THERMODYNAMIC ANALYSIS OF HIGH TEMPERATURE NUCLEAR REACTOR COUPLED WITH ADVANCED GAS TURBINE COMBINED CYCLE

by

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One of the most advanced and most effective technology for electricity generation nowadays based on a gas turbine combined cycle. This technology uses natural gas, synthesis gas from the coal gasification or crude oil processing products as the energy carriers but at the same time, gas turbine combined cycle emits SO_2, NO_x, and CO_2 to the environment. In this paper, a thermodynamic analysis of environmentally friendly, high temperature gas nuclear reactor system coupled with gas turbine combined cycle technology has been investigated. The analysed system is one of the most advanced concepts and allows us to produce electricity with the higher thermal efficiency than could be offered by any currently existing nuclear power plant technology. The results show that it is possible to achieve thermal efficiency higher than 50% what is not only more than could be produced by any modern nuclear plant but it is also more than could be offered by traditional (coal or lignite) power plant.

Keywords: *high temperature nuclear reactor, gas turbine combined cycle, thermodynamic analysis*

Introduction

Significant decrease in the CO_2 emissions is required in order to limit the global concentration of CO_2 to 450 ppm by 2050 [1]. However, energy demand is expected to grow and the burning of fossil fuels is likely to continue in the medium-term future. Therefore, it is important to find viable routes to achieve CO_2 emissions limits before the deployment of new, less carbon-intensive sources of energy becomes dominant in our global energy mix [1]. Nuclear energy remains the largest source of low carbon electricity production in the OECD and the second largest source in the world [2]. Its importance as a current and future source of carbon-free energy must be recognised and should be treated on an equal footing with other low-carbon technologies. As a proven and mature technology nuclear may play a key role in future energy systems in many parts of the world [3]. However, public acceptance of nuclear energy decreased significantly in many countries after the Fukushima Daiichi accident. The challenges in great energy capital-intensive projects have made the development of nuclear power even more difficult today [4, 5].

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The focus of the vision presented in (2DS – 2 °C) [2] scenario vision for nuclear energy and the contribution that nuclear power can make the decarbonization of the power systems. Energy Technology Perspectives 2015 projects that as much as 930 GW of gross nuclear capacity will be needed globally to support the transition of the energy system [2]. The 2DS vision focuses essentially on nuclear fission technologies for electricity generation, and although the potential for other energy applications such as combined heat and power, district heating, hydrogen production and desalination is very promising, for future energy sector [2]. In 2014, 72 reactors were under construction, which is the highest amount for more than 25 years. However, only three reactors were ready to operate. Nuclear power plant under construction Pressurized Light-Water-Moderated and Cooled Reactor (PWR), Pressurized Heavy-Water-Moderated and Cooled Reactor (PHWR), fast breeder reactor (FBR), and Boiling Light-Water-Cooled and Moderated Reactor (BWR) in 2018 are presented in tab. 1 [6]. To achieve the goal of limiting global temperature increases to just 2 °C by the end of the century, a halving of global energy-related emissions by 2050 will be required. This requires an unprecedented transition in the way energy is consumed and produced. A wide range of low-carbon energy technologies needs to support this transition, including a variety of renewable energy technologies, energy efficiency, advanced vehicles, carbon capture, storage units and nuclear energy.

Table 1. Nuclear power plant under construction

Reactor type	Number of reactors under constructions	Total net electrical capacity [MW_e]
PWR	48	50680
PHWR	4	2520
HTGR	**1**	**200**
FBR	1	470
BWR	4	5253

High temperature nuclear reactor

A new generation of high temperature gas-cooled nuclear reactors (HTGR) is the most innovative concept among current advanced nuclear reactor technologies [4]. The US Department of Energy (DoE) developed the very high temperature gas-cooled reactor with a helium coolant and this technological cornerstone for advanced applications that further expand the safe use of nuclear energy [7, 8]. A new program for future nuclear energy systems, Generation IV, has been created to provide next-generation technologies that will compete in all markets with the most cost-effective technologies expected to be available over the next three decades tab. 2.

Table 2. Examples of projects with HTR

Program	Size [MW]	t [°C]	p [bar]	Energy efficiency
MHTGR IGT [12, 13]	200_{th}	850	60	48%
GTHTR 300 [14, 15]	600_{th}	850	70	45.8%
PBMR [16, 17]	$400_{th}/165_e$	900	70	42.7%
MPBR [13]	$250_{th}/120_e$	879	78	48%
GT-MHR [9, 14, 18]	$600_{th}/286_e$	850	70	>47%

Gas-cooled reactor systems have several fundamental characteristic features that distinguish them from other types of reactors and provide significant operational advantages. In particular, the fuel is in the form of small ceramic-coated particles tri-structural isotropic fuel (TRISO) capable of operating at very high temperatures, the moderator is made of solid graphite, and the helium is used as a coolant [9, 10]. The high temperature nuclear reactor (HTR) is designed to work with average coolant outlet temperatures 850-900 ^{o}C while the very high temperature nuclear reactor (VHTR) for temperatures 900-1000 ^{o}C while operational fuel temperature is above 1250 ^{o}C. These solutions provide the potential for increased energy conversion efficiency as well as for high temperature process heat applications such as refinery, chemical industry, coal gasification or thermochemical hydrogen production.

