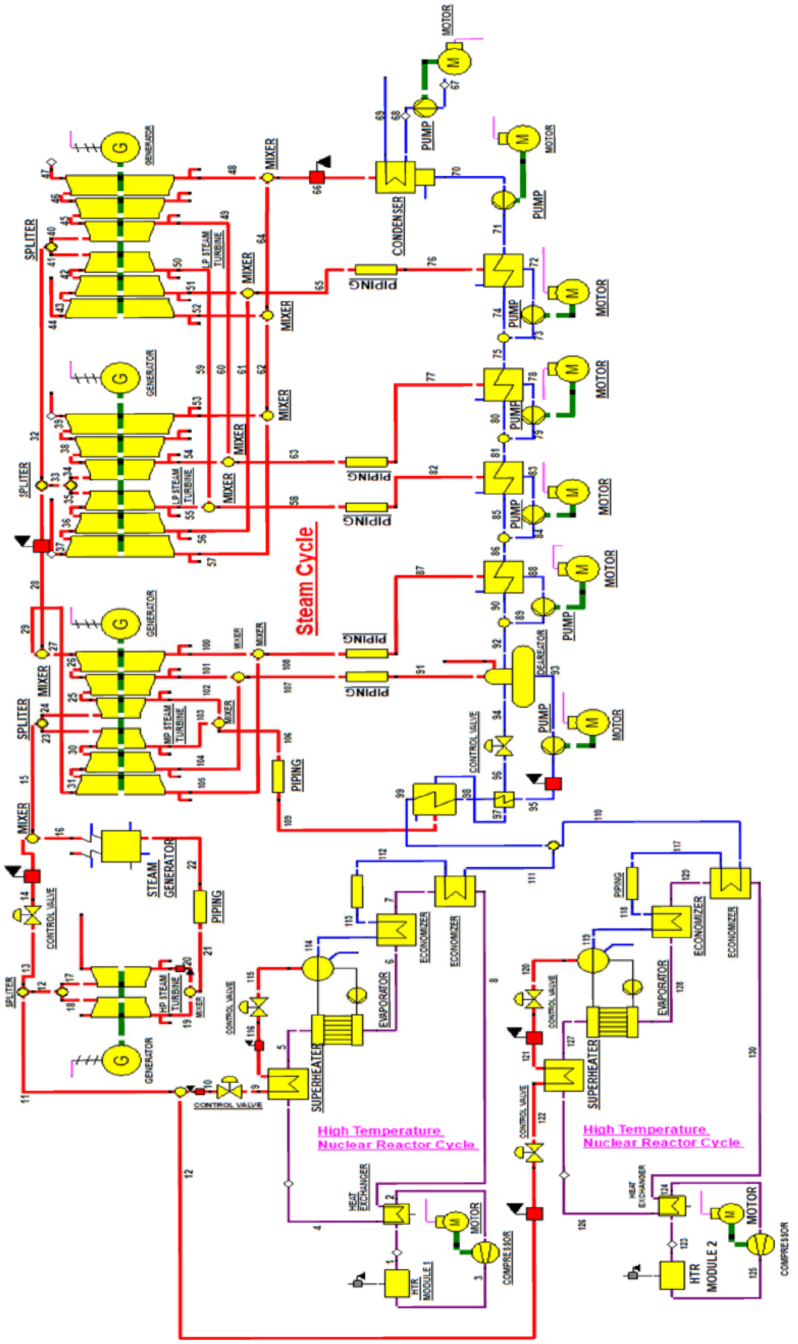

Figure 3: The set of two high-temperature nuclear reactors (HTR) coupled with the steam cycle for power generation.

high-temperature nuclear reactors, heat exchangers, blowers, steam generators. The third cycle is a Rankine cycle with four steam turbines, that operate in a heat recovery system. General assumptions for calculation and main thermodynamic parameters are described in Tab. 3.

Table 3: General assumptions for calculation.

