Dynamic Modelling of Hydrogen Production Plant Based on MHTRG

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Abstract: Hydrogen energy as a kind of clean energy has been widely studied in the world. It is very promising to use nuclear energy to produce hydrogen for realizing the sustainable hybrid energy system. In this paper, a new type of hydrogen production plant based on modular high temperature gas-cooled reactor (MHTGR), copper-chlorine (Cu-Cl) cycle and high temperature electrolysis (HTE) is proposed and the scheme feasibility is verified by the software in MATLAB/Simulink platform. The result shown that the plant can product hydrogen of 25.6t/h at full power operation and its transient characteristics is in accordance with the physical mechanism.

Keywords: Hydrogen, hybrid energy system, MHTGR, Cu-Cl cycle, HTE, feasibility.

1. INTRODUCTION

With the development strategy of sustainable clean energy, hydrogen energy, as a promising energy, has been widely studied in the world. It is an important direction of energy development in the future to combine hydrogen energy with nuclear energy to form a sustainable and environment-friendly hybrid energy system. Copper-chlorine (Cu-Cl) cycle, which only needs thermal and electric energy to convert water (H_2O) into hydrogen (H_2) and oxygen (O_2), is one of the most popular hydrogen production schemes with high efficacy over the world. Nowadays, several universities and research institutions in the world, such as University of Ontario Institute of Technology and Argonne National Laboratory (ANL), have carried out a series of studies on the combination of nuclear and Cu-Cl cycle to realize hydrogen production, in which the most studied is using supercritical water reactor (SCWR) to provide the required heat for Cu-Cl cycle (Maan et al., 2017, Naterer et al., 2010). Other researchers also have proposed that sodium-cooled fast reactor (SFR) is also an ideal heat source for Cu-Cl cycle (Yildiz et al., 2006). The utilization of SCWR and SCR for Cu-Cl cycle shows that the fourth generation of advanced nuclear energy system has the possibility of realizing nuclear hydrogen production with Cu-Cl cycle to some extent.

The nuclear steam supply system (NSSS) based on the modular high temperature gas-cooled reactor (MHTGR), which is developed by the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University (Zhang et al., 2016, Dong et al., 2018), can also provide high quality steam of nearly 600°C, and has potential to match with Cu-Cl cycle. However, the feedwater temperature of the SCWR is much higher than that of the MHTGR, which is because that the coolant of the MHTGR is helium, and the temperature difference between the feedwater and steam needs to be increased

so that the heat exchange efficiency can be improved. Therefore, direct combination of MHTGR and Cu-Cl cycle to produce hydrogen will make the steam after utilization still have a better quality. So, it is better to continually use these steam for high temperature electrolysis (HTE) hydrogen production and heating feedwater, from which the utilization efficiency of steam is improved as much as possible.

In this paper, a dynamic modelling of hydrogen production plant based on MHTGR, Cu-Cl cycle and HTE is given and both steady state and transient state are verified by numerical simulation based on MATLAB/Simulink platform.

