An numerical analysis of high-temperature helium reactor power plant for co-production of hydrogen and electricity

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Abstract. In the present work, the feasibility of using a high temperature gas cooled nuclear reactor (HTR) for electricity generation and hydrogen production are analysed. The HTR is combined with a steam and a gas turbine, as well as with the system for heat delivery for medium temperature hydrogen production. Industrial-scale hydrogen production using copper-chlorine (Cu-Cl) thermochemical cycle is considered and compared with high temperature electrolysis. Presented cycle shows a very promising route for continuous, efficient, large-scale and environmentally benign hydrogen production without CO_2 emissions. The results show that the integration of a high temperature helium reactor, with a combined cycle for electric power generation 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 key the indicator 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 lower unit cost of energy conversion and new possibilities in energy and fuel production. New generation of high temperature nuclear reactors (HTR/VHTR) are today the most innovative constructions and belongs to the most advanced reactor technology. HTR/VHTR reactors give possibilities to use high outlet temperature ranged from 750°C up to 1000°C [2]. Nowadays, modern power plants working in combined cycle represent the most advanced power generation system and allow to today achieve thermal efficiencies up to 50%, contrary to about of 33% of conventional power generation which utilize fossil fuels [2,3] and even less in the case of nuclear power plants [3,6]. Beside high energy conversion system efficiency another goal of the world energy policies is reducing pollution generated by burning of fossil fuels. The solution to this problem should be replacing the existing fossil fuel system by the another energy technologies. The most promising fuel turns out to be hydrogen. In contrast to the fossil fuels hydrogen is much cleaner. By using this fuel will avoid all kinds of pollutions, greenhouse gases, acid rain and others unwanted unions. Several methods to production of this gas are known. The most common methods are steam reforming of natural gas, high-temperature electrolysis, direct thermal, thermochemical, electrochemical, photoelectrochemical decomposition of hydrocarbons. In order to avoid the rise of CO_2 during the hydrogen production method could use a cracking or pyrolysis process. All of these processes are limited by value of thermal or electrical energy. The most promising thermochemical cycles for hydrogen production are sulphur-iodine and copper–chlorine

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cycles. The maximum theoretical efficiency for both processes is about 74%. But in real process thermodynamic losses increases. Therefore the total thermal efficiency is ranged 37 to 54%. In contrast to conventional electrolysis, the efficiency of process is higher. The efficiency is depending on the temperature, the type of electrolyte, current density and voltage. Therefore, it is reported in the range of 40-90%, but the typical efficiency is 37-55% [8].

The combined cycle operation employs gas turbine and heat recovery steam generator (HRSG) that uses exhaust gas from a gas turbine in order to produce high quality steam, which is used to supplied a steam turbine [3,6]. The main constraints in operations of the gas turbine combined cycle GTCC power plant are HRSG systems, as it is located directly after gas turbines where changes in temperature and pressure of the exhaust gases may cause significant thermal and mechanical stresses [6,9]. Additionally, when such plant will be used in a load-following operation mode, which is typical this can lent to increase thermal stress in practical application and can eventual damage some components of the system. Working conditions for the steam turbine are directly coupled with the gas turbine and heat recovery system [9]. The situation has become even more complex if additional heat exchanger is installed after gas turbine in order to extract heat for high temperature thermochemical process. Set up proper conditions for all components which allow as effectively use high temperature combined cycle with hydrogen production is a very complex problem [3,6].

A lot of projects are actually at research phase by United States, Russia, Japan and France [4]. Table 2 includes basic thermodynamic parameters of high-temperature cycle world concepts [5].

Table 1. High Temperature Combined Cycle Power Plant world concepts.