Main Parameter	Value	Unit
High-temperature nuclear reactor power	2×300	MW_{th}
Helium pressure	7	MPa
Helium inlet temperature	673	K
Helium outlet temperature	1073	K

Following equations are used in a mathematical model of the modular high-temperature nuclear reactor coupled with the power generation steam cycle. The calculations were made using Ebsilon software, and the details about computer modelling and additional model equations for components of the high-temperature nuclear reactor coupled with the gas turbine combined cycle can be found in other works [28,29].

Table 4: List of general equation for HTR nuclear reactor.

Heat injection	
Parameter	Relation
Reactor thermal power	$N_R = q_j \sum_f \phi V = q_j \sigma_f \phi m \frac{N_A}{A}$
Pressure drop	$dp_{12} = dp_{12N} f \qquad f = (M_1/M_{1N})^2$
Outlet pressure	$p_2 = p_i - dp_{jk}$
Mass balance	$m_i = m_j$
Outlet specific enthalpy	$h_i = (m_i h_i + m_j h_j)/m_k$
Outlet temperature	$T_2 = f(p_i, h_i)$

Table 5: List of general equation for high-temperature heat exchanger and superheater.

High-temperature heat exchanger/superheater	
Parameter	Relation
Pressure outlet – hot side	$p_i = p_j - dp_{jkN}$
Outlet temperature – hot side	$T_i = T_j + dT_N$
Outlet specific enthalpy – hot side	$h_i = f(p_i, T_i)$
Mass balance – hot side	$m_i = m_j$
Heat delivered from hot side flow	$dq_{jk} = q_j - q_k$
Pressure outlet – cold side	$p_i = p_j - dp_{jkN}$
Mass balance – cold side	$m_j = m_i$
Heat given to – cold side flow	$dq_{ji} = q_j - -q_i$
Outlet specific enthalpy – cold side	$h_i = q_i/\mathrm{m}_i$
Lower terminal temperature difference	$dT_{LO} = T_j - T_i$
Upper terminal temperature difference	$dT_{UP} = T_k - T_o$
Mean log temperature difference	$lmTd = (dT_{UP} - dT_{LO})/(\ln[dT_{UP}/dT_{LO}])$
Heat transfer coefficient *area	$K_{AN} = dq/lmTd$
Heat given to cold side flow	$K_{AN}lmTd = \ m_ih_i - m_jh_j$
Heat delivered from hot side flow	$K_{AN}lmTd = \ m_jh_j - m_jh_j$
Superheater energy balance ideal equation	$\dot{m}_{He1}c_{pHe}\left[T_{out1} - T_{ot}\right] + \dot{m}_{pp}c_{p\,sp\,Tot}^{Tinp}[T_{inp} - T_{ot}]$ $= \dot{m}_{He1}c_{pHe}\left[T_{out2} - T_{ot}\right] + \dot{m}_{pp}c_{p\,pp\,Tot}^{Toutp}[T_{outp} - T_{ot}]$

Table 6: List of general equation for compressors.

Compressor	
Parameter	Relation
Outlet specific enthalpy	$h_j = h_i + dh$
Isentropic outlet temperature	$T_{2S} = f(p_i, s_i)$
Isentropic outlet enthalpy	$h_{2S} = f(p_i, T_{iS})$
Isentropic drop of enthalpy	$dh_S = h_{iS} - h_j$
Drop of enthalpy	$dh = d_{HS}/\eta$
Outlet temperature	$T_2 = f(p_i, h_i)$
Shaft specific enthalpy	$h_3 = (m_ih_i - m_jh_j)/(\eta_{mech}m_k)$
Compressor work	$W_{comp} = \dot{m}_{He}\left(h_2 - h_1\right)/\eta_{comp}$

Table 7: List of general equation for the evaporator.

