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High-temperature nuclear reactor power plant cycle for hydrogen and electricity production – numerical analysis

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Abstract. High temperature gas-cooled nuclear reactor (called HTR or HTGR) for both electricity generation and hydrogen production is analysed. The HTR reactor because of the relatively high temperature of coolant could be combined with a steam or gas turbine, as well as with the system for heat delivery for high-temperature hydrogen production. However, the current development of HTR's allows us to consider achievable working temperature up to 750°C. Due to this fact, industrial-scale hydrogen production using copper-chlorine (Cu-Cl) thermochemical cycle is considered and compared with high-temperature electrolysis. Presented calculations show and confirm the potential of HTR's as a future solution for hydrogen production without CO_2 emission. Furthermore, integration of a high-temperature nuclear reactor with a combined cycle for electricity and hydrogen production may reach very high efficiency and could possibly lead to a significant decrease of hydrogen production costs.

1 Introduction

Energy consumption is one of the key indicators showing the development stages of countries. The growing demand for electricity and contemporary development of nuclear power technology, computer technology, and materials science allow today design and implement new solutions for nuclear energy, energy security as well as an energy conversion system, to provide a lower unit cost of energy conversion and new possibilities in energy and fuel production [1]. A new generation of high-temperature nuclear reactors (HTR) is one of the most innovative concept among current advanced nuclear reactor technologies [2,3]. A new program for future nuclear energy systems Generation IV has been created in an effort 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 [4]. 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 capable of operating at very high temperatures, the moderator is solid graphite and the coolant is helium or carbon dioxide inert for neutrons [4]. VHTR are designed with average coolant outlet temperatures above 900°C and operational fuel temperatures above 1250°C. These designs provide the potential for increased energy conversion efficiency and for high-temperature processes heat applications, such as coal gasification or thermochemical hydrogen production. In contrary to the fossil fuels, hydrogen is cleaner and less harmful to the environment. By using this fuel we avoid all kinds of pollution, greenhouse gases, and acid rains. Several methods of production of this gas are known. The most common methods are steam reforming of natural gas, high-temperature electrolysis, direct thermal, thermochemical, electrochemical and photoelectrochemical decomposition of hydrocarbons. The most promising thermochemical method for hydrogen production are sulphur-iodine and copper–chlorine cycles [4]. The efficiency of high-temperature I-S cycle is about 52%, while the medium-temperature Cu-Cl cycle efficiency is about 47%.

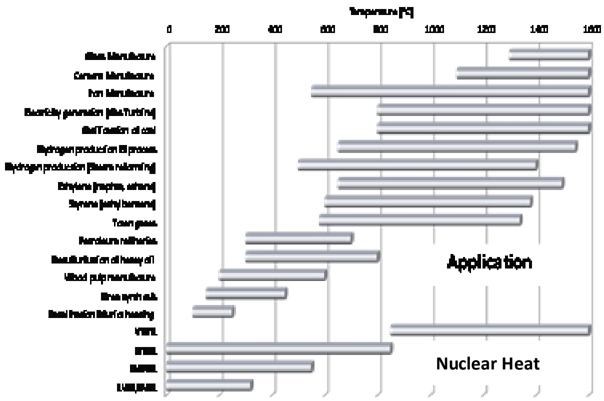

Figure 1. Operational temperatures in various industry application vs operational temperatures in various nuclear reactor types [4].

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2 HTR development status

Although the HTR's are a very promising concept for using high outlet temperature for industrial purposes, there is only one demonstration site in the world where such reactors are currently in construction. This place is Shidao Bay NPP in China and the reactors are two 250 MW_t HTR-PM (High-Temperature Reactors-Pebble-bed Module), together able to generate power of 210 MW_e. The construction has begun in 2012 and the operation is predicted for 2017. The outlet temperature of about 750˚C is in the lower range of heat needed for efficient hydrogen production [5]. Several projects were implemented and investigated by means of test reactors in the UK with the DRAGON reactor, the US with the Peach Bottom reactor and in Germany with the pebble bed AVR reactor.

The HTR's designed to supply higher temperatures, up to 1000˚C are called VHTR's but they are still at the research stage with no industrial use. 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 a process heat to produce hydrogen. The prototype of NGNP reactor is likely to be deployed by approximately 2030 [6,7].