Gas turbine combined cycle

The objective of thermodynamic optimization is to enhance the efficiency of the CCGT and to maximize the electrical power in the steam cycle (steam turbine gross power) [10]. The operation of the gas turbine (GT) combined cycle employs GT and heat recovery steam generator (HRSG) that uses exhaust gas from a GT to produce high-quality steam, which is supplied to a steam turbine [11]. The main constraint in operation of the GTCC power plants is HRSG which is located directly after GT, where changes in temperature and pressure of the exhaust gases may cause significant thermal and mechanical stresses [5]. The most common type of HRSG for combined cycle power plant contains three sections of heat exchanger modules, for high-, intermediate-, and low-pressure steams [18-20]. Addi-

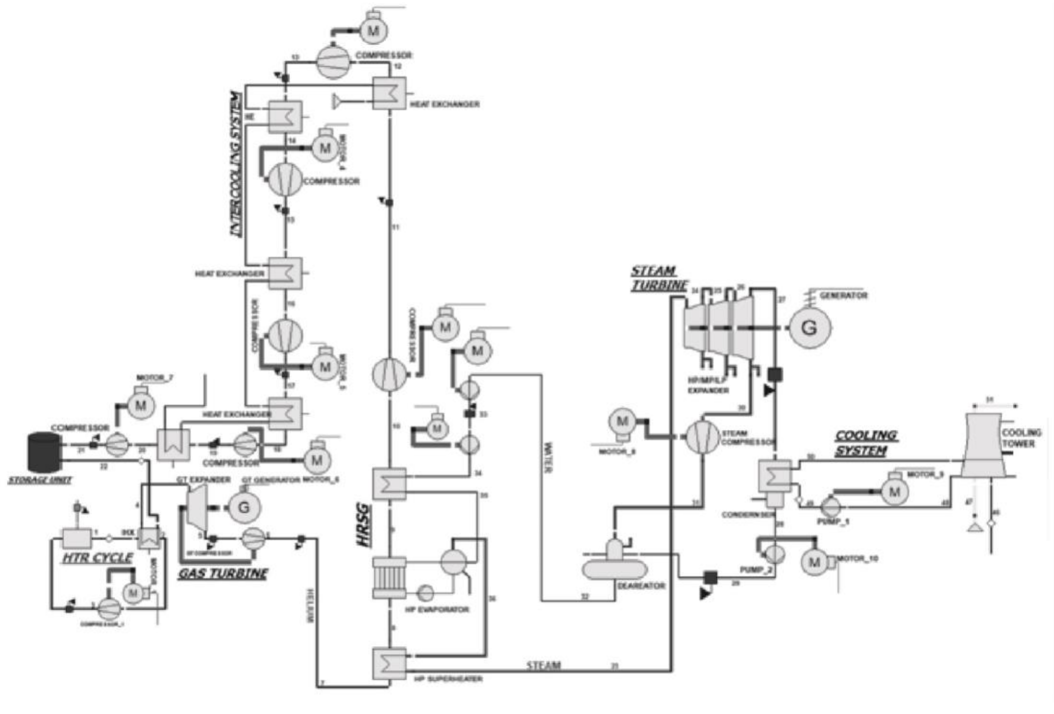


Figure 1. Advanced GT combined cycle coupled with high temperature nuclear reactor and one pressure level heat recovery steam generator (1P HRSG)

tionally, operating conditions of the steam turbine are directly connected to the GT and heat recovery steam generation system. In fig. 1 advanced GT combined cycle coupled with high temperature nuclear reactor and one pressure level (1P) HRSG is presented [21, 22]. For comparison, the structure of the advanced GT combined cycle coupled with HTR and three pressure level (3P) HRSG is shown in the fig. 2.