Evaporator	
Parameter	Relation
Inlet temperature of water	$T_i = T_j - T_{APPN}$
Inlet specific enthalpy of water	$h_1 = f(p_i, Ti)$
Outlet enthalpy of saturated steam	$h_2 = fsat(p_j, T_j, X = 1)$
Outlet specific enthalpy of water	$h_5 = fsat(pi, T_i, X = 0)$
Helium outlet pressure	$P_j = p_i - dp_{34N}$
Drop of enthalpy	$dh = dh_s/\eta$
Outlet temperature	$T_i = T_k + P_{INPN}$
Mass balance – primary side	$m_i = m_j$
Outlet specific enthalpy of gas – primary side	$h_i = f(p_i, T_i)$
Heat delivered from hot side flow	$q_N = q_i - q_j$
Heat delivered from hot side flow with heat loss	$q_l = (q_3 - q_4)(1 - dq_{LR})$
Mass balance of water – secondary side	$m_1 = m_2 + m_5$
Evaporator energy balance – ideal equation	$\dot{m}_{He1} c_{p\,He} \left[T_{out2} - T_{ot}\right] + \dot{m}_w c_{p\,w\,Tot}^{Tinw} [T_{inw} - T_{ot}]$ $= \dot{m}_{He1} c_{p\,He} \left[T_{out3} - T_{ot}\right] + \dot{m}_{pp} c_{p\,wp\,Tot}^{Tinp} [T_{inp} - T_{ot}]$

3 Numerical results

Analysis of the system presented in Fig 3 was carried out for steady-state conditions with the use of software for power engineering calculations delivered by Steag [21]. Results of these numerical calculations for modular HTR system coupled steam cycle are presented in Figs. 4–7. Figure 4 shows enthalpy-entropy (h-s) diagram for the high-temperature modular nuclear reactor.

Table 8: List of general equation for the turbine.

Turbine	
Parameter	Relation
Inlet steam content	$X_1 = f(p_i, h_i)$
Outlet steam content	$X_2 = f(p_i, h_i)$
Specific volume	$v_1 = f(p_i, h_i)$
Inlet volume flow	$mv_1 = M_i V_i$
Isentropic enthalpy	$h_{2S} = f(p_i, S_{iS})$
Isentropic drop of enthalpy	$dh_S = h_i - h_{jS}$
Mass coefficient	$FAK = M_1/M_{1N}$
Isentropic efficiency	$\eta i = \eta_N f(FAK)$
Drop of enthalpy	$dh = dh_S \eta i$
Outlet enthalpy	$h_j = h_i - dh + dh_{kL}$
Outlet temperature	$T_2 = f(p_i, h_i)$
General equation of mass balance	$m_i = m_j + m_k + m_m$
Isentropic efficiency	$\eta_n = \frac{h_{1tot} - h_{2tot}}{h_{1tot} - h_{2isenttot}}$
HP steam turbine power	$P_{HP} = \eta_{gen} \eta_{isent} \eta_{mech} 0.5 \dot{m}_1 [h_{pp1} - h_{pout}]$
MP steam turbine power	$P_{MP} = \eta_{gen} \eta_{isent\,MP} \eta_{mechMP} [\dot{m}_1 [h_{ppim} - h_{ppoim1}]$ $+[\dot{m}_1 - \dot{m}_{pp5}][h_{ppom1} - h_{ppoim2}]$ $+[\dot{m}_1 - \dot{m}_{pp5} - \dot{m}_{p1}][h_{ppom2} - h_{ppoim3}]]$

Table 9: List of the energy balance equation for another device.

Parameter	Relation
Deareator	
Energy balance	$m_w h_w + \dot{m}_{p1} h_s = [m_w + \dot{m}_{p1}] h_g$
Feed water preheater 1	
Energy balance	$\dot{m}_{p1} h_{p1} + \dot{m}_{w1} h_{w1} = \dot{m}_{w1} h_{w2} + \dot{m}_{p1} h_{w3}$
Feed water preheater 2	
Energy balance	$\dot{m}_{p2} h_{p2} + m_{w1} h_{w2} = \dot{m}_{w1} h_{w4} + \dot{m}_{p2} h_{w5}$
Feed water preheater 3	
Energy balance	$\dot{m}_{p3} h_{pn3} + m_{w1} h_{w4} = \dot{m}_{w1} h_{w5} + \dot{m}_{p2} h_{w6}$

