

An analysis of high-temperature nuclear reactor coupled with gas turbine combined cycle

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Abstract. At present many companies from the energy sector have to follow new regulations and concerns three crucial aspects of energy production: the impact on the environment, the efficiency of energy conversion and the cost of energy. From a technical point of view, the most efficient technology available today for electricity generation is based on a gas turbine combined cycle. In the present paper, an 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 allow electricity generation 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 for nuclear power plant higher than 50% which is not only more than could be produced by any modern nuclear plant but it is also more than could be offered by most of the traditional power plants.

1 Introduction

Nuclear energy remains the most significant source of low carbon electricity production in the OECD and the second in the World [1]. 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 nuclear technology can play an important role in future energy systems for electricity production in many parts of the World [2].

In 2DS (2°C) scenario vision [1] for nuclear energy, it is assumed that the contribution of atomic technology makes significant progress in decarbonisation of the power systems. The 2DS vision focuses primarily on new generation nuclear technologies for electricity generation. However, it takes into account the potential of other energy applications such as combined heat and power, district heating, hydrogen and other fuels production or desalination [1].

In 2014, under construction were as much as 72 reactors and this was the highest amount for almost 3 decades. However, only 3 reactors were ready to operate. It is predicted according to the 2DS scenario, that China would account for the most significant increase in nuclear capacity from 17 GW in 2014 up to almost 250 GW until 2050 [1]. In the other countries mainly the Middle East, India, and the Russian Federation also significant increase in nuclear power capacity is predicted. It is also worth to notice that according to the 2DS scenario, nuclear capacity in most OECD countries, (except the Republic of Korea, Poland, Turkey and the UK) would decline or remain at a constant level at the same time.

In Table 1 nuclear power plant in 2018 under construction are presented accounting for different technologies: PWR (Pressurized Light-Water-Moderated and Cooled Reactor), PHWR (Pressurized Heavy-Water-Moderated and Cooled Reactor) and BWR (Boiling Light-Water-Cooled and Moderated Reactor) [4].

To achieve the goal of energy sector decarbonisation and in order to limit global temperature growth to just 2 degrees Celsius by the end of the century, a halving of global energy-related emissions up to the middle of XXI century is required. This requires an unprecedented transition in the energy production and a wide range of low-carbon energy technologies is needed to support this transition, including renewable energy technologies, energy efficiency gain, carbon capture and storage units.

Table 1. Nuclear Power Plant under construction in 2018.

Reactor Type	Number of Reactors under constructions	Total Net Electrical Capacity (MWe)
PWR	48	50680
PHWR	4	2520
BWR	4	5253
HTGR	1	200

In this work, an analysis of high-temperature gas nuclear reactor (HTGR) system coupled with a gas turbine (GT) and steam turbine (ST) combined cycle technology has been presented. The proposed plant system includes one of the most advanced concepts and technology available today and allows electrical energy generation with the higher thermal efficiency than could be offered by any currently existing nuclear power plant. The considered

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system consists of the HTGR as a primary source of heat, gas turbine, the heat recovery steam generation system (HRSG) and a steam turbine with a regeneration.

2 High-temperature nuclear reactor

A new generation high temperature gas-cooled nuclear reactors is the most innovative concept among current advanced nuclear reactor technologies available at present [3]. The U.S. Department of Energy (DoE) developed the very high-temperature gas-cooled reactor (VHTR) with a helium coolant for advanced applications and for further expand and safe use of nuclear energy [5,6]. This type of reactor posses several features that distinguish them from any available or currently under work type of reactors as well as provide significant operational advantages. In HTGR the fuel is in the form of small ceramic-coated particles tri-structural isotropic fuel (TRISO) capable of operating at very high temperatures and the helium is used as a coolant [7,8]. For this reason, the high-temperature nuclear reactor is designed to run continuously at an outlet temperature in the range 850-900°C. On the other hand, at the same time more advanced version of this reactor is also developed. The very high-temperature nuclear reactor able to operate with outlet temperature 900-1000°C. Proposed solution provides the potential for high energy conversion efficiency and allows to obtain high-temperature process heat for various applications such as cement manufacture, hydrogen production [15], petroleum refineries, desulfurization of heavy oil, chemical industry and coal gasification (see Figure 1).