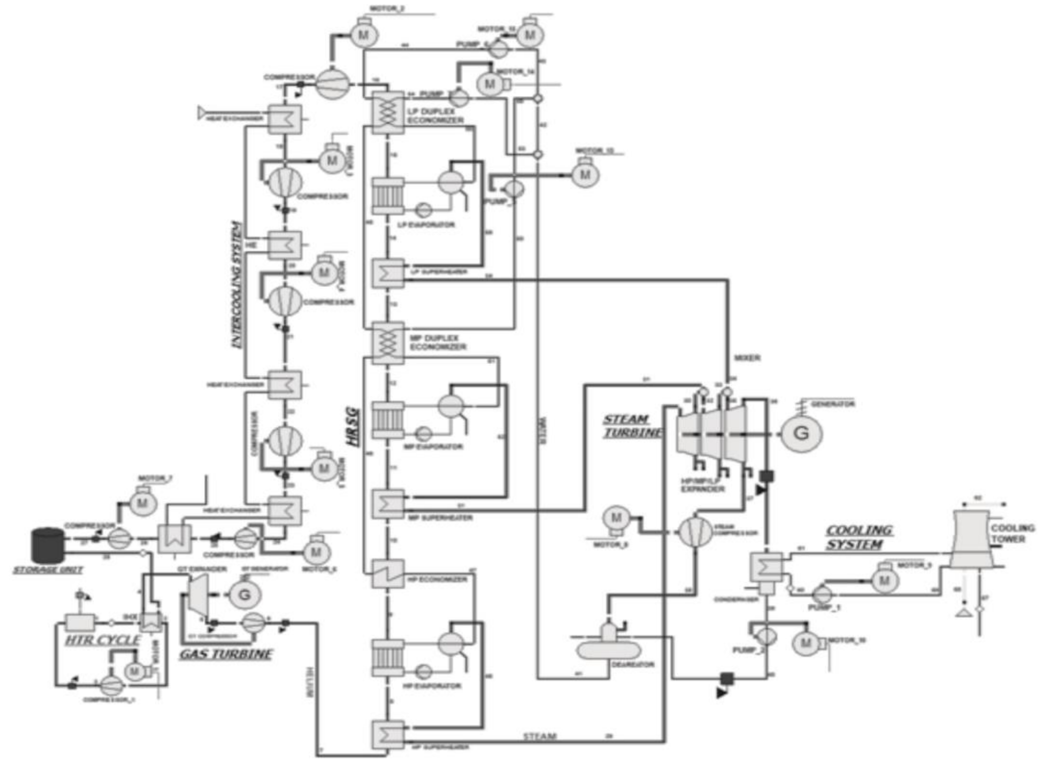


Figure 2. Advanced GT combined cycle coupled with high temperature nuclear reactor and three pressure level heat recovery steam generator (3P HRSG)

Mathematical modelling

The calculations were made using software provided by Steag Energy Services - Ebsilon Professional. A mathematical model for the key components of high temperature nuclear reactor coupled with the advanced GT combined cycle is presented in tabs. 3 and 4 [23].

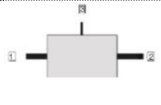
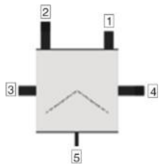
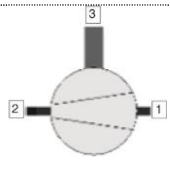
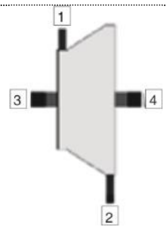
Assumption for calculations

Assumptions, thermodynamic parameters and calculation results are presented in tab. 5.

Results and discussion

The use of the system based on the layout of GT combined cycle coupled with high temperature nuclear reactor with one pressure heat recovery steam generation system from fig. 1 allows generating more than 183.23 MW_e of electricity. However, when the pre-

Table 3. General model formulations

General model formulations			
Heat Source			
$t_2 = f(p_2,h_2)$	$f = (m_1/m_1n)^2$		$dp_{12} = dp_{12}nf$
$p_2 = p_1 - dp_{12}$	$m_2 = m_1$		$ncv_2 = ncv_1$
	$h_2m_2 = m_1h_1 + q_3$		
Thermodynamic equations for HTHE			
$p_4 = p_3 - \mathrm{d}p_{34}N$	$t_4 = \mathrm{DTN}$		$h_4 = f(p_4,t_4)$
$m_4 = m_3$	$Q_4 = m_4h_4$		$\mathrm{d}Q = Q_3 - Q_4$
$p_2 = p_1 - Dp_{12}N$	$Q_2 = Q_1 + \mathrm{d}Q$		$m_2 = m_1$
$h_2 = Q_2/m_2$	$t_2 = f(p_2,h_2)$		$DT_{\mathrm{LO}} = T_4 - T_1$
$DT_{\mathrm{UP}} = T_3 - T_2$	$LM_{\mathrm{TD}} = (DT_{\mathrm{UP}} - T_{\mathrm{LO}})/[\ln(DT_{\mathrm{UP}}) - \ln(DT_{\mathrm{LO}})]$		$KA_{\mathrm{N}} = DQ/LM_{\mathrm{TD}}$
Thermodynamic equations for the compressor			
$m_2 = m_1$	$s_1 = f(p_1,t_1)$		$t_{2S} = f(p_2,s_1)$
$h_2s = f(p_2,t_{2S})$	$\mathrm{d}h_S = h_{2S} - h_1$		$Dh = \mathrm{d}_{hS}/ETA_{\mathrm{I}}$
$h_2 = h_1 + \mathrm{d}h$	$t_2 = f(p_2,h_2)$		$Q_2 = m_2h_2$
$h_3 = (m_2h_2 - m_1h_1)/(m_3ETA_{\mathrm{M}})$	$V_1 = f(p_1,t_1)$		$V_{\mathrm{m1}} = m_1v_1$
Thermodynamic equations for GT			
$(ETA_{\mathrm{I}}/ETA_{\mathrm{IN}}) = f(m_1/m_{1\mathrm{N}})$	$ETA_{\mathrm{I}} = (ETA_{\mathrm{I}}/ETA_{\mathrm{IN}})ETA_{\mathrm{IN}}$		$m_2 = m_1$
$s_1 = f(p_1,t_1)$	$t_{2S} = f(p_2,s_1)$		$h_{2S} = f(P_2,t_{2S})$
$\mathrm{d}h = \mathrm{d}h_sETA_{\mathrm{I}}$	$h_2 = h_1 - \mathrm{d}h$		$t_2 = f(p_2, h_2)$
$Q_2 = m_2h_2$	$Q = (m_1h_1 - m_2h_2)ETA_{\mathrm{MN}}$		$P_1 = P_{1N}F$
$h_4 = (Q + m_3h_3\mathrm{FAC})/m_4$	$F = m_1/m_{1N}Sqrt \cdot$ $\cdot\ [(t_1 + 273.14)/(t_{1N} + 273.14)]$		

sented system is equipped with two or three pressure heat recovery steam generation (fig. 2) they allow producing 196.06 and 201.41 $\mathrm{MW_e}$ of electricity respectively what is shown in fig. 3(a) and 3(b).