Parameter	HTR Gas Turbine Plant Concepts			
	GTMHR	GTHTR300	ANTARES	VHTR NGTCC
Power [MW$_{th}$]	600	600	600	350
Thermodynamic cycle	Brayton	Brayton	Combined	Combined
Working fluid	He	He	He/N$_2$	He
Reactor inlet/outlet temperature [^{o}C]	**491/850**	**587/850**	**355/850**	**400/950**
Turbine inlet temperature [$^\circ$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 [MW$_e$]	286	274	280 (80/200)	180 (50/130)
Thermal efficiency [%]	47.6	45.6	47.0	51.5
Compressor stages	9	6	4	6
Turbine blade cooling	Uncooled	Uncooled	Uncooled	First two stages

2. Model description

High temperature hybrid combined cycle is presented at Figure 2, where works in two independent cycles consisting of three subsidiary circuit (He, He and steam). Primary loop where the helium directly flows through the reactor, graphical moderator and heats gas up to 750°C -1000°C, secondary loop where helium flows into gas turbine and HRSG and tetrtiary loop where steam has realized independent at Rankine'a cycle. Presented system is equipped with a gas turbine, three stages steam turbines and with gas splitter (after gas turbine), able to redirect heat for hydrogen production. Secondary cycle is able to realized complex Brayton cycle in gas turbine with the simultaneous production of hydrogen at medium-temperature thermochemical copper-chlorine (Cu-Cl) cycle [7]. In general a lot of technologies is available in which hydrogen should be produced. The most known are electrolysis where hydrogen can be produced in two ways. At a low temperature using liquid water and at high temperature using high temperature steam in high temperature steam electrolysis (HTSE). Energy demand for the electrolysis reaction as a function of temperature has been presented in Figure

1, The graph show that total electrical energy demand should be decrease when temperature will be increased. This application can be particularly useful, when alternative cheaper heat sources are available, but the heat energy demand increase and total energy demand also increase [10].
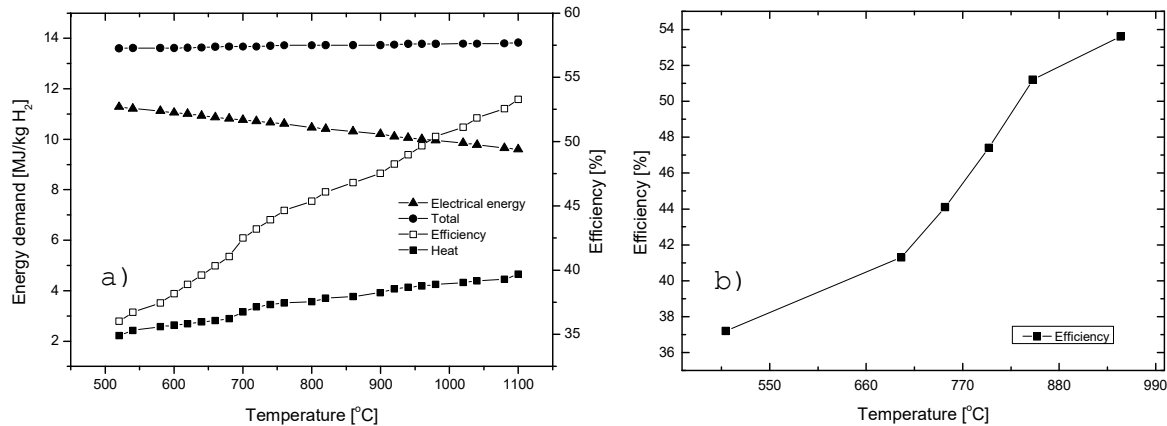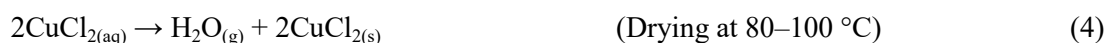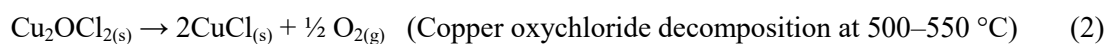

Figure 1. Energy demand for electrolysis (a), efficiency of copper-chlorine (Cu-Cl) cycle (b). [8]