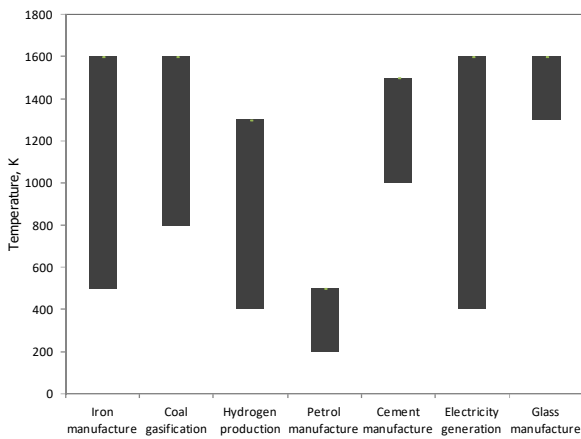


Fig. 1. Application for High-Temperature Nuclear Reactor's.

The example of selected High-Temperature Reactor's projects is shown in Table 2.

Table 2. Examples of HTR projects.

Program	Size MW _{th}	Temperature, °C	Energy Efficiency
MHTGR IGT [9,10]	200	850	48%
GTHTR300 [11,12]	600	850	45.8%
MPBR [10]	250	879	48%
GT-MHR [7,11,13]	600	850	>47%

2.1 Gas turbine combined cycle

The proposed gas turbine combined cycle (GTCC) employs single gas turbine (GT) and heat recovery steam generator that uses exhaust gas from a gas turbine to produce high-quality steam, which is supplied to a steam turbine (ST) [10]. In Figure 2 the advanced gas turbine combined cycle coupled with High-Temperature Nuclear Reactor and one pressure level Heat Recovery Steam Generator (1P HRSG) is presented while in Figure 3 the cycle with three pressure level Heat Recovery Steam Generator (3P HRSG) is also shown. The primary constraint in operation of the GTCC power plants is HRSG which is located directly after the gas turbine, where changes in temperature and pressure of the exhaust gases may cause significant thermal and mechanical stresses. The HRSG unit for combined cycle power plant contains three sections of heat exchanger modules for high, intermediate, and low-pressure steam respectively. In addition to that when the plant is operated in a common load-following operation mode, it can lead to sizeable thermal stress and in consequence may damage some components of the system. In order to solve this issue heat storage unit is implemented.

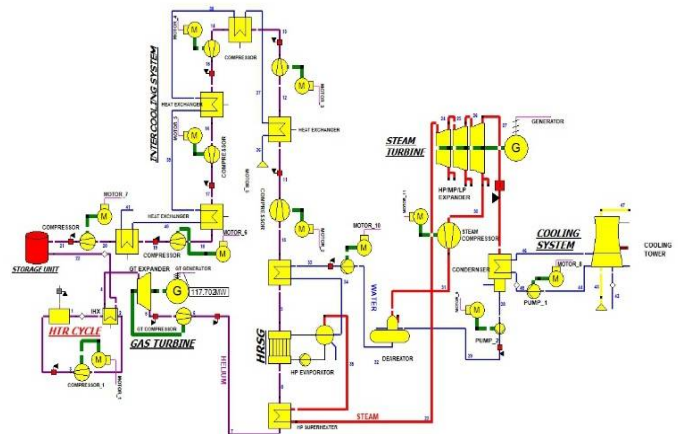


Fig. 2. Advanced Gas Turbine Combined Cycle coupled with HTR and one pressure level Heat Recovery Steam Generator.