Another program dedicated to VHTRs' development was submitted 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 [8].

With the outlet temperature of 900-1000˚C supplied by a Very High-Temperature Reactor, the hydrogen is to be produced on efficient processes of the sulfur-iodine cycle or the electrolysis. However, with such high temperatures the problem of safe and reliable heat exchangers occurs [9]. The aim of the present work is to analyse the possibility of hydrogen production with the lower temperatures and using the nuclear systems that will be introduced to the industry in the near future. That is why the process of the Cu-Cl cycle was chosen which has a temperature requirement of about 500˚C while maintaining a reasonable efficiency over 40%.

3 Gas Turbine Combined Cycle

The operation of a gas turbine combined cycle (GTCC) employs a gas turbine and heat recovery steam generator (HRSG) that uses exhaust gas from a turbine in order to produce high-quality steam, which is then supplied to a steam turbine [2,10]. The main constraint in the operation of the GTCC power plants is HRSG which is located directly after gas turbine where changes in temperature and pressure of the exhaust gases may cause significant thermal and mechanical stresses [10]. The most common type of HRSG for combined cycle power plant contains three sections of heat exchanger modules – for high pressure (HP), intermediate pressure (IP) and low-pressure (LP) steam. Additionally, when such plant is operated in a common load-following operation mode it can lead to a large thermal stress in practical application and can eventual damage some components of the system. Operating conditions of the steam turbine are in the presenting system directly connected to the gas turbine and heat recovery steam system. The situation has become even more complex since the additional heat exchanger is installed after or before the gas turbine in order to extract heat from a high-temperature thermochemical process using I-S or Cu-Cl cycle. Determining the proper thermodynamic and mechanical conditions for all components to ensure efficient work of the cycle has become a very complex problem [2,10].

The exhaust gases from the classical gas turbine in combined cycle can actually reach 600ºC or more while exhaust gases from high temperature combined cycle can achieve 830ºC what significantly increases thermal and mechanical stresses in the first section of Heat Recovery Steam Generator and therefore generate additionally outlays on materials structure [11]. HT-GTCC may produce electricity, heat, and hydrogen and allow as to optimize investment and maintenance cost. An example of classical gas turbine combined cycle is referred to figure 2.

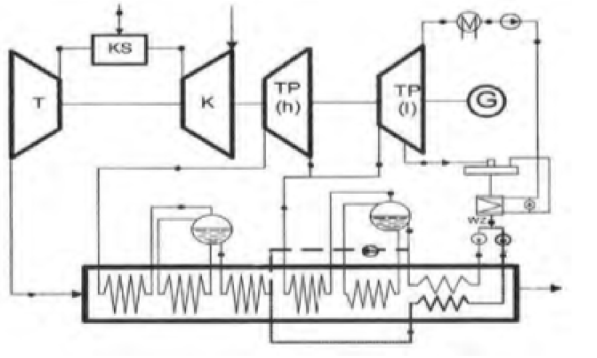

Figure 2. Gas Turbine Combined Cycle with HP and LP Heat Recovery Steam Generator system

The main thermodynamic parameters of high temperature combined projects developed in the word are described at table 1.

4 Power system

High-temperature gas turbine combined cycle (HT-GTCC) analysed in this paper which employs nuclear reactor is presented in figure 3. It consists of three subsidiary circuits. In primary loop, the helium directly flows through the reactor and by the intermediate heat exchanger it heats the gas to 700ºC–950ºC. The gas is then moved into the gas turbine and HRSG system in the secondary circuit. The steam is produced in the last cycle which realizes an independent Rankine cycle. The first loop of presented system is equipped with High-Temperature Nuclear Reactor (HTR), Intermediate Heat Exchanger (IHX) and Blower. The second cycle is equipped with High-Temperature Gas Turbine (GT), Medium Temperature Heat Exchanger, Heat Recovery Steam Generation system and Main Helium Compressor. The independent Rankine cycle is realized by three-stage Steam Turbine (ST), Condenser, Pump, Economizer, Evaporator, and Superheater.

Table 1. Main thermodynamic parameters of high-temperature gas turbine combined cycle concepts [12].