Most of thermochemical methods for hydrogen production required very high temperature at level 800°C and much more. Thus, the copper-chlorine cycle for thermochemical water decomposition is a one of the very promising method. In the literature several types of Cu–Cl cycles are presented [8]. Three different variations of the Cu-Cl cycle are currently under investigation: 3-step, 4-step and 5-step cycles. The Cu-Cl thermochemical cycle uses a series of copper and chlorine compounds. Its chemical reactions form a closed internal loop that recycles all chemicals on a continuous basis, without emitting any greenhouse gases or other substances. The thermochemical copper - chlorine cycle (Cu-Cl), realized in four stage is carried out in a lower temperature range and requires also lower thermal and electric demand. It is recommended to use when the working fluid is in low temperature but still at least 500°C (the efficiency of hydrogen production should be equal **47%** at 800°C for HTR [8]). The main chemical reactions are as follows:

$$2CuCl_{2(s)} + H_2O_{(g)} \rightarrow Cu_2OCl_{2(s)} + 2HCl_{(g)} \qquad \text{(Hydrolysis at 370–400 °C)} \qquad (1)$$

$$Cu_2OCl_{2(s)} \rightarrow 2CuCl_{(s)} + \tfrac{1}{2} O_{2(g)} \quad \text{(Copper oxychloride decomposition at 500–550 °C)} \qquad (2)$$

$$2HCl_{(aq)} + 2CuCl_{(aq)} \rightarrow H_{2(g)} + 2CuCl_{2(aq)} \qquad \text{(Hydrogen production at 25–100 °C)} \quad (3)$$

$$2CuCl_{2(aq)} \rightarrow H_2O_{(g)} + 2CuCl_{2(s)} \qquad \text{(Drying at 80–100 °C)} \qquad (4)$$

3. Mathematical model

In the present work the power plant cycle for electricity generation with hydrogen production is analysed. The design data for proposed concept, general model assumptions and main thermodynamic parameters are presented in Table 2. A thermodynamic analysis is conducted for three independent loops presented in Figure 2. The main primary loop focus on the high temperature nuclear reactor where the coolant is helium and the mass flow have been changed between 160 to 514kg/s, is heated to a temperature in the range of 750-1000°C. The main high temperature heat exchanger IHX (heat exchange between first and second loop) was designed to temperature drop between hot inlet and cold outlet in IHX is equal 50K. Hot high pressure helium enters into the gas turbine (GT) where is expanded and next is transported to hydrogen production systems and to HRSG. Cooled helium coming back to the heat exchanger where is again heated at IHX. The HTR reactor kept its power on constant level witch is equal 600MW, thus the mass flow depends on the outlet temperature of helium from reactor.
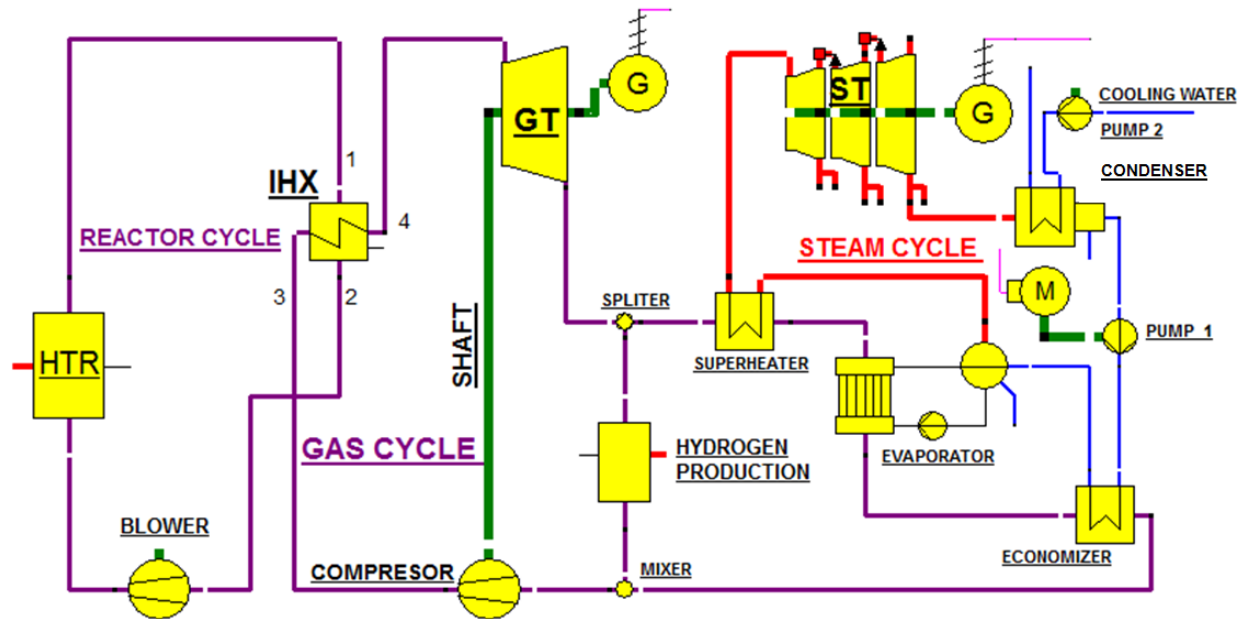
Figure 2. High temperature hybrid combined cycle for electricity and hydrogen co – production.