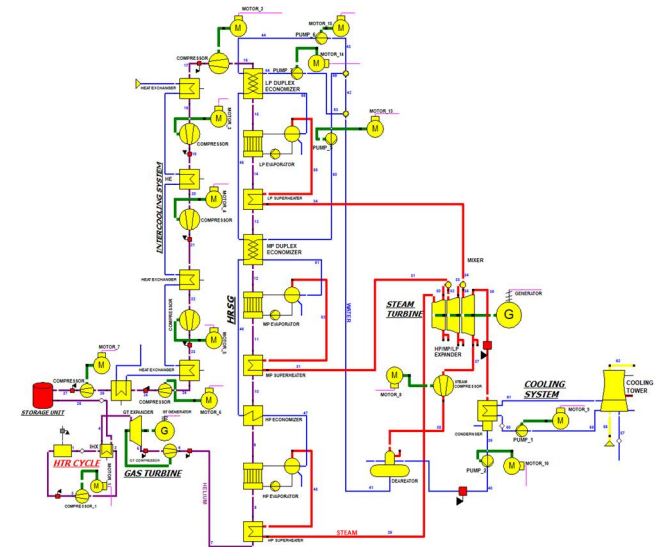


Fig. 3. Advanced Gas Turbine Combined Cycle coupled with HTR and three pressure level Heat Recovery Steam Generator.

2.2 Mathematical model

A mathematical model consist of the thermodynamic equations for High-Temperature Heat Exchanger (HTHE), compressor, gas turbine, steam turbine, evaporator, deareator, pumps, condenser and cooling tower. The calculations were made using software Epsilon software, and the details about computer modelling as well as a model equations for all key components of the high-temperature nuclear reactor coupled with the gas turbine combined cycle are presented in other the authors work [14].

The heat recovery steam generator is considered as a one of the critical components of combined cycle power plants. Any change in its design directly affects the performance of the steam cycle and therefore the performance of the combined cycle power plant. The maximum heat transfer occurs in the evaporator section for the high-pressure level, and it occurs in the economiser section for the low-pressure level.

The heat from the gas turbine exhausted gases is recovered in a Heat Recovery Steam Generator to produce steam at the required pressure and temperature. This steam is then used to provide additional electricity using steam turbines. HRSGs are classified into single, dual, and triple pressure types depending on the number of drums in the boiler. As a consequence, the thermal efficiency of a power plant strongly depends on the HRSG design.

The thermal efficiency for all presented cases has been calculated according to the following formula:

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

where: P_{GT} is the gas turbine power, P_{ST} is steam turbine power, and $\sum N_{mi}$ are the pumps consumption, Q_{HTR} is the heat supplied from high-temperature nuclear reactor. Gas turbine power is given by the following equation [9]:

$$P_{GT} = \eta_{is} \eta_m \eta_e \eta_{mg} \dot{m}_{He1} c_{p,He} [T_{IT} - T_{OUT}] - \frac{\eta_m \dot{m}_{He1} c_{p,He} [T_{OUT} - T_{OUT-1}]}{\eta_{isc}} \quad (2)$$

and power of steam turbine coupled with 1P (one pressure) level Heat Recovery Steam Generator is:

$$P_{ST} = \eta_{is} \eta_m \eta_e \eta_{mg} \dot{m}_s c_{p,s} [T_{IT} - T_{OUT}] - u \dot{m}_s c_{p,s} [T_u - T_{OUT}] \quad (3)$$

while for 2P (two pressure) level Heat Recovery Steam Generator) [9]:

$$P_{ST} = \eta_{is} \eta_m \eta_e \eta_{mg} \left(\begin{aligned} & \left[\dot{m}_{sHP} c_{p,sHP} [T_{IT} - T_{OUTHP}] + \right. \\ & \left. (\dot{m}_{sHP} + \dot{m}_{sIP}) c_{p,sIP} [T_{ITIP} - T_{OUTLP}] \right] \\ & - u (\dot{m}_{sHP} + \dot{m}_{sIP}) c_{p,s} [T_{ITLP} - T_{OUTLP}] \end{aligned} \right) \quad (4)$$