2. SYSTEM DESCRIPTION

Fig. 1 shows the schematic diagram of a hydrogen production plant based on MHTGR, Cu-Cl cycle, and HTE, from which it can be seen that the plant is divided into nuclear island and conventional island two parts. Nuclear island consists of n modules NSSS based on MHTGR as well as once through steam generator (OTSG) and conventional island is composed of feedwater heating system, Cu-Cl cycle and HTE. The coolant helium flows from bottom to top in the reactor and carries out the heat generated by the fuel elements. Then helium flows through the primary side of OTSG, and after heating the feedwater of secondary side to the superheated steam, the helium flows back to the bottom of the core and forms natural circulation. The superheated steam generated by multiple NSSS modules are combined together before entering conventional island and the main steam directly flows into the Cu-Cl cycle hydrogen production process. In the Cu-Cl cycle, the steam heats the hydrolysis and decomposition reactors to provide required temperature. Then part of steam form Cu-Cl cycle is extracted into feedwater heater and the other part is continually delivered into HTE process for preheating the reactant H_2O. The exhausted steam from HTE and water from feedwater heater are fed into condenser
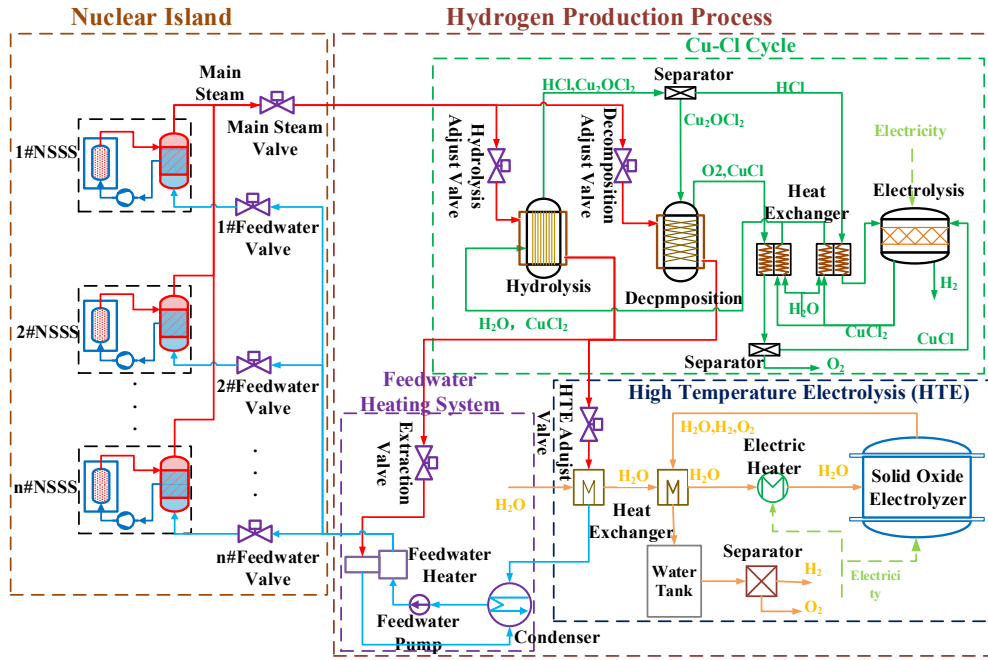
Fig. 1. Simplified diagram of hydrogen production plant based on MHTGR.

together. After the condensed water is pressured by feedwater pump and reheated by feedwater heater, it is redistributed into each NSSS module by feedwater valve.

Moreover, the details of Cu-Cl cycle and HTE processes are described as follows. Cu-Cl cycle includes three chemical reactions, namely hydrolysis, decomposition and electrolysis. Prat of the live steam into Cu-Cl cycle is used to heat the hydrolysis reactor to around 400°C. In the hydrolysis reactor, H_2O and $CuCl_2$ react and form HCl as well as Cu_2OCl_2. The mixed product is then separated, and Cu_2OCl_2 is delivered into decomposition reactor for the next reaction, where the rest of live steam provide higher required temperature of 500 to 540°C. Cu_2OCl_2 solid decomposes to CuCl and O_2. The high-temperature products of hydrolysis and decomposition reactions are used to heat the reactants of electrolysis reaction, then the cooled HCl and CuCl enter the electrolyzer, transform to H_2 and $CuCl_2$ under the action of external voltage. The key process of HTE is that the H_2O decomposes into H_2 and O_2 under the external voltage and high temperature. H_2O is first heated by the steam from Cu-Cl cycle and high temperature products of HTE, then further heated by electric heater to the required 800°C, and is delivered into electrolyzer for hydrogen production.

3. DYNAMIC MODELLING

In this section, the lumped parameter models of nuclear island and conventional island are both proposed. All these models are based on the conversation laws of mass, energy and momentum. The NSSS modules and feedwater heating system have been given by Dong (2018), and not listed concretely in this paper.