continued Tab. 9

Parameter	Relation
Feed water preheater_4	
Energy balance	$\dot{m}_{p4}h_{p4} + m_{w1}h_{w5} = \dot{m}_{w1}h_{w7} + \dot{m}_{p2}h_{w8}$
Water pump	
Pump work	$W_{pump,i} = \dot{m}_{H2O}\left(h_{out,i} - h_{in,i}\right)/\eta_{pump,i}$
Cycle efficiency	
Cycle total thermal efficiency	$\eta_{TH2} = \dfrac{P_{HP} + P_{MP} + P_{LP} - \sum_{i=1}^{7} W_{pi} - \sum_{i=1}^{2} W_{comp}}{N_R}$

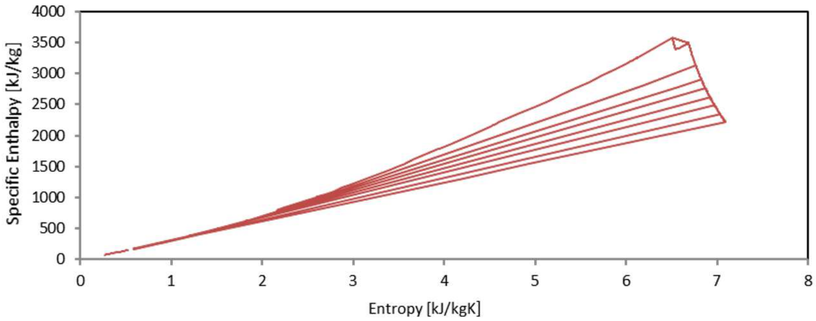

Figure 4: High-temperature nuclear reactor coupled with the steam cycle for the power generation *h-s* diagram.

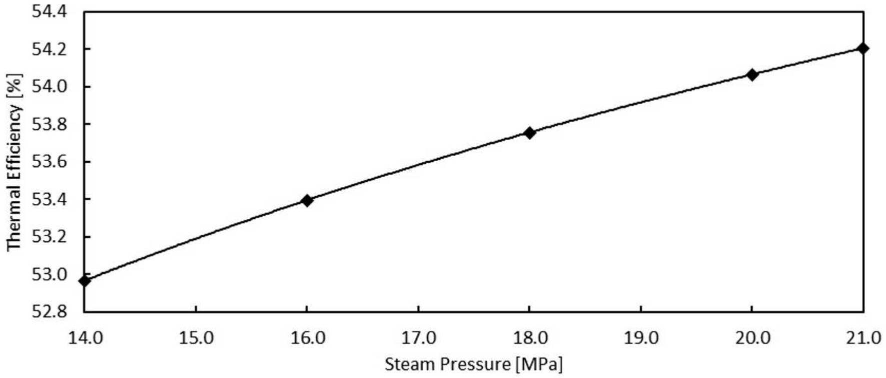

Figure 5: Thermal efficiency *vs.* steam pressure at the inlet at high-pressure steam turbine.

Figure 5 shows global thermal efficiency versus steam pressure at the inlet to high-pressure steam turbine the graph shows that high-temperature nuclear reactor can achieve a high thermal efficiency of above 50%. The analysis indicates that it is possible to achieve significantly higher efficiency than could be offered by traditional nuclear reactor technology (PWR and BWR).

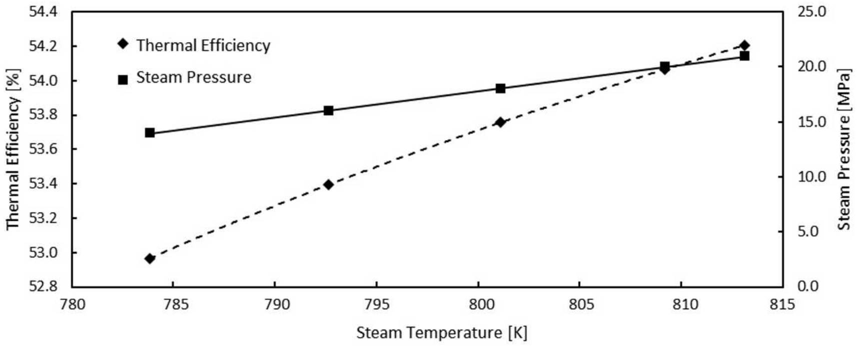

Figure 6: Thermal efficiency *vs.* steam pressure at the inlet to the steam turbine.