The main mathematical model of the high-temperature hybrid combined cycle are as follows:
Thermal reactor (HTR) power was calculated by as follow:

$$\dot{Q}_r = \dot{m}_{He} c_{pHe} \left(T_{out} - T_{in} \right) \tag{5}$$

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:

$$\dot{Q}_s = \dot{m}_{1He} \left(h_1 - h_2 \right) \tag{6}$$

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.

$$\dot{Q}_R = \dot{m}_{2He} \left(h_4 - h_3 \right) \tag{7}$$

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].
High Temperature heat exchanger **(IHX)** enthalpy balance.

$$\dot{m}_{1He} c_{pHe} \left[T_1 - T_0 \right] + \dot{m}_{2He} c_{pHe} \left(T_3 - T_0 \right) = \dot{m}_{1He} c_{pHe} \left(T_2 - T_0 \right) + \dot{m}_{2He} c_{pHe} \left(T_4 - T_0 \right) \tag{8}$$

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:

$$P_{GT} = \eta_{gen} \dot{m}_{2He} (\eta_{iGT} \eta_{mech} w_{GT} - \eta_{iC} \eta_{mech} w_C) \tag{9}$$

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].
Gas turbine and compressor work were calculated as fallow:

$$w_{GT} = h_4 - h_{out} \tag{10}$$

$$w_C = h_{he-out} - h_{he-in} \tag{11}$$

where: w_{GT} - gas turbine work [kJ/kg], h_4/h_{out} - helium inlet/outlet enthalpy to/from gas turbine [kJ/kg], w_C – main compressor work [kJ/kg], h_{he-out}/h_{he-in} – helium outlet/inlet enthalpy from/to main compressor [kJ/kg]. Steam turbine electrical power was calculated as follow:

$$P_{ST} = \eta_{gen}\eta_{mech}\dot{m}_{p1}(\eta_i\eta_{mech}w_{HPST} + \eta_i\eta_{mech}w_{MPST} + \eta_i\eta_{mech}w_{LPST}) - \eta_{ip}\eta_{mech}\dot{m}_w w_{P_1} \tag{12}$$

High, medium, low pressure steam turbine work were calculated as follow.

$$w_{HPST} = h_{sin} - h_{sout} \tag{13}$$

$$w_{MPST} = h_{sout} - h_{sout1} \tag{14}$$

$$w_{LPST} = h_{sout1} - h_{sout2} \tag{15}$$

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_{HPST} / w_{MPST} / w_{LPST} - high/medium/low pressure steam turbine work [kJ/kg], w_{P_1} - water pump work [kJ/kg], $\dot{m}_w$ - water mass flow [kg/s], h_{sin}/h_{sout} – enthalpy at inlet and outlet to/from high pressure steam turbine, h_{sout}/h_{sout1} – enthalpy at inlet and outlet at medium pressure steam turbine, h_{sout1}/h_{sout2} – enthalpy at inlet/outlet at low pressure steam turbine. Main model and thermodynamic parameters for numerical calculations of high temperature hybrid combined cycle are listed in Table 2.

Table 2. Model assumptions and main thermodynamic parameters.