The real, idle and apparent power of steam turbine coupled with 1P, 2P, and 3P (three pressure level heat recovery steam generator) can be seen in fig. 3. One may infer from this figure significant increase in the power when two or three pressure heat recovery steam generation unit is implemented.

The thermal efficiency for presented system is calculated according to the following formula:

$$\eta_{\mathrm{GTCC}} = \frac{P_{\mathrm{GT}} + P_{\mathrm{ST}} - \sum_{i=1}^{n} N_{mi}}{Q_{\mathrm{HTR}}} \tag{1}$$

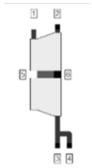
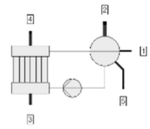
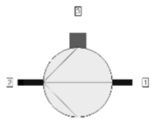
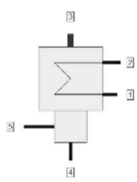
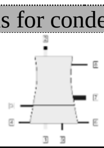
where P_{GT} is the GT power, P_{ST} – the steam turbine power, $\sum N_{mi}$ – the motors consumption, Q_{HTR} – the heat supplied from high temperature nuclear reactor. The GT power is given by the equation [9]:

$$P_{\mathrm{GT}} = \eta_{is}\eta_m\eta_e\eta_{mg}\dot{m}_{He1}cp_{He}\left(T_{\mathrm{IT}} - T_{\mathrm{out}}\right) - \frac{\eta_m\dot{m}_{He1}cp_{He}\left(T_{\mathrm{out}} - T_{\mathrm{out\_1}}\right)}{\eta_{\mathrm{ISC}}} \tag{2}$$

and power of steam turbine coupled with one pressure level (1P heat recovery steam generator) is:

$$P_{\mathrm{ST}} = \eta_{is}\eta_m\eta_e\eta_{mg}\dot{m}_s cp_s\left(T_{\mathrm{IT}} - T_{\mathrm{out}}\right) - u\dot{m}_s cp_s\left(T_u - T_{\mathrm{out}}\right) \tag{3}$$