and for 3P (three pressure) level Heat Recovery Steam Generator is as follows [8]:

$$P_{ST} = \eta_{is} \eta_m \eta_e \eta_{mg} \left(\begin{aligned} & \left[\dot{m}_{sHP} c_{p,sHP} [T_{ITHP} - T_{OUTHP}] + \right. \\ & \left. (\dot{m}_{sHP} + \dot{m}_{sIP}) c_{p,sIP} [T_{ITIP} - T_{OUTLP}] \right] \\ & + (\dot{m}_{sHP} + \dot{m}_{sIP} + \dot{m}_{sLP}) c_{p,sLP} [T_{ITLP} - T_{OUTLP}] \\ & - u (\dot{m}_{sHP} + \dot{m}_{sIP} + \dot{m}_{sLP}) c_{p,s} [T_{ITLP} - T_{OUTLP}] \end{aligned} \right) \quad (5)$$

2.3 Assumption for calculations

The main assumptions for the thermodynamic cycle from Figure 2 and Figure 3 are shown in Table 3.

Table 3. Thermodynamic parameters used for calculation.

Parameters	Symbol	Value
Thermal power	Q_{HTR}	300 MW _{th}
Reactor outlet temperature	T_{ROUT}	850/900°C
Reactor coolant pressure	p_R	70 bar
Primary loop flow rate	\dot{m}_{He}	128 kg/s
Coolant pressure before Gas Turbine	P_{inGT}	70 bar
Coolant pressure after Gas Turbine	P_{ouGT}	35 bar
Gas Turbine Inlet Temperature	G_{TIT}	800/850°C
Coolant flow rate in gas cycle	\dot{m}_{He1}	104.5 kg/s
Gas expander mech. efficiency	η_m	99%
Gas expander isent. efficiency	η_{is}	90%
Steam temperature before ST	S_{TIT}	565 °C
Steam pressure before ST	S_{INP}	177 bar
Steam flow rate case1/case2	\dot{m}_s	48.9/57.7kg/s
Steam temperature after ST		28.96 °C
Steam turbine mech. efficiency	η_m	99.8%
Steam turbine isent. efficiency	η_{is}	88%
Gas Turbine power generation	P_{GT}	117.7 MW _e / 123.1 MW _e
Compressor power consumption		6.1 MW
Steam Turbine power generation case1	P_{ST}	65.5/78.3/83. 7MW _e
Steam Turbine power generation case2	P_{ST}	77.4/91.4/93. 8MW _e
generator electrical efficiency	η_e	0.9856

3 Results and discussion

The results for an analysed Gas Turbine Combined Cycle coupled with High-Temperature Nuclear Reactor are shown in Figures 4-9. One may infer from the Figure 4 that the proposed system can generate electricity with a thermal efficiency in the range 44.8-51.4% depending on the case: 1P (one pressure) and 3P (three pressure) level Heat Recovery Steam Generator.

The use of the system based on the layout of Gas Turbine Combined Cycle coupled with High-Temperature Nuclear Reactor with one pressure heat recovery steam generation system from Figure 2 can generate of about 183.23 MW_e of electricity (see Figure 5 and Figure 6).

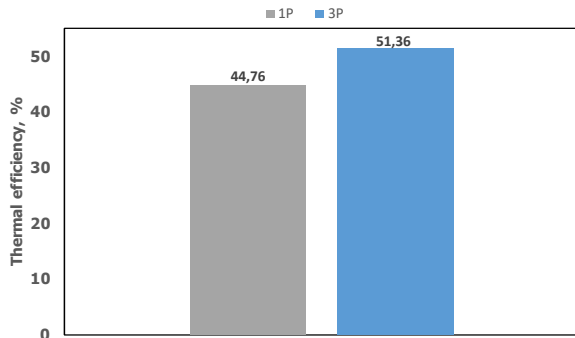


Fig. 4. The thermal efficiency for the 1P (one pressure) and 3P (three pressure) HRSG.