Figure 6 shows the influence of pressure and temperature of superheated steam on the cycle efficiency, while the amount of heat exchanged in steam generator is shown in Fig. 7.

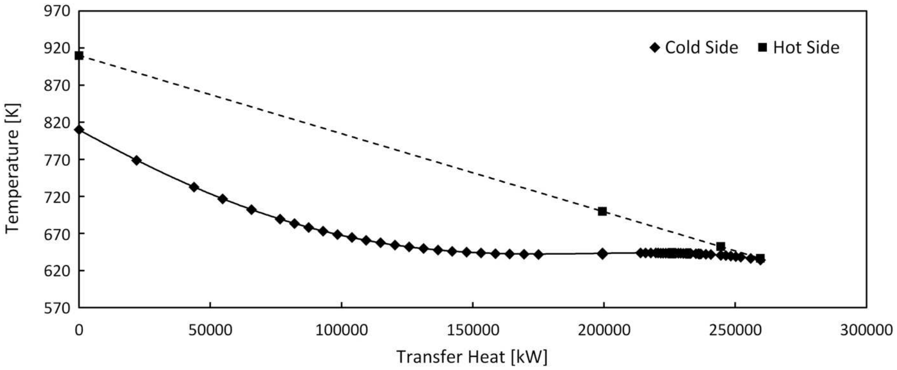

Figure 7: Heat transfer rate at the high-temperature steam generator.

Tables 10 and 11 show the results of numerical computations for steam turbines and generators.

Table 10: Steam turbine parameters.

Component	Isentropic efficiency/ mechanical efficiency	Inlet pressure [MPa]	Outlet pressure [MPa]	Inlet enthalpy [kJ/kg]	Inlet temperature [K]	Mass flow [kg/s]	Inlet volume flow [m^3/s]	Inlet steam content	Outlet steam content	Outlet speed [m/s]
HP turbine	0.880/0.998	18.00	12.00	3348.86	799.09	81.98	1.46	1	1	2.02
MP_turbine		11.50	2.94	3379.01	781.54	163.96	4.68	1	1	14.15
MP turbine		2.94	1.05	3038.28	589.92	148.98	12.85	1	1	29.39
MP turbine		1.05	4.80	2833.26	476.25	139.18	27.46	1	0.978	53.05
LP turbine_1		0.24	0.08	2292.33	337.05	54.12	300.76	0.862	0.831	814.05
LP turbine_1		1.92	0.24	2561.43	391.92	58.55	50.39	0.935	0.862	325.38
LP turbine_1		4.80	1.92	2701.01	423.30	65.38	24.92	0.978	0.935	56.28
LP turbine_1		4.80	0.75	2701.01	423.30	65.38	24.92	0.978	0.899	130.38
LP turbine_1		0.75	0,10	2433.15	364.75	58.77	117.20	0.899	0.837	722.04
LP turbine_1		0.10	0.08	2194.89	318.81	58.77	722.04	0.837	0.831	884.37
LP turbine_2		4.80	1.92	2701.01	423.30	65.39	24.92	0.978	0.935	56.28
LP turbine_2		1.92	0.24	2561.43	391.92	58.55	50.39	0.935	0.862	325.39
LP turbine_2		0.24	0.08	2292.33	337.05	54.12	300.76	0.862	0.831	814.05
LP turbine_2		4.80	0.75	2701.01	423.30	65.38	24.92	0.978	0.899	130.39
LP turbine_2		0.75	0.10	2433.15	364.76	58.77	117.20	0.899	0.837	722.04
LP turbine_2		0.10	0.08	2149.89	318.80	58.77	722.04	0.837	0.831	884.37

HP – high pressure, MP – medium pressure, LP – low pressure

Table 11: Outlet Parameter from the generator.