3.1 Fluid Flow Network

The secondary side of OTSGs and primary side of various kinds heaters in Cu-Cl cycle, HTE as well as feedwater heater system are connected by pipes, which is essentially a complex fluid flow network (FFN). Fig. 2 shows the FFN topology of hydrogen production plant in Fig.1.
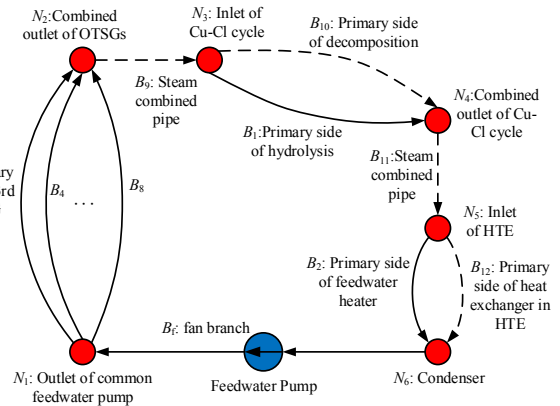

Fig. 2 Topology of plant secondary loop FFN.

As shown in the Fig. 2, select solid line branches as trees and dotted line branches as links. According to the result proposed by Dong (2016), the fluid network model can be expressed as

$$\begin{cases} \dot{\boldsymbol{Q}} = \boldsymbol{K}_c\left(-\boldsymbol{Q}_{cD}^2\boldsymbol{R}_c - R_f\boldsymbol{e}_{Qfc}^T\boldsymbol{e}_{Qfc}\boldsymbol{Q}_c + \boldsymbol{E}_{Qc}^T\boldsymbol{H}_a + \boldsymbol{e}_{Qfc}^T H_d\right), \\ \left(\boldsymbol{E}_{Qc}\boldsymbol{K}_c\boldsymbol{E}_{Qc}^T + \boldsymbol{K}_a\right)\boldsymbol{H}_a = \boldsymbol{K}_a\boldsymbol{Q}_{aD}^2\boldsymbol{R}_a + \\ \boldsymbol{E}_{Qc}\boldsymbol{K}_c\left(\boldsymbol{Q}_{cD}^2\boldsymbol{R}_c + R_f\boldsymbol{e}_{Qfc}^T\boldsymbol{e}_{Qfc}\boldsymbol{Q}_c - \boldsymbol{e}_{Qfc}^T H_d\right), \end{cases} \quad (1)$$

where $\boldsymbol{Q}=[Q_1,…,Q_{12}]^T$, $\boldsymbol{Q}_c=[Q_1,…,Q_8]^T$, $\boldsymbol{Q}_a=[Q_9,…,Q_{12}]^T$, $\boldsymbol{K}_c$=diag([$K_1,..K_{12}$]), $\boldsymbol{K}_c=[K_1,…,K_8]^T$, $\boldsymbol{K}a=[K_9,…K_{12}]^T$, $\boldsymbol{R}_c=[R_1,…,R_8]^T$, $\boldsymbol{R}_a=[R_9,…,R_{12}]^T$, $\boldsymbol{H}_a=[H_9,…,H_{12}]^T$, $\boldsymbol{Q}_{cD}^2$ =diag([$Q_1|Q_1|,…,Q_8|Q_8|$]), $\boldsymbol{Q}_{aD}^2$ =diag([$Q_9|Q_9|,…,Q_{12}|Q_{12}|$]),

Q_i, K_i, R_i and H_i is repetitively the flowrate, resistance, pressure drop and inertia coefficient of branch i. H_d is the pressure head by the pump, R_f is the resistance coefficient of pump branch. E_{Qc} and e_{Qfc} are the matrixes described FFN topology. For the FNN shown in the Fig. 2, it can be obtained that

$$\begin{cases} E_{Qc} = \begin{bmatrix} 0 & 0 & -1 & -1 & -1 & -1 & -1 & -1 \\ 1 & 0 & -1 & -1 & -1 & -1 & -1 & -1 \\ 0 & 0 & -1 & -1 & -1 & -1 & -1 & -1 \\ 0 & 1 & -1 & -1 & -1 & -1 & -1 & -1 \end{bmatrix}, \\ e_{Qfc} = \begin{bmatrix} 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \end{bmatrix}. \end{cases} \qquad (2)$$