Table 4. General model formulations

Thermodynamic equations for steam turbine		
$x_1 = f(p_1,h_1)$ $V_{m1} = m_1 v_1$ $\mathrm{d}h_S = h_1 - h_{2S}$ $F_{AK} = (p_1/p_2)/(p_{1N}/p_{2N})$ $ETA_I = ETA_{IN} f(F_{AK})$ $\mathrm{d}h_{2L} = \mathrm{d}h_{2LN} F_{AK}^2\}$ $x_2 = f(p_2,h_2)$ $p_3 = p_2$ $Q_3 = m_3 h_3$ $h_4 = h_2$	 $s_1 = f(p_1,h_1)$ $s_{2S} = s_1$ $F_{AK} = m_1/m_{1N}$ $ETA_I = ETA_{IN} f(F_{AK})$ $\mathrm{d}h_{2L} = \mathrm{d}_{h2LN}$ $\mathrm{d}h = \mathrm{d}h_s ETA_I$ $t_2 = f(p_2,h_2)$ $t_3 = t_2$ $p_4 = p_2$ $Q_4 = m_4 h_4$	$V_1 = f(p_1,h_1)$ $h_{2S} = f(p_2,s_{2S})$ $ETA_I = ETA_{IN} f(F_{AK})$ $F_{AK} = V_{m1}/V_{m1N}$ $F_{AK} = V_{m2}/V_{m2N}$ $h_2 = h_1 - \mathrm{d}_h + \mathrm{d}h_{2L}$ $m_1 = m_2 + m_3 + m_4$ $h_3 = h_2$ $t_4 = t_2$
Thermodynamic equations for the evaporator		
$p_8 = p_6 = p_5 = p_2 = p_1$ $hh_1 = f(p_1,t_1)$ $s_6 = f(p_6,t_6)$ $\mathrm{d}_{hs} = h_{7S} - h_6$ $t_7 = f(p_7,h_7)$ $h_4 = f(p_4,t_4)$ $Q_4 = m_4 h_4$ $m_2 h_2 - m_1 h_1 + m_5 h_5 - Q_{PUM} = Q_{87}$ $Q_{PUM} = m_6 \mathrm{d}h$ $m_2 = [Q_{87} - m_5(h_5 - h_1)]/(h_2 - h_1 - \mathrm{CNd}h)$ $Q_7 = m_7 h_7$ $\mathrm{LM_{TD}} = (DT_{UP} - DT_{LO})/[\ln(DT_{UP}) - \ln(DT_{LO})]$	 $t_2 = t_5 = t_6 = t_8 = f_{sat}(p_1)$ $h_2 = f_{sat}(p_2,t_2,\ x = 1)$ $p_7 = p_6 + \mathrm{d}p_{12N}$ $\mathrm{d}h = \mathrm{d}_{hs}/ETA_{IN}$ $p_4 = p_3 - \mathrm{d}p_{34N}$ $m_4 = m_3$ $Q_N = Q_3 - Q_4$ $m_6 = m_2 \mathrm{CN}$ $DT_{LO} = T_4 - T_7$ $KA_N = \mathrm{d}Q/LM_{TD}$ $KA_N LM_{TD} = (m_3 h_3 - m_4 h_4)(1 - \mathrm{D_{QLR}})$ $KA_N LM_{TD} = m_8 h_8 - m_7 h_7$	$t_1 = t_2 - t_{APPN}$ $h_5 = f_{sat}(p_5,t_5,X = 0)$ $h_{7S} = f(p_7,s_6)$ $h_7 = h_6 + \mathrm{d}h$ $t_4 = t_7 + \mathrm{PINPN}$ $Q_3 = m_3 h_3$ $Q_{87} = (Q_3 - Q_4)(1 - D_{QLR})$ $m_1 = m_2 + m_5$ $m_8 = m_7 = m_6$ $DT_{UP} = T_3 - T_8$
Thermodynamic equations for deareator		
$F = (m_3/m_{3N})^2$ $t_2 = f'(p_2)$ $Q_2 = m_2 h_2$ $h_5 = f''(t_5)$	$\mathrm{d}p_{32} = \mathrm{d}p_{32N} F$ $h_2 = f(p_2,t_2)$ $p_5 = p_2 = p_1 = p_4$ $q_5 = m_5 h_5$	$p_2 = p_3 - \mathrm{d}p_{32}$ $m_2 = m_1 + m_3 + m_4 - m_5$ $t_5 = t_2$ $m_3 = (m_2 h_2 - m_1 h_1 - m_4 h_4 + m_5 h_5)/h_3$
Thermodynamic equations for pump		
$s_1 = f(p_1,h_1)$ $h_2 = h_1 + \mathrm{d}h$ $\mathrm{d}h_s = h_{2S} - h_1$ $v_{m1} < m_{INFLOW}$ $d_{HEAD} = 100000(p_2 - p_1)v_1/9.81$ $vm_1 = R_{ZHF} Z_{HF}$ $F_{CALC} = 1$ i $F_{SPEC} = 1$ $p_2 = p_1 + 9.81 d_{HEAD}/v_1 0.00001$	$t_{2S} = f(p_2,s_1)$ Fluid Oil: $\mathrm{d}_{hs} = 0.1(p_2 - p_1)/\rho$ $R_{CIRC} = M_{INFLOW}/v_{m1}$ $R_{ZHF} = f(d_{HEAD}/S_{OH})$ $m_1 = v_{m1}/(R_{CIRC} v_1)$ $ETA_I = ETA_{IN} f(m_1/m_{1N})$ $h_3 = (m_2 h_2 - m_1 h_1) R_{CIRC}/ETA_M$	 $h_{2S} = f(p_2,s_1)$ $m_2 = m_1$ $v_1 = 1/\rho$ $R_{CIRC} = 1$ $\mathrm{d}h = \mathrm{d}h_s/ETA_I$ $R_{CIRC} = 1$ $d_{HEAD} = f(v_{m1})$
Thermodynamic equations for condenser and cooling tower		
Condenser $\mathrm{KA} = kA_{TUBE}$ $UW = \mathrm{d}_{x(1)}/[\rho N_{TUBE} 3.141592(D_{TUBEIN}/2)]$ $R_{HOW} = 1/\mathrm{SPEZVOL}[p_{x(1)},T_{X(1)}]$ $CT = 1.395 - \mathrm{EXP}(-T_{X(1)}/22.61°\mathrm{C}) - (T_{X(1)} - 21°\mathrm{C})/166°\mathrm{C}$ $L_{TUBEFF} = (\rho C_{PW} UW D_{TUBEIN}^2)/(4ZWkD_{TUBEOU})$* $\mathrm{LOG}[(T_{SAT(3)} - T_{X(1)})/(T_{SAT(3)} - T_{X(2)})]$ $C_{PW} = C_{PW}[P_{X(1)},T_{X(1)}]$		$k = 6.47878(441.325_{mm} - d_{TUBE} AU) S_{QRT}(UW) CTCMCL_{TUBE}$
Thermodynamic equations for condenser and cooling tower		
$\Delta p = (\rho_{ambient,\ air} - \rho_{exit,\ air})gH$ $\Delta P_{design} = (\zeta \rho_{design})/2(\upsilon_{design})^2$		$\dfrac{\Delta P_{design}}{\Delta P_{offdesign}} = \dfrac{(m_{design})^2}{(m_{offdesign})^2} \dfrac{\rho_{offdesign}}{\rho_{design}}$

where KA - coefficient KA, ρ - the specific density of cooling water from a specified volume, CT - the correction factor for cooling water temperature, when differs from 21 °C, L_{TUBEFF} - the correction factor for thickness tubes other than 1.24 mm and raw materials other than $CuZn_{28}Sn$: CM (VDI Energietechnischen Arbeitsmappe) Effective length of the cooling pipe, C_{pw} - coefficient of specific heat cooling water