Component	Electrical efficiency	Power factor	Generator frequency	Voltage	Power at generator inlet	Real power	Ideal power	Apparent power
Units	–	–	1/min	V	kW	kW	kvar	kVA
HP_generator	0.9856	0.85	3000	10000	17909.9574	17652.05	10939.76	20767.12
MP_generator	0.9856	0.85	3000	10000	209222.0850	206209.30	127797.00	242599.20
LP_generator	0.9856	0.85	3000	10000	64273.0666	63347.53	39259.28	74526.51
LP_generator	0.9856	0.85	3000	10000	64273.0661	63347.53	39259.28	74526.51

4 Conclusions

This work presents the results of numerical calculations for the two-modular high-temperature nuclear reactor (HTR) coupled with the steam turbine cycle for electricity production. High standards in the development of high-temperature energy conversion system enforce solutions that require different technologies and aims. Changes to the existing paradigm directly resulting from the climate package, which is especially important in the case of Poland. In the last few years, attention has been paid to the possibility of using HTR as a high-temperature heat source in place of traditional energy systems based on fossil fuel combustion systems. Especially interesting is the use of HTR technology in electricity production and high-temperature heat. This paper shows the possibility of electric energy production in such system. Such a solution leads to a significant increase in efficiency in comparison to the classical water nuclear reactors technology (33%). The high (HTR) or the very high (VHTR) temperature gas-cooled nuclear reactors are nowadays the most innovative constructions and belong to the most advanced reactor technology. The presented reactor system is designed to provide very high safety level and a high value of thermal efficiency.

Received 19 January 2018

References

[1] World Energy Council, World Energy Resources 2016.

[2] Jaskólski M., Reński A., Minkiewicz T.: *Thermodynamic and economic analysis of nuclear power unit operating in partial cogeneration mode to produce electricity and district heat.* Energy **141**(2017), 2470–2483.

[3] Majumdar D.: *Desalination and other non-electric applications of nuclear energy.* In Workshop on Nuclear Reaction Data and Nuclear Reactors Physics, Design and Safety, Trieste, February 2002.

[4] Mitenkov F.M., Kusmartsev E.V.: *Nuclear Heat Applications in Russia: experience, status and prospects.* IAEA-TECDOC 1056, 1998.

[5] Nuclear Energy Agency *On the role and economics of nuclear cogeneration in a low carbon energy future.* OECD, NEA, 6887, 2012.

[6] Shin Y., Lee T., Lee K., Kim M.: *Modeling and simulation of HI and* H_2 SO_4 *thermal decomposers for a 50NL/h sulfur-iodine hydrogen production test facility.* Appl. Energy **173**(2016), C, 460–469.

[7] Stanek W., Szargut J., Kolenda Z., Czarnowska L.: *Exergo-ecological and economic evaluation of a nuclear power plant within the whole life cycle.* Energy **117**(2016), 369–377.

[8] Khan S.U.D., Khan S.U.D.: *Karachi Nuclear Power Plant (KANUPP): As case study for techno-economic assessment of nuclear power coupled with water desalination.* Energy **127**(2017), 372–380.

[9] Sayyaadi H.: *A conceptual design of a dual hydrogen-power generation plant based on the integration of the gas-turbine cycle and copper chlorine thermochemical plant.* Int. J. Hydrog. Energy **42**(2017), 48, 28690–28709.

[10] Jędrzejewski J., Hanuszkiewicz-Drapala M.: *Analyses of the efficiency of a high temperature gas-cooled nuclear reactor (HTGR) generating heat for the sulphur-iodine cycle.* J. Energ Rresour-ASME **140**(2018), 11, 112001–112011.

[11] Stanek W., Szargut J., Kolenda Z., Czarnowska L.: *Influence of nuclear power unit on decreasing emissions of greenhouse gases.* Arch. Thermodyn. **36**(2015), 1, 55–65.