Parameter	HTR Gas Turbine Plant Concepts			
	GTMHR	**GTHTR300**	**ANTARES**	**VHTR NGTCC**
Power [MWth]	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 [°C]	491/850	587/850	355/850	400/950
Turbine inlet temperature[°C]	850	850	800	950
Reactor gas pressure [MPa]	7.1	7.0	5.5	7.1
Compression ratio	2.86	2	2	1.94
Plant Net Power [MWe]	286	274	280 (80 GT, 200 ST)	180 (50 GT, 130 ST)
Thermal efficiency [%]	47.6	45.6	47.0	51.5
Turbine blade cooling	Uncooled	Uncooled	Uncooled	First two stages cooled

In the literature several types of Cu–Cl cycles are presented [13]. Three different variations of the Cu-Cl cycle are currently under investigation: 3-step, 4-step and 5-step cycles. The copper-chlorine thermochemical cycle uses a series of intermediate copper and chlorine compounds. The chemical reactions form a closed internal loop that recycles all chemicals in a continuous basis, without emitting any greenhouse gases or waste. The thermochemical copper - chlorine cycle, realized in four steps is carried out in a lower temperature range and requires heat and electricity supply. It is recommended to employ when the working fluid is at low temperature but still at least 500°C (the efficiency of hydrogen production is 47**%** at 800°C for HTR [13], see figure 4 for reference). The main chemical reactions are as follows:

Hydrolysis at 370 – 400°C
$2CuCl_{2(s)} + H_2O_{(g)} \rightarrow Cu_2OCl_{2(s)} + 2HCl_{(g)}$

Copper oxychloride decomposition at 500–550°C
$Cu_2OCl_{2(s)} \rightarrow 2CuCl_{(s)} + ½O_{2(g)}$

Hydrogen production at 25–100°C
$2HCl_{(aq)} + 2CuCl_{(aq)} \rightarrow H_{2(g)} + 2CuCl_{2(aq)}$

Drying at 80–100°C
$2CuCl_{2(aq)} \rightarrow H_2O_{(g)} + 2CuCl_{2(s)}$

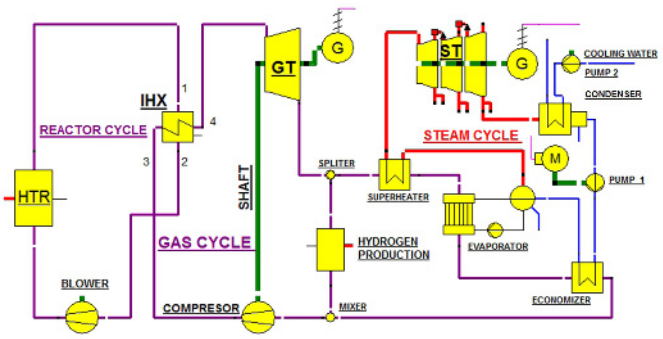

Figure 3. High temperature combined cycle for hydrogen and electricity production.

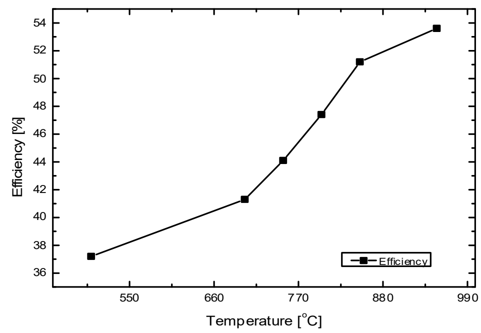

Figure 4. The thermal efficiency of copper-chlorine (Cu-Cl) cycle.

5 Numerical Model

HT-GTCC power plant is a main topic of present research for hydrogen and electricity production. General data and main thermodynamic assumptions are described in Table 2.

The main mathematical model of the high-temperature hybrid combined cycle is presented below.

Thermal reactor (HTR) power was calculated as follow:

$$\dot{Q}_r = \dot{m}_{1He}\, c_{pHe}\left(T_{out} - T_{in}\right) \quad (1)$$

where: $\dot{m}_{1He}$ - helium mass flow rate [kg/s], c_{pHe} - helium specific heat [kJ/kgK], T_{out} - reactor outlet temperature [K], T_{in} - reactor inlet temperature [K].