3.2 Cu-Cl Cycle

3.2.1 Hydrolysis

Regarding hydrolysis reactor as a type of heat exchanger. Ignoring the mass and specific heat of the reactor, the thermal dynamic equation of the primary side is

$$V_{Hst}\rho_{Hst}C_{Hst}\dot{T}_{Hp} = G_{Hst}(h_{Hp,in} - h_{Hp,out}) - K_H A_H \Delta T_H, \qquad (3)$$

where V_{Hst}, ρ_{Hst}, C_{Hst} and G_{Hst} are respectively the volume, density, specific heat and mass flowrate of steam of the primary side, T_{Hp} is the primary average temperature, $h_{Hp,in}$ and $h_{Hp,out}$ are the specific enthalpy of the steam at inlet and outlet of the primary side, K_H and A_H are the heat transfer coefficient and area, ΔT_H is the average temperature difference, which can be computed by

$$\Delta T_H = \frac{(T_{Hp,out} - T_{Hs,in}) - (T_{Hp,in} - T_{Hs,out})}{\ln(T_{Hp,out} - T_{Hs,in})/(T_{Hp,in} - T_{Hs,out})}, \qquad (4)$$

where $T_{Hp,in}$, $T_{Hp,out}$, $T_{Hs,in}$ and $T_{Hs,out}$ are respectively the inlet and the outlet steam temperature at the primary side and secondary side. The dynamic of secondary side are as follows.

$$\left(\sum_i^{M_1} N_i C_i\right)\dot{T}_{Hs} = G_{CuCl_2,in}C_{CuCl_2,in}(T_{CuCl_2,in} - T_{Hsin0})$$

$$+ G_{H_2O,in}C_{H_2O,in}(T_{H_2O,in} - T_{Hsin0}) - G_{H_2O,out}C_{H_2O,out}(T_{H_2O,out} - T_{Hsout0}) \qquad (5)$$

$$- G_{HCl,out}C_{HCl,out}(T_{HCl,out} - T_{Hsout0}) + K_H A_H \Delta T_H - \Delta H_{H_2O}v_{H_2O},$$

where M_1 is a collection of materials $CuCl_2$, H_2O, HCl and Cu_2OCl_2. N, C, G and T are respectively the amount of substance, specific enthalpy, mass flow and temperature of corresponding material. The subscript in and out represent the inlet and outlet. T_{Hs} is the average temperature of secondary side, T_{Hsin0} and T_{Hsout0} represent the rated inlet and the outlet temperature of the secondary side. ΔH_{H2O} is the heat absorption by 1 mol H_2O, v_{H2O} is the H_2O reaction rate. During the hydrolysis reaction, an excess of H_2O is required to suppress other competing reactions. Therefore, the gas in the reactor is the mixture of H_2O and HCl, so do the outlet. The dynamic equation of various materials in the hydrolysis reactor are

$$\begin{cases} \dot{N}_{H_2O} = G_{H_2O,in} - v_{H_2O} - G_{H_2O,out}, \\ \dot{N}_{HCl} = v_{HCl} - G_{HCl,out}, \\ \dot{N}_{CuCl_2} = G_{CuCl_2,in} - v_{CuCl_2}, \\ \dot{N}_{Cu_2OCl_2} = v_{Cu_2OCl_2} - G_{Cu_2OCl_2,in}, \end{cases} \qquad (6)$$

where v is the reaction rate of corresponding materials. According to the Arrhenius theorem and chemical equation, the rate of H_2O can be expressed as

$$v_{H_2O} = k_H \exp\left[-E_H/(RT_{Hs,out})\right]p_{H_2O}/p_{HCl}^2, \qquad (7)$$

where p_{H2O} and p_{HCl} are respectively the partial pressure of H_2O and HCl, E_H is the activation energy of hydrolysis reaction, R is ideal gas constant, k_H is the standard reaction rate coefficient. The partial pressure of HCl can be expressed as

$$p_{HCl} = N_{HCl}RT_{Hs}/V_H, \qquad (8)$$

where V_H is the volume of hydrolysis reactor. And the partial pressure of H_2O is calculated by

$$p_{H_2O} = P_{WS}\left[T_{Hs}, V_1/(M_{H_2O}N_{H_2O})\right], \qquad (9)$$

where P_{WS} is given by IAPWS-IF97 database for water/steam thermodynamic parameters. M_{H2O} is molecular weight of H_2O.