Main Parameter	Value	Unit
Reactor Cycle		
Power	600	MWth
Pressure	6	MPa
Coolant	Helium	--
Outlet Temperature	750-1000	°C
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	-
Compresion 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	-

The efficiency of high temperature combined cycle without hydrogen production was calculated as follow:

$$\eta_c = \frac{P_{GT} + P_{ST} - W_B - W_{P2}}{\dot{Q}_r} \tag{16}$$

where: W_B – blower work [kW], W_{P2} – second pump work [kW]. For cases when hydrogen production has been taken in to account the following formula for cycle efficiency was used.

$$\eta_c = \frac{P_{GT} + P_{ST} - W_B - W_{P2} + \eta_{CuCl}\left(\Delta G + T\Delta S\right)}{\dot{Q}_r} \qquad (17)$$

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, ΔG - electrical energy [kJ], $T\Delta S$ - heat demand [MW$_{th}$], $\dot{Q}_r$ - is the nuclear reactor thermal power.

4. Results

In the Figure 3 results of numerical calculation for high temperature hybrid combined cycle without hydrogen production are shown. The first graph show gas turbine power P_{GT} work when compression ratio and inlet temperature will be changed between 750°C – 1000°C. From thermodynamic point of view optimal compression ratio for gas turbine is located between 1.5 to 2.5 and depend of the inlet temperature. The graph 3b show steam turbine power P_{ST} versus compression ratio. The steam turbine work with the highest efficiency when compression ratio is between 1.1 to 1,5.
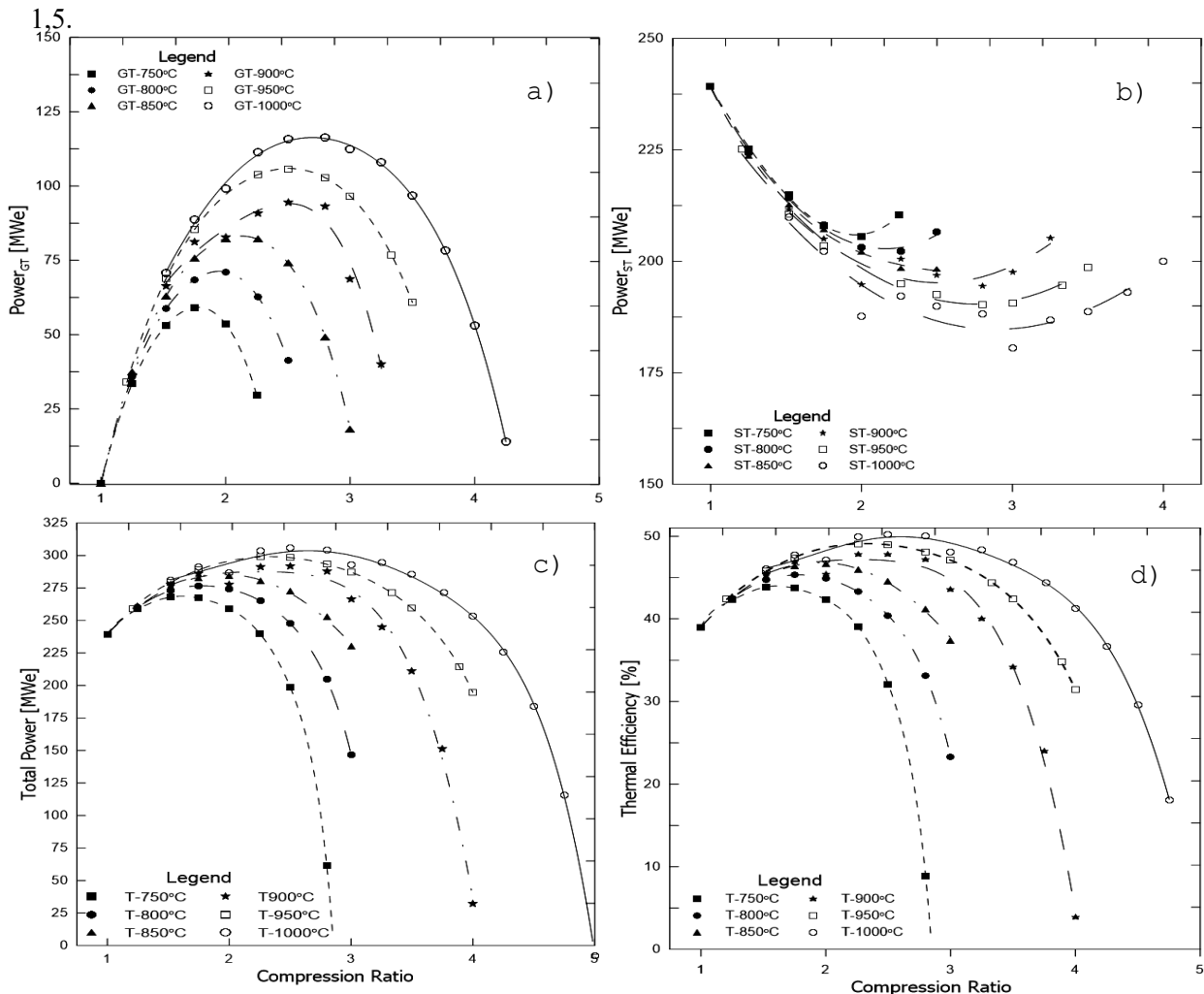