Table 5. Thermodynamic parameters for calculation

Parameters	Symbol	Value
Thermal power	Q_{HTR}	300 $\mathrm{MW_{th}}$
Coolant in the primary loop	–	helium
Working fluid in the gas cycle	–	helium
Reactor outlet temperature [4]	t_{ROUT}	850/900 $^{\mathrm{o}}$C
Reactor coolant pressure	p_{R}	70 bar
Coolant flow rate in primary loop	$\dot{m}_{He}$	128 kg/s
Coolant pressure before GT	p_{inGT}	69.95 bar
Coolant pressure after GT	P_{ouGT}	35 bar
GT inlet temperature	G_{TIT}	800/850 $^{\mathrm{o}}$C
Coolant flow rate in gas cycle	$\dot{m}_{He1}$	104.5 kg/s
Gas expander mechanical efficiency	η_m	99%
Gas expander isentropic efficiency	η_{is}	90%
Steam temperature before steam turbine	S_{TIT}	565 $^{\mathrm{o}}$C
Steam pressure before steam turbine	S_{INP}	177 bar
Steam flow rate variant 1/variant 2	$\dot{m}_s$	48.918/57.788 kg/s
Steam temperature after the steam turbine	–	28.96 $^{\mathrm{o}}$C
Steam turbine mechanical efficiency	η_m	99.8%
Steam turbine isentropic efficiency	η_{is}	88%
GT power generation	P_{GT}	117.7 $\mathrm{MW_e}$/123.1 $\mathrm{MW_e}$
Gas compressor power consumption	–	6.1 MW
Steam turbine power generation (case 1)	P_{ST}	65.53/78.36/83.71$\mathrm{MW_e}$
Steam turbine power generation (case 2)	P_{ST}	77.42/91.48/93.81$\mathrm{MW_e}$
Gas/steam turbine electrical efficiency	η_e	0.9856

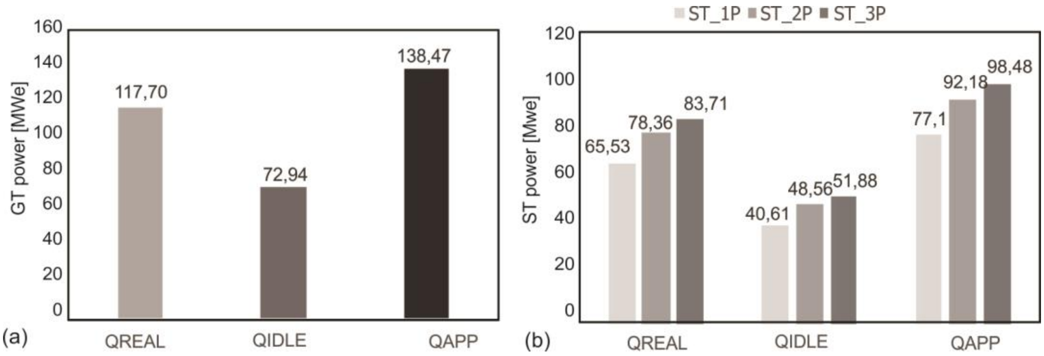


Figure 3. The power of a GT (a) and steam turbine (b) divided into real, idle, and apparent electrical part

For two pressure level (2P heat recovery steam generator) [9]:

$$P_{\mathrm{ST}} = \eta_{is}\eta_m\eta_e\eta_{mg}\left\{\begin{matrix}\left[\dot{m}_{\mathrm{sHP}}cp_{\mathrm{sHP}}\left(T_{\mathrm{IT}}-T_{\mathrm{outHP}}\right)+\left(\dot{m}_{\mathrm{sHP}}+\dot{m}_{s\mathrm{IP}}\right)cp_{\mathrm{sIP}}\left(T_{\mathrm{ITIP}}-T_{\mathrm{outLP}}\right)\right]- \\ -u\left(\dot{m}_{\mathrm{sHP}}+\dot{m}_{\mathrm{sIP}}\right)cp_s\left(T_{\mathrm{ITLP}}-T_{\mathrm{outLP}}\right)\end{matrix}\right\} \tag{4}$$

and for three pressure level (3P heat recovery steam generator) is [9]:

$$P_{ST} = \eta_{is}\eta_m\eta_e\eta_{mg}\left\{\begin{matrix}\left[\dot{m}_{sHP}cp_{sHP}\left(T_{ITHP}-T_{outHP}\right)+\left(\dot{m}_{sHP}+\dot{m}_{sIP}\right)cp_{sIP}\left(T_{ITIP}-T_{outIP}\right)\right]+ \\ +\left(\dot{m}_{sHP}+\dot{m}_{sIP}+\dot{m}_{sLP}\right)cp_{sLP}\left(T_{ITLP}-T_{outLP}\right)-u\left(\dot{m}_{sHP}+\dot{m}_{sIP}+\dot{m}_{sLP}\right)cp_s\left(T_{ITLP}-T_{outLP}\right)\end{matrix}\right\} \tag{5}$$

Detailed results for all systems analysed in this paper systems are presented in figs. 4-7. In fig. 4 the thermal efficiency for different configuration of GT combined cycle is shown.

In figs. 5(a)-5(c) overall cycle q, T diagrams are presented for the 1P, 2P, and 3P heat recovery steam generator and the cold side and hot side.