3.2.2 Decomposition

The thermal dynamic of decomposition is similar with hydrolysis

$$\begin{cases} V_{Dst}\rho_{Dst}C_{Dst}\dot{T}_{Dp} = G_{Dst}(h_{Dp,in} - h_{Dp,out}) - K_D A_D \Delta T_D, \\ \left(\sum_i^{M_2} N_i C_i\right)\dot{T}_{Ds} = G_{Cu_2OCl_2}C_{Cu_2OCl_2}(T_{Cu_2OCl_2,in} - T_{Dsin0}) \\ - G_{CuCl}C_{CuCl}(T_{CuCl,out} - T_{Dsout0}) - G_{O_2}C_{O_2}(T_{O_2,out} - T_{Hsout0}) \\ + K_D A_D \Delta T_D - \Delta H_{Cu_2OCl_2}v_{Cu_2OCl_2}, \end{cases} \qquad (10)$$

where M_2 is material collection of Cu_2OCl_2, $CuCl$ and O_2, $\Delta H_{Cu2OCl2}$ is heat absorption by 1 mol Cu_2OCl_2, the mixture in secondary side are Cu_2OCl_2, $CuCl$ and O_2, according to conservation of mass, each reactant and resultant satisfies

$$\begin{cases} \dot{N}_{Cu_2OCl_2} = -v_{Cu_2OCl_2} + G_{Cu_2OCl_2,in}, \\ \dot{N}_{CuCl} = v_{CuCl} - G_{CuCl,out}, \\ \dot{N}_{O_2} = v_{O_2} - G_{O_2,out}. \end{cases} \qquad (11)$$

The reaction rate of Cu_2OCl_2 can be expressed as

$$v_{Cu_2OCl_2} = k_D \exp\left[-E_D/(RT_{Ds})\right]/p_{O_2}, \qquad (12)$$

where k_D is the standard reaction rate coefficient of decomposition, E_D is the activation energy of decomposition, and p_{O2} can be computed by ideal gas equation.

3.2.3 Electrolysis

The thermal dynamic of electrolysis can be ignored since the reaction can be carried out under normal temperature. The dynamic equation of various materials in electrolyzer are

$$\begin{cases} \dot{N}_{CuCl_2} = v_{CuCl_2} - G_{CuCl_2,out}, \\ \dot{N}_{CuCl} = G_{CuCl,in} - v_{CuCl}, \\ \dot{N}_{H_2} = v_{H_2} - G_{H_2,out}, \\ \dot{N}_{HCl} = G_{HCl,in} - v_{HCl}. \end{cases} \qquad (13)$$

Considering that the electrolysis reaction is carried out in a solution, and each reactant and product affect the reaction rate. Therefore, the reaction rate of H_2 can be expressed as

$$v_{H_2} = k_E e^{-\frac{E_E}{RT_{Es}}}\left(\frac{N_{HCl}N_{CuCl}}{N_{HCl,0}N_{CuCl,0}}\right)\left(\frac{N_{CuCl_2}}{N_{CuCl_2,0}}\right)^{-1}\left(\frac{p_{H_2}}{p_{H_2,0}}\right)^{-0.5}, \qquad (14)$$

where k_E is the standard reaction rate coefficient, E_E is electrolysis reaction activation energy, T_{Es} is the reaction temperature. $N_{HCl,0}$, $N_{HCl,0}$, and $N_{HCl,0}$ are respectively the amount of substance for each material under rated operation state, $p_{H2,0}$

is the rated reaction pressure, and p_{H2} is the actual reaction pressure calculated from the ideal gas equation.