[12] Grodzki M., Darnowski P., Niewiński G.: *Monte Carlo analysis of the battery-type high temperature gas cooled reactor.* Arch. Thermodyn. **38**(2017), 4, 209–227.

[13] Al-Zareer M., Dincer I., Rosen M.A.: *Development and assessment of a novel integrated nuclear plant for electricity and hydrogen production.* Energy Convers. Manag. **134**(2017), 221–234.

[14] Santini L., Accornero C., Cioncolini A.: *On the adoption of carbon dioxide thermodynamic cycles for nuclear power conversion: A case study applied to Mochovce 3 Nuclear Power Plant.* Appl. Energy 181(2016), 446-463.

[15] Liu Z., Karimi I.A.:*New operating strategy for a combined cycle gas turbine power plant.* Energy Convers. Manag. **171**(2018), 1675–1684.

[16] International Atomic Energy Agency, Power Reactor Information System International Atomic Energy Agency (IAEA) 2015.

[17] Dudek M., Jaszczur M.: *An analysis of the thermodynamic cycles with high-temperature nuclear reactor for power generation and hydrogen co-production.* E3S Web of Conf. **14**(2017), 01046, 1–12.

[18] Jezierski G.: *Energetyka jądrowa a konwencjonalna.* Energetyka Cieplna i Zawodowa **10**(2009), 11–17 (in Polish).

[19] Wang C., Yan C., Wang J., Tian C., Yu, S.: *Parametric optimization of steam cycle in PWR nuclear power plant using improved genetic-simplex algorithm.* Appl. Therm. Eng. **125**(2017), 830–845.

[20] Sarr J.A.R., Mathieu-Potvin F.: *Increasing thermal efficiency of Rankine cycles by using refrigeration cycles: A theoretical analysis.* Energy Convers. Manag. **121**(2016), 358–379.

[21] Manual of Ebsilon Profesional software, STEAG GmbH 2017.

[22] Zhang Z., Dong Y., Li F., Zhang Z., Wang H., Huang X., Li H., Liu B., Wu X., Wang H., Diao X., Zhang H., Wang J.: *The Shandong Shidao Bay 200 MW a high-temperature gas-cooled reactor pebble-bed module (HTR-PM) demonstration power plant: An engineering and technological innovation.* Engineering **2**(2016), 1, 112–118.

[23] Idaho National Engineering and Environmental Laboratory Bechtel BWXT Idaho LLC, *Next Generation Nuclear Plant Research and Development Program Plan*, INEEL/EXT-05-02581, 2005.

[24] Mylavarapu S.K., Sun X., Glosup R.E., Christensen R.N., Patterson M.W.: *Thermal hydraulic performance testing of printed circuit heat exchangers in a high-temperature helium test facility.* Appl. Therm. Eng. **65**(2014), 1, 605–614.

[25] Fic A., Składzień J., Gabriel M.: *Thermal analysis of heat and power plant with high temperature reactor and intermediate steam cycle.* Arch. Thermodyn. **36**(2015), 1, 3–18.

[26] Alobaid F., Mertens N., Starkloff R., Lanz T., Heinze C., Epple B.: *Progress in dynamic simulation of thermal power plants.* Prog. Energy Combust. Sci. **59**(2017), 79–162.

[27] Dudek M., Podsadna J., Jaszczur M.: *An numerical analysis of high-temperature helium reactor power plant for co-production of hydrogen and electricity.* J. Phys. Conf. Ser. **745**(2016), 032009, 032009-1-032009-8.

[28] Jaszczur M., Dudek M., Kolenda Z.: *Thermodynamic analysis of high temperature nuclear reactor coupled with advanced gas turbine combined cycle.* Thermal Sci. **4**(2019), 4, 1187–1197.

[29] Jaszczur M., Dudek M.: *Thermodynamic analysis of a gas turbine combined cycle integration with a high-temperature nuclear reactor.* E3S Web Conf. **113**(2019), 02019, 1–6.