The heat flux supplied in primary helium circuit:

$$\dot{Q}_s = \dot{m}_{1He}\left(h_1 - h_2\right) \quad (2)$$

where: h_1 - helium specific enthalpy at the inlet to the heat exchanger hot side [kJ/kg], h_2 - helium specific enthalpy at the outlet from the heat exchanger hot side.

The heat flux received in the second circuit:

$$\dot{Q}_R = \dot{m}_{2He}\left(h_4 - h_3\right) \quad (3)$$

where: $\dot{m}_{2He}$ - helium mass flow rate [kg/s], h_4 - enthalpy at the outlet from the heat exchanger cold side [kJ/kg], h_3 - enthalpy at the inlet to the heat exchanger cold side [kJ/kg].

Table 2. General model data and thermodynamic assumptions for HT-GTCC.

Main Parameter	Value	Unit
Reactor Cycle		
Power	600	MWth
Pressure	6	MPa
Coolant	Helium	--
Outlet Temperature	750-1000	°C
Helium Mass Flow	140,2 -541,1	Kg/s
Gas Cycle/Steam Cycle		
Pressure	6	MPa
Gas Turbine Inlet Temperature	750-1000	C
Gas Turbine –Isentropic Efficiency	0,9	-
Gas Turbine – Mechanical Efficiency	0,99	-
Expansion Ratio	1-0.2	-
Compression Ratio	1-5	-
Generator Electrical Efficiency	0,9856	-
Steam Turbine – Isentropic Efficiency	0,88	-
Steam Turbine – Mechanical Efficiency	0,998	-
Motor Efficiency – Electrical/Mechanical	0.85/0.998	-
Compressor Mechanical/Isentropic Efficiency	0.99/0.9	-

High Temperature heat exchanger **(IHX)** enthalpy balance:

$$\dot{m}_{1He}c_{pHe}\left[T_1 - T_0\right] + \dot{m}_{2He}c_{pHe}\left(T_3 - T_0\right) = \\ = \dot{m}_{1He}c_{pHe}\left(T_2 - T_0\right) + \dot{m}_{2He}c_{pHe}\left(T_4 - T_0\right) \quad (4)$$

where: $\dot{m}_{1He}/\dot{m}_{2He}$ - helium mass flow at hot/cold side [kg/s], c_{pHe} - helium specific heat [kJ/kgK], T_1/T_2– inlet/outlet temperature to/from heat exchanger - hot side [K], T_3/T_4 - inlet/outlet temperature to/from heat exchanger - cold side [K], T_0 - reference temperature [K].

Gas turbine electrical power was calculated from the following equation:

$$P_{GT} = \eta_{gen}\dot{m}_{2He}(\eta_{iGT}\eta_{mech}w_{GT} - w_C / \eta_{mech}\eta_{iC}) \quad (5)$$

where: η_{gen} - electrical efficiency, η_{iGT} - gas turbine isentropic efficiency, η_{iC} - compressor isentropic efficiency, η_{mech} - mechanical efficiency, w_{GT} - gas turbine work [kJ], w_C - compressor work [kJ].

Steam turbine electrical power was calculated as follows:

$$P_{ST} = \eta_{gen}\eta_{mech}\dot{m}_{p1}\left(\sum_{WHPST}^{LPST}\eta_i\eta_{mech}w_i\right) - \dot{m}_w\, w_{P_1} / \eta_{ip}\eta_{mech} \quad (6)$$

where: η_{gen} - generator efficiency, η_{mech} - mechanical efficiency η_i - isentropic steam turbine efficiency, η_{ip} - isentropic pump efficiency, $\dot{m}_{p1}$ - steam mass flow rate [kg/s], w_i - high/medium/low pressure steam turbine work [kJ/kg], w_{P1} - water pump work [kJ/kg], $\dot{m}_w$ - water mass flow [kg/s].

For cases when hydrogen production has been taken into account the following formula for cycle efficiency was used.

$$\eta_c = \frac{P_{GT} + P_{ST} - W_B - W_{P2} + \eta_{CuCl}\Delta H_{H2}}{Q_r} \quad (7)$$

where: P_{GT}/P_{ST} - gas turbine/steam turbine electrical power [MW_e], W_B - blower work [MW], W_{P2} - water cooling pump work [MW], η_{CuCl} - thermochemical copper chlorine efficiency, ΔH_{H2} - enthalpy H_2 [kJ], $\dot{Q}_r$ - is the nuclear reactor thermal power. All calculations have been performed using Ebsilon Professional software which was delivered by (Steag).