Figure 3. High Temperature Hybrid Combined Cycle – (a) gas turbine power - P_{GT}, (b) steam turbine power - P_{ST}, (c) total power - P_T, (d) thermal Efficiency - $P_{\eta c}$.

From Figure 3 it is easy to see that it is possible to achieve more than 50% of thermal efficiency, when helium from nuclear reactor could achieve 1000°C The highest thermal efficiency has been obtained when compression ratio will be changed from 1,5 to 2,5. From thermodynamic point of

view optimal compression ratio for these cycle is located between 1.5 to 2.5 and most depend on temperature. For increasing reactor temperature optimal compression ratio also increases. For reactor outlet temperature 1000°C and optimal compression ratio 115,7 MW$_e$ is produce by gas turbine and 189,9 MW$_e$ with steam turbine.
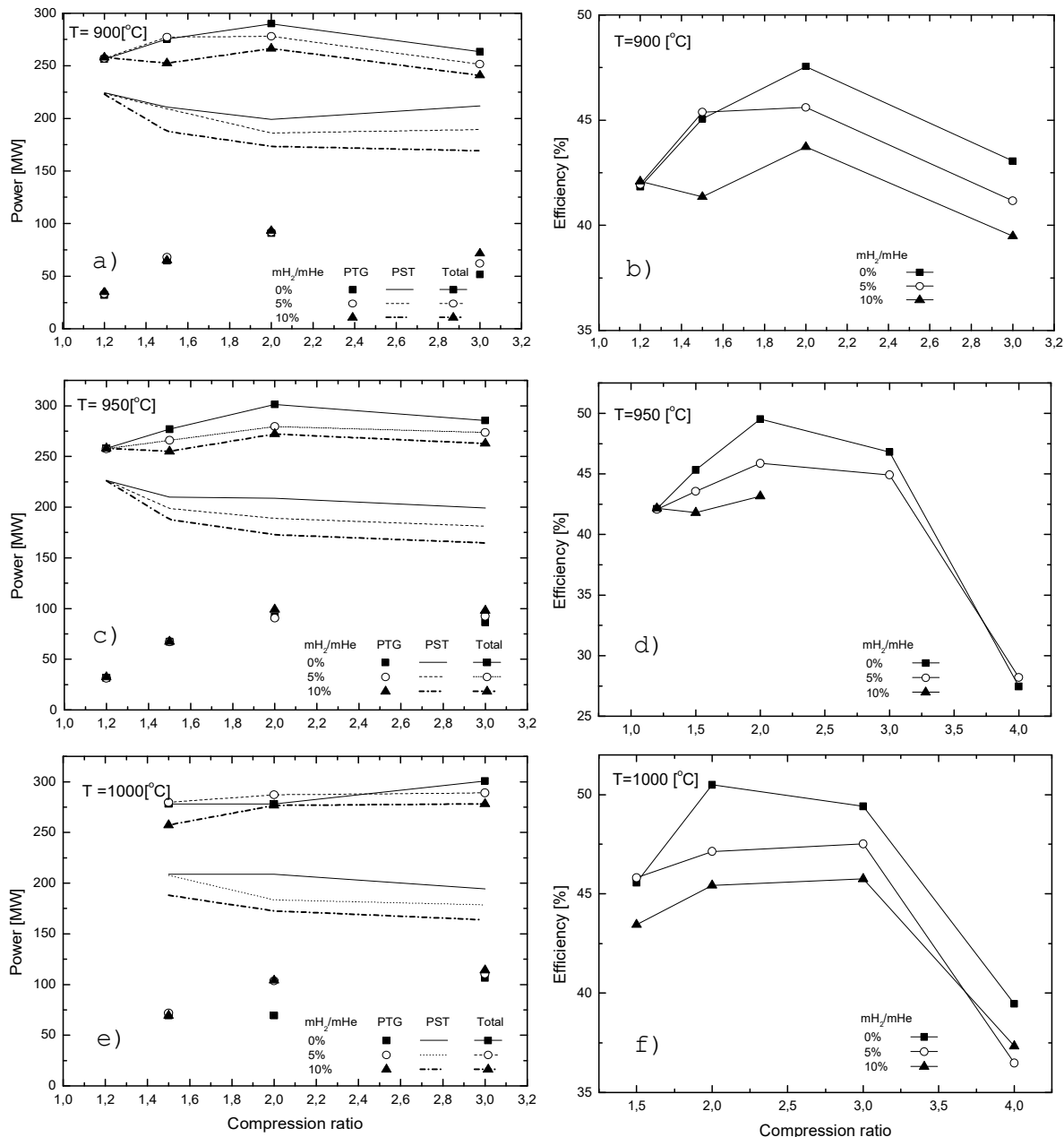