When the system is equipped with three pressure Heat Recovery Steam Generation, it is possible to obtain electrical power equal to 201.41 MW_e (see Figure 5 and Figure 6). One may obtain a significant growth in the electrical power when three pressure heat recovery steam generation unit is used.

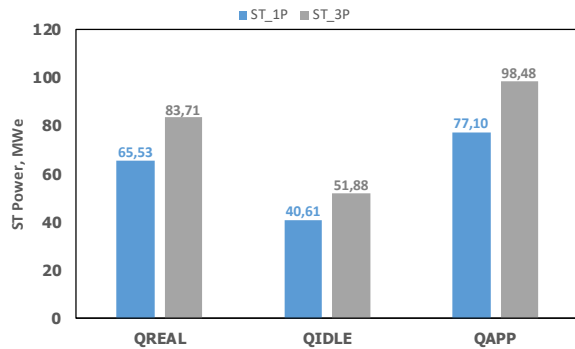


Fig. 5. The real, idle and apparent electrical power of steam turbine for the 1P (one pressure), and 3P (three pressure) HRSG.

The thermodynamic analysis has also been performed in order to investigate the effect of High-Temperature Nuclear Reactor temperature increase - from 800°C to 850°C – however, assuming the constant thermal power of the reactor equal to 300MW_{th} as well as constant temperature difference (about 50°C) in the primary heat exchanger. The results of this analysis are presented in Figures 6-8.

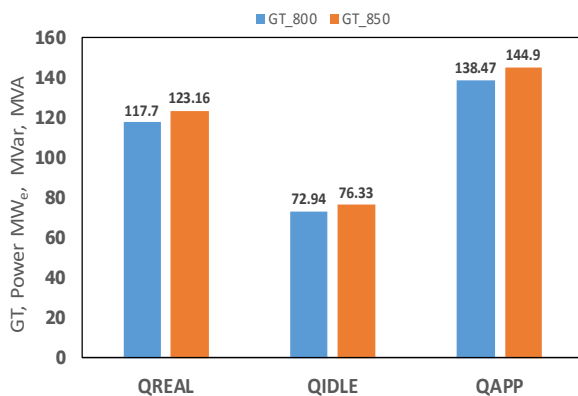


Fig. 6. The real, idle and apparent power for gas turbine and HTR output temperatures 800°C and 850°C.

It is clear that the thermodynamic cycle conditions depend on High-Temperature Nuclear Reactor parameters and steam parameters delivery to Steam Turbine (SST-3000 with a constant value of inlet pressure $p_0=177$ bar and inlet temperature $T_0=565^\circ\text{C}$) as well as on the cycle configuration. The influence of the High-Temperature Nuclear Reactor temperature on the real, idle and apparent electrical power of the gas turbine is presented in Figure. 6.

In Figure 7 the real, idle and apparent electrical power of the Steam Turbine for the two different nuclear reactor outlet temperatures 800°C and 850°C and for the 1P (one pressure), and 3P (three pressure) Heat Recovery Steam Generator level are shown.

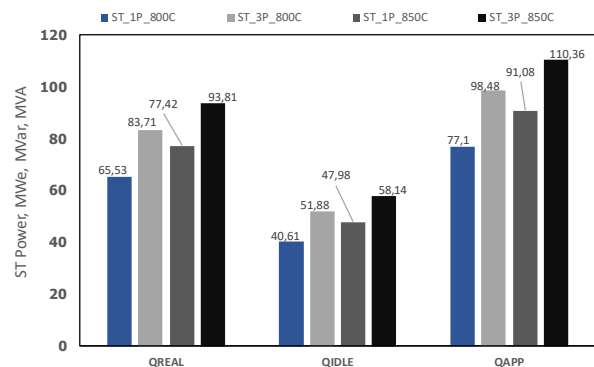


Fig. 7. The real, idle and apparent electrical power of steam turbine for cases 800°C, 850°C and for the 1P (one pressure), 3P (three pressure) HRSG levels.