6 Results

Results of numerical calculation for high-temperature hybrid combined cycle without hydrogen production are presented in figure 5. The first graph shows gas turbine power P_{GT} vs compression ratio and different inlet temperature into the gas turbine. This graph shows that gas turbine in high temperature combined cycle coupled with nuclear reactor effectively works when optimal compression ratio varies from 1.4 to 2.5 at different nuclear reactor temperature. However, from a thermodynamic point of view not all cycle conditions the as possible to realize, due to a significant power decrease in the steam system (see figure 6). The system will work effectively only when the compression ratio is between 1.2 and 2 for the lowest nuclear reactor outlet temperature and for higher compression ratio if higher reactor outlet temperature is available. From a thermodynamic point of view, the optimal value of expansion ratio for effective work varies from 1.5 to 3.5.

It can be seen from figure 6 and 7 that it is possible to achieve more than 50% of thermal efficiency when reactor outlet temperature achieves 1000°C. The highest system efficiency has been obtained for compression ratio 1.5 up to 2.5.

Figure 8 shows inlet temperature available for the steam turbine. These temperature calculations are based on the assumption of a constant temperature difference between inlet and outlet temperature delivered to the HRSG system equal 15°C. The graph shows that it is possible to achieve more than 40% of thermal efficiency when the sluice of heat is equal 15% at the lowest of available nuclear reactor outlet temperature. The achievable efficiency is higher with higher reactor outlet temperature.

Figure 9 shows the numerical calculation for high-temperature hybrid combined cycle with hydrogen production at a thermochemical cooper-chlorine cycle

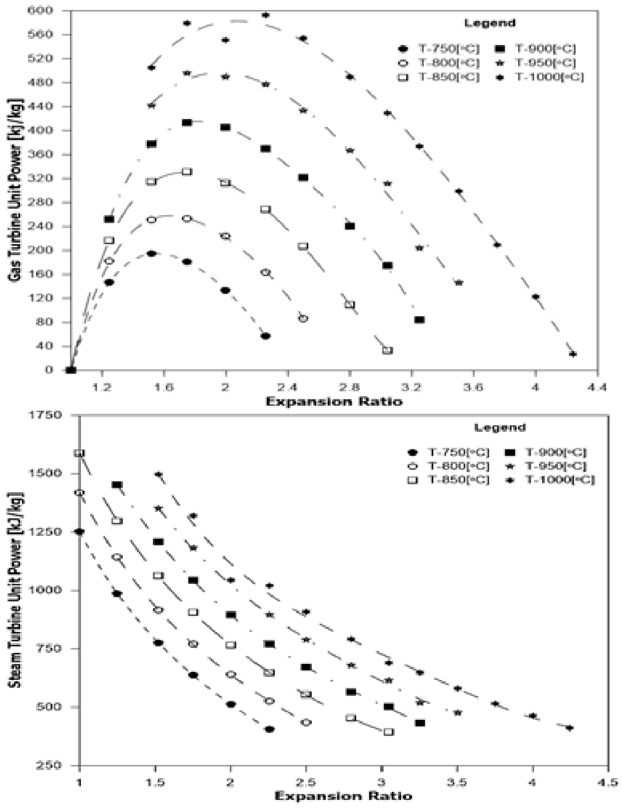

Figure 5. Gas turbine and steam turbine electrical power vs different outlet temperature from a nuclear reactor.

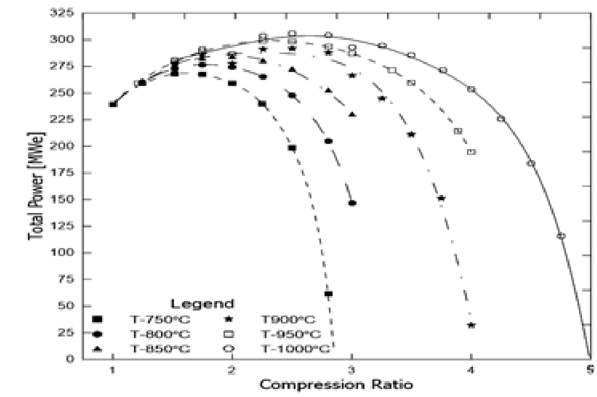

Figure 6. High-temperature hybrid combined cycle - total power vs different nuclear reactor outlet temperature and different compression ratio.