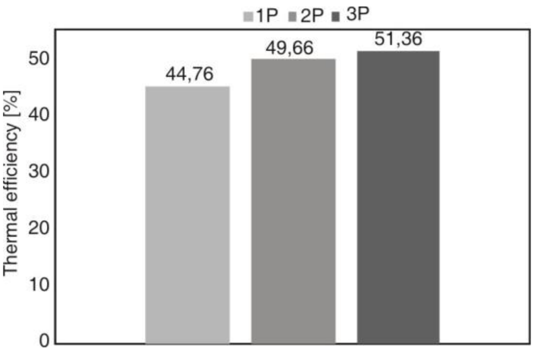


Figure 4. The thermal efficiency of the 1P, 2P, and 3P system

The thermodynamic analysis was also performed to investigate the effect of high temperature nuclear reactor temperature increase from 800 °C to 850 °C but still assuming the constant thermal power of the reactor equal to 300 MW_{th} as well as constant temperature difference in the main heat exchanger (about 50 °C). The results of this analysis are presented in figs. 6(a)-6(b).

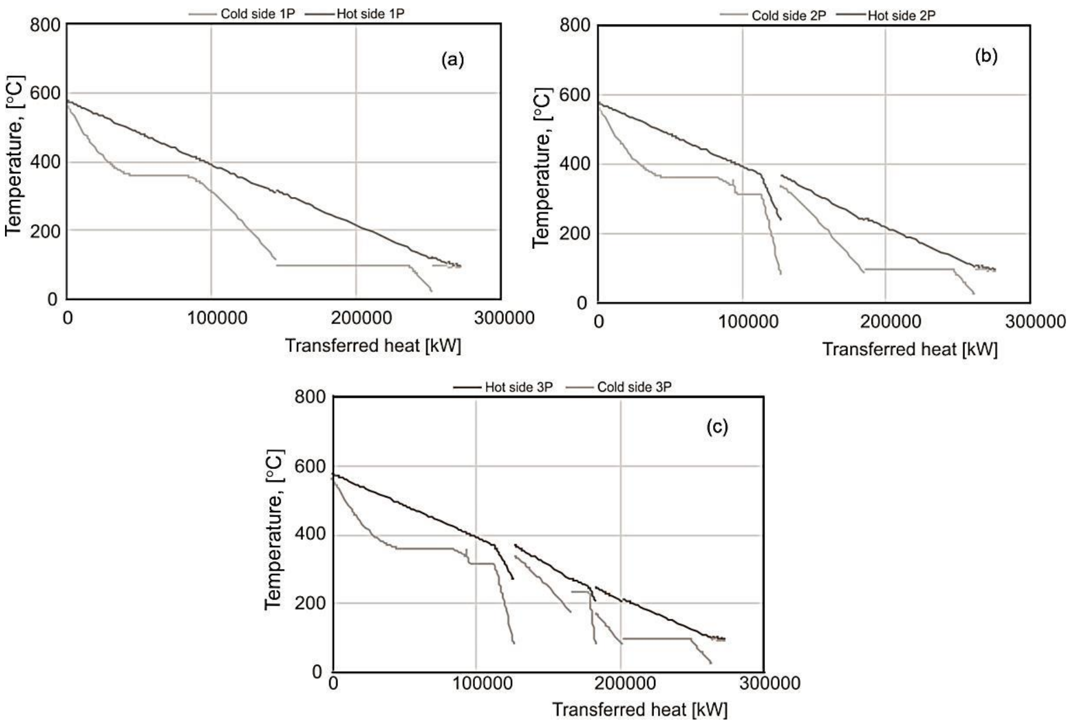


Figure 5. The *q,T* diagram for 1P (a), 2P (b), and 3P (c) heat recovery steam generator

It is clear that the thermodynamic cycle conditions depend on high temperature Nuclear Reactor parameters of steam turbine (SST-3000 with a constant value of inlet pressure p_0 = 177 bar and inlet temperature T_o = 565 °C) and the system configuration. The comparison between the two proposed combined cycles shown in figs. 1 and 2 is presented in figs. 5 an 6. In fig. 6 the relation between the real, idle, and apparent electrical power generated by the steam turbine for the different outlet temperature of working fluid from high temperature nuclear reactor and GT inlet temperature is presented. The thermal effi-

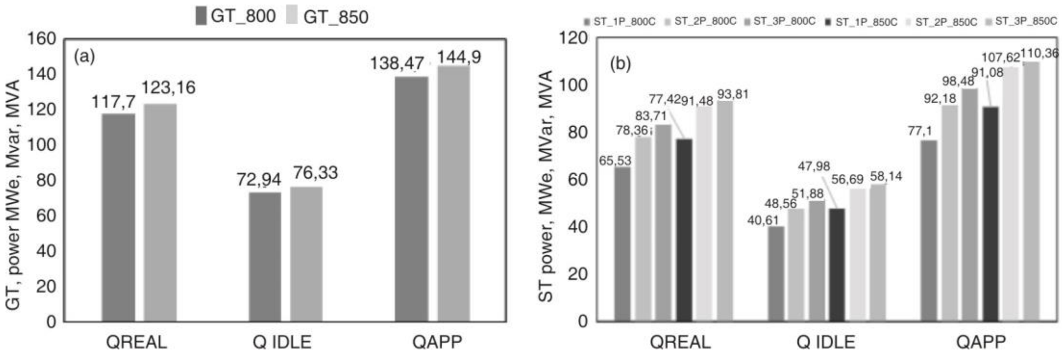


Figure 6. The real, idle, and apparent power of GT (a) and steam turbine for cases 800 ^{o}C, 850 ^{o}C