The thermal efficiency for two different outlet temperatures of working fluid from High-Temperature Nuclear Reactor is shown in Figure. 8. As can be seen, the highest thermal efficiency can be observed for the system 3P (three pressure) HRSG levels system and reactor outlet temperature 800°C while for the system 1P (one pressure) HRSG system and temperature 850°C the efficiency is (due to reactor assumption) more than 10 percentage points lower.

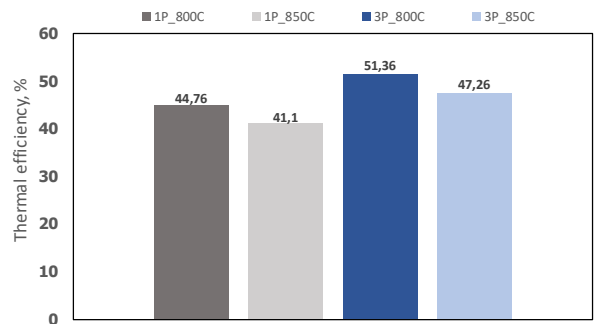


Fig. 8. The thermal efficiency comparison for the 1P (one pressure), 3P (three pressure) HRSG levels and for reactor outlet temperature 800°C, 850°C.

The value for the main thermodynamic parameters obtained from the calculation at the key points of analysed cycle (see numbering in Figure 2 and Figure. 3) and for the 1P (one pressure) and 3P (three pressure) HRSG levels are presented in Table 4, and 5.

Table 4. Thermodynamic parameters at selected points of the layout and for the reactor outlet temperature 850°C.

Lp.	1P				3P			
	p bar	t °C	m kg/s	h kJ/kg	p bar	T °C	m kg/s	h kJ/kg
1	70	850	128	4414	70	850	128	4414
4	69.5	800	104	4155	69.5	800	104	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

Table 5. Thermodynamic parameters at selected points of the layout and for reactor outlet temperature 900°C.

Lp.	1P				3P			
	p bar	t °C	m kg/s	h kJ/kg	p bar	t °C	m kg/s	h kJ/kg
1	70	900	128	4673	70	900	128	4673
4	69.5	850	104.5	4414	69.5	850	104.5	4414
5	35	605		3144	35	605		3144
6	36	617		3205	36	617		3205
10/15	35.9	302.4		1570	35.7	206.7		1072
21/26	42	99.7		518	42	99.7		517
23/28	177	565	57.8	3463	177	565	57.8	3463
31	-	-	-	-	100	447.6	71.78	3235
34	-	-	-	-	28	276.9	74.67	2941
27/35	0.04	28.9	49.7	2101	0.04	28.9	67.6	2069
32/41	1.7	115.1	57.8	483	0.5	81.3	74.67	340

4 Conclusions

Proposed advanced gas turbine combined cycle coupled with the High-Temperature Nuclear Reactor is a desirable alternative to traditional and even modern energy production systems. It is based on one of the most advanced technologies which give the opportunity to produce electricity as well as technological heat for industrial and thermochemical processes without emissions of toxic or greenhouse gasses to the environment and with thermal efficiency higher than a traditional coal-fired power plant or nuclear power plants.

Presented system coupled with 1P (one pressure) or 3P (three pressure) level Heat Recovery Steam Generator is able to generate electrical energy at two stages: using Gas Turbine and Steam Turbine what have a significant impact on the system efficiency and system flexibility.

An increase in the reactor outlet temperature has a significant impact on the entire cycle thermal efficiency. However, under the current assumption (constant mass flow rate and constant reactor power) when increasing reactor temperature the energy efficiency conversion for the (1P, 3P) system is not growing due to the higher energy demand by the compressor.

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