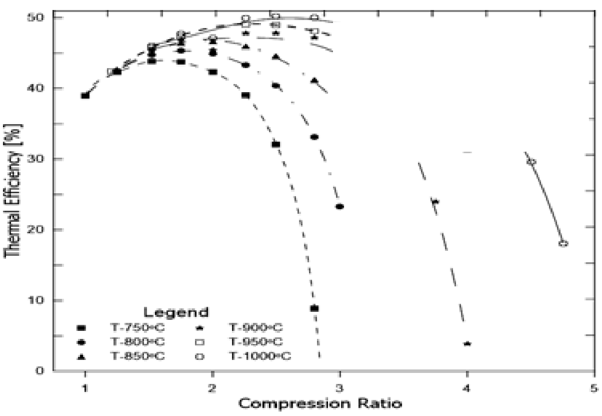

Figure 7. High-temperature hybrid combined cycle – thermal efficiency vs different nuclear reactor outlet temperature, compression ratio.

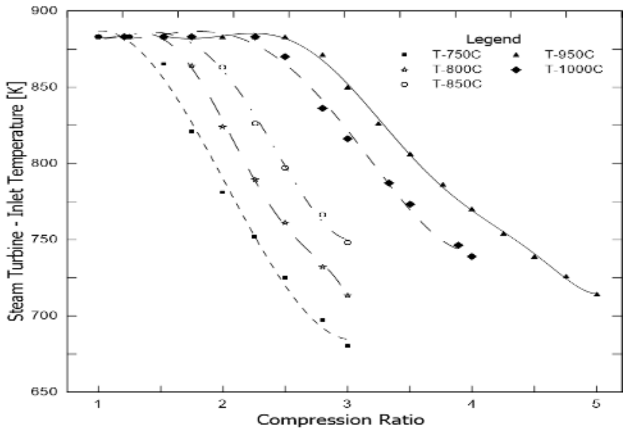

Figure 8. Steam turbine inlet temperature vs different nuclear reactor outlet temperature and compression ratio.

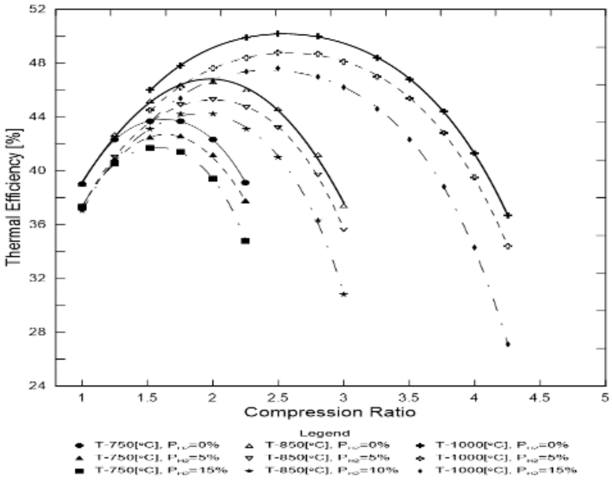

Figure 9. High-temperature hybrid combined cycle – thermal efficiency vs different nuclear reactor outlet temperature, compression ratio.

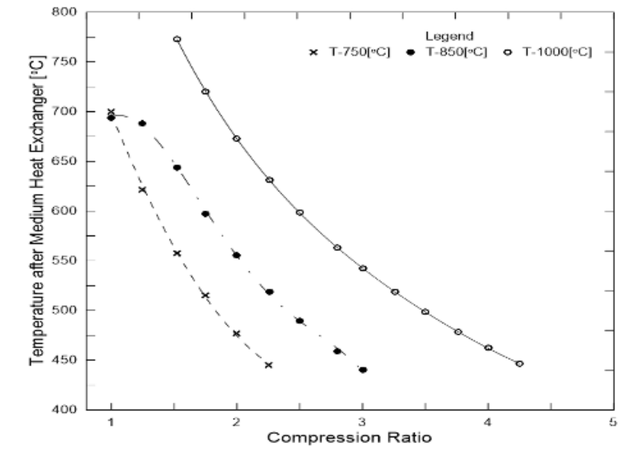

Figure 10. Temperature available after medium heat exchanger to realize hydrogen production process vs different nuclear reactor temperature and different compression ratio.

for thermal efficiency vs compression ratio and different nuclear reactor outlet.