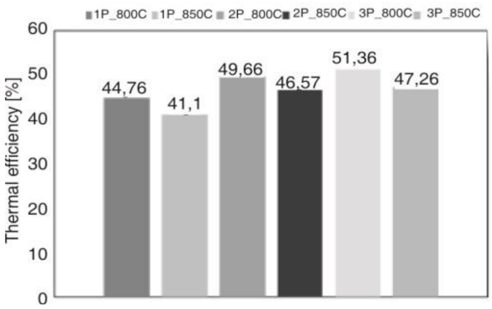


Figure 7. The thermal efficiency comparison between 1P, 2P, and 3P systems for cases 800 ^{o}C, 850 ^{o}C

ciency at two different outlet temperature of working fluid from HTR is shown in fig. 7. As one may infer from this figure, the highest thermal efficiency can be observed for the three-pressure level HRSG system (3P) 800 ^{o}C while for the system one pressure (1P) HRSG 850 ^{o}C the efficiency is more than 10% points lower.

The value of the critical thermodynamic parameter from the calculation at the main points of analysed cycles (see point numbering in fig. 1 or fig. 2) are presented in tab. 6.

Table 6. Thermodynamic parameters of working fluid at selected points of the layout and for the reactor outlet temperature 850 ^{o}C

Lp.	1P				3P			
	p [bar]	*t* [^{o}C]	*m* [kg/s]	*h* [kJ/kg]	*p* [bar]	*t* [^{o}C]	*m* [kg/s]	*h* [kJ/kg]
1	70	850	128	4414	70	850	128	4414
4	69.5	800	104.5	4155	69.5	800	104.5	4155
5	35	566		2941	35	566		2941
6	36	577		3000	36	577		3000
10/15	35.9	311.2		1616	35.7	206.6		1072
21/26	42	104.8		544	42	99.7		517
23/28	**177**	**565**	**48.9**	**3463**	**177**	**565**	**48.9**	**3463**
31	**–**	**–**	**–**		**100**	**444.9**	**61.78**	**3228**
34	**–**	**–**	**–**		**28**	**272.3**	**68.4**	**2929**
27/35	0.04	28.9	42.1	2101	0.04	28.9	61.9	2061
32/41	1.7	115.1	48.9	483	0.5	81.3	68.4	340

Conclusions

High temperature nuclear reactor is a very attractive alternative to traditional and modern energy production systems. It is based on one of the most advanced technologies which give the opportunity to produce electricity and technological high temperature heat (for example for thermochemical processes) without any emissions of GHG and with thermal efficiency higher than a traditional coal-fired power plant, or conventional nuclear power plant technology:

- Proposed high temperature nuclear reactor coupled with 1P (one-pressure), 2P (two-pressure), 3P (three-pressure) level heat recovery steam generator give the opportunity to produce electricity in two stages, directly from GT and steam turbine what have a positive influence on the value of thermal efficiency.
- The inclusion of an advanced interstage cooling system in parallel with a high temperature nuclear reactor and a GT combined cycle allows reducing the energy demand of the main compressor to bring the working medium to the parameters enabling its re-introduction into the primary heat exchanger which is coupled with HTR in the primary cycle.
- Increasing the temperature of the working fluid in the HTR (primary cycle) have a positive impact on the thermal efficiency of the entire cycle, however, maintaining a constant mass-flow rate and constant reactor power does not improve the conversion energy efficiency of the entire system (1P, 2P, 3P GT combined cycle which is coupled with high temperature Nuclear Reactor) due to the increasing energy demand of the main compressor.

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Nomenclature

C_{pw} – cooling water specific heat, [$kJkg^{-1}K^{-1}$]
CT – correction factor for cooling water temperature, [K]
dp – pressure drop, [Pa]
ETA – efficiency, [–]
ETA_M – mechanical efficiency, [–]
F_{AK} – correction factor, [–]
HTHE – high-temperature heat exchanger, [–]
h – enthalpy, [$kJkg^{-1}$]
k – thermal conductivity, [$Wm^{-1}K^{-1}$]
L_{TUBEFF} – correction factor for wall thickness, [–]
LMTD – logarithmic mean difference temperature, [K]
$\dot{m}$ – mass flow rate, [kgs^{-1}]
P – power, [MW]
p – pressure, [Pa]
p_R – reactor coolant pressure, [bar]
Q – heat, [kJ]
Q_{HTR} – Nuclear reactor thermal power, [MW_{th}]
S – entropy, [kJK^{-1}]
s – specific entropy, [$kJkg^{-1}K^{-1}$]
t – temperature, [^oC]
UW – cooling water flow, [m^3s^{-1}]
V – volume, [m^3]
x – moisture content, [–]

Greek symbols

η_e – gas/steam turbine electrical efficiency, [–]
η_{is} – gas/steam turbine expander isentropic efficiency, [–]
η_m – gas/steam turbine expander mechanical efficiency, [–]
η_{GTCC} – system overall thermal efficiency, [–]
ρ – density, [kgm^{-3}]

Subscripts

i – location in thermodynamic cycle
GT – gas turbine
ST – steam turbine

Acronyms

1P, 2P, 3P – 1, 2 or 3 pressure level HRSG
GTCC – gas turbine combined cycle
HRSG – heat recovery steam generator
HTGR – high temperature gas-cooled nuclear reactor

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