Figure 4. High Temperature Combined Cycle Total Power and Thermal Efficiency for different reactor temperature T$_{out}$ and with hydrogen production.

The figure 4 shows numerical calculation for high temperature hybrid combined cycle with hydrogen production for different reactor outlet temperature. The top graph shows how high temperature hybrid combined cycle work under different compression ratio with and without hydrogen production at temperature 900°C, where it is possible to achieve 48% of thermal efficiency, but the second line show how result should be changed at 950°C, the optimum compression ratio is should be around 2, where is possible to achieve 49% of thermal efficiency without hydrogen production and

45% with hydrogen production. The best results was achieved at the third line when outlet temperature from high temperature nuclear reactor was determined as 1000°C. Thermal efficiency without hydrogen production can achieve 50.2%, but without hydrogen production can achieve 45 – 46%.

5. Conclusions

High temperature gas cooled nuclear reactors can be used to produce electrical energy and hydrogen at thermochemical Cu-Cl cycle or high temperature electrolysis. Hydrogen produced in high temperature thermochemical cooper chlorine cycle can achieve much higher value of thermal efficiency than hydrogen produced in high temperature electrolysis at the lowest outlet temperature, from nuclear reactor while High temperature electrolysis is much more efficient in terms of the highest outlet temperature.The power conversion system was analysed with hydrogen production in order to maximize the cycle efficiency. Optimal efficiency for various hydrogen production rates and corresponding conditions at different outlet temperature from nuclear reactor and compressor compression ratios has been calculated. The resulting system power output rates and efficiencies are determined. All cycles exhibit an increase in efficiency if the reactor outlet temperature is raised. Certainly the temperatures are not only one parameter to improve efficiency. Other parameters like isentropic and mechanical efficiencies of the turbines and the compressor have significant influences. The Cu-Cl process can be advantageous, both generally and especially if the system cannot operate with the resulting temperature 800°C and higher. High temperature reactors used for electricity and hydrogen production have significant future potential to improve efficiency by raising the reactor outlet temperature or steam temperature. Safety and compact unit size, low costs, high temperature may offer benefits for various applications beyond electricity generation (e.g., district heating). The high efficiency energy conversion, hydrogen production with thermochemical process that require large amounts of heat can be accommodated with HTR.

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