Figure 10 shows temperature distribution vs different expansion ratio for medium temperature heat exchanger for hydrogen production. A prerequisite for the realization of the thermochemical cooper-chlorine process is keeping the temperature at a level needed to realize Copper oxychloride decomposition reaction at 500–550°C,

$Cu_2OCl_{2(s)} \rightarrow 2CuCl_{(s)} + ½O_{2(g)}$. The analysis shows that it is possible to achieve required temperature when the compression ratio varies from 1.2 to 2 for the lowest available nuclear reactor outlet temperature 750°C.

Conclusions

High or very high-temperature nuclear reactors can be effectively used to produce electricity and hydrogen with the Cu-Cl thermochemical cycle. The power conversion system has been analysed with and without hydrogen production in order to maximize the cycle efficiency. From a thermodynamic point of view, the most appropriate value of the compression ratio for high-temperature gas turbine coupled with high-temperature nuclear reactor should be maintained between 1.2 and 1.8 at the lowest nuclear reactor outlet temperature 750°C. When the outlet temperature from a nuclear reactor is increased up to 1000°C it is possible to work with higher compression ratio what gives the opportunity to increase gas turbine power, steam turbine power, and thermal efficiency. The analysis shows that high-temperature nuclear reactor allows effective realization of coupled electricity generation and thermochemical hydrogen production process. What is more the analysis show that it is possible to achieve a high value of thermal efficiency with and without hydrogen production. When the high temperature combined cycle works without hydrogen production it is possible to achieve 44% at the lowest temperature and much higher when reactor temperature is increased.

The temperatures are not only parameter to improve the thermal efficiency of high-temperature hybrid combined cycle. Another most important parameters are isentropic and mechanical efficiencies of the turbines and the compressor which has significant influence. High-temperature reactors used for electricity and hydrogen production have significant potential to improve efficiency by raising the reactor outlet temperature or steam temperature. Safety and compact unit size, low costs and high temperature may offer a lot of benefits for various applications beyond electricity generation (e.g., district heating). The high-efficiency energy conversion, hydrogen production with a thermochemical process that requires large amounts of heat can be accommodated with HTR or VHTR.

Acknowledgments

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References

1. S.J. Bae, J. Lee, Y. Ahn, J.I. Lee, Ann Nucl Energy **75**, 11-19 (2015).
2. U. Guven, G. Velidi. Proceedings of International Congress on Advances in Nuclear Power Plants, ICAPP (2011).
3. B.J. Marsden, S.L. Fok, G. Hall, International Conference on Global Environment and Advanced Nuclear Power Plants (2003).
4. *Generation IV Roadmap: R&D Scope Report for Gas-Cooled Reactor Systems*, Generation IV International Forum (2002).
5. Z. Zhang et al., *An Engineering and Technological Innovation*. Engineering **2**, 112-118 (2016).
6. *Next Generation Nuclear Plant Research and Development Program Plan*, Idaho National Laboratory, (2005).
7. *International Prismatic Block HTGR Commercial Deployment Meeting Summary in Washington DC*, March 8-10 (2016).
8. S.K. Mylavarapu et al., Appl Thermal Eng **65**, 605-614 (2014).
9. Y. Shin et al., Appl Energy 173, 460-469 (2016).
10. M.M. Rahman, K.T. Ibrahim, A.N. Abdalla, Int Journal of Phys Sci **6(14)**, 3539-3550 (2011).
11. J. Mougin, Comp Hydr Energy, 225-253 (2015).
12. C.F. McDonald, Appl Thermal Eng **73**, 82-103 (2014).
13. Z.L. Wang, G.F. Naterer, K.S. Gabriel, R. Gravelsins, V.N. Daggupati, International Journal of Hydrogen Energy **35**, 4820–4830 (2010).