Electrolysis reaction also needs external voltage U. According to Faraday's law, the current and reaction rate during electrolysis satisfy the following relationship

$$I = nF v_{H_2}, \qquad (15)$$

where n is the number of electrons transferred by redox reaction when form 1mol of H_2. F is Faraday constant. Therefore, the electric power consumed by electrolysis is

$$W_e = UI. \qquad (16)$$

3.2.4 Heat exchanger

The primary side of the heat exchanger is high temperature H_2O, HCl, $CuCl$ and O_2, and the secondary side is $CuCl_2$ solution composed of $CuCl_2$ and H_2O, neglecting the dynamic of primary side, the dynamic model of heat exchanger is

$$\begin{cases} N_{sEH}\overline{C}_{sEH}\dot{T}_{sEH} = Q_{EH} + G_{sEH}(\overline{h}_{sEH,in} - \overline{h}_{sEH,out}), \\ Q_{EH} = \sum_{i}^{M_4} G_i \left(h_{i,pEHin} - h_{i,pEHout} \right), \end{cases} \qquad (17)$$

where N_{sEH} and G_{sEH} are the total substance amount and flowrate of secondary, $\overline{C}_{sEH}$ is the average specific heat, $\overline{h}_{sEH,in}$ and $\overline{h}_{sEH,out}$ are respectively the average specific enthalpy of secondary side inlet and outlet. Q_{EH} is the transferred heat from primary side to secondary side, M_4 is the substance collection of H_2O, HCl, $CuCl$ and O_2, $h_{i,pEHin}$ and $h_{i,pEHout}$ are the specific enthalpy of corresponding material at primary side inlet and outlet.

3.3 High Temperature Electrolysis

3.3.1 Solid oxide electrolyser

It is simplified to only consider the reduction reaction occurring at the cathode, and further considered that the reaction temperature of the electrolyser is constant. So, it can be obtained the dynamic of electrolyser according to the mass conservation equation for reactants and resultants in cathode

$$\begin{cases} \dot{N}_{H_2O} = G_{H_2O,in} - v_{H_2O} - G_{H_2O,out}, \\ \dot{N}_{H_2} = v_{H_2} - G_{H_2,out}, \end{cases} \qquad (18)$$

It is considered that the cathode reaction rate is only related to the partial pressure of H_2O and H_2. According to the Arrhenius theorem and the chemical reaction equation, the reaction rate expression can be obtained as

$$v_{H_2O} = v_{H_2} = k_{HTE0}\exp\left[-E_{HTE}/\left(RT_{HTE}\right)\right]p_{H_2O}/p_{H_2}, \qquad (19)$$

where k_{HTE0} is standard reaction rate coefficient of high temperature electrolysis, E_{HTE} is reaction activation energy, T_{HTE} is reaction temperature.

3.3.2 Heat exchanger

The secondary side of both heat exchangers are H_2O, the primary side of 1#heat exchanger is steam form Cu-Cl cycle while that of 2#heat exchanger is high temperature mixture of

reactant and resultant from electrolysis. The dynamic equations of both heat exchangers are respectively

$$\begin{cases} V_{st1}\rho_{st1}C_{st1}\dot{T}_{HE1p} = G_{st1}(h_{HE1p,in} - h_{HE1p,out}) - K_{HE1}A_{HE1}\Delta T_{HE1}, \\ V_{H_2O1}\rho_{H_2O1}C_{H_2O1}\dot{T}_{HE1s} = G_{H_2O}(h_{HE1s,in} - h_{HE1sout}) + K_{HE1}A_{HE1}\Delta T_{HE1}, \end{cases} \qquad (20)$$

and

$$\begin{cases} \overline{V}_{HE2p}\overline{\rho}_{HE2p}\overline{C}_{HE2p}\dot{T}_{HE2p} = \sum_{i}^{M_{HTE}} G_i(h_{i,in} - h_{i,out}) - K_{HE2}A_{HE2}\Delta T_{HE2}, \\ V_{H_2O2}\rho_{H_2O2}C_{H_2O2}\dot{T}_{HE2s} = G_{H_2O}(h_{HE2s,in} - h_{HE2s,out}) + K_{HE2}A_{HE2}\Delta T_{HE2}, \end{cases} \qquad (21)$$

where $\overline{V}_{HE2p}$, $\overline{\rho}_{HE2p}$ and $\overline{C}_{HE2p}$ are the average volume, density and specific heat of the mixed materials at primary side, M_{HTE} is the material collection of H_2O, H_2 and O_2, G_i, $h_{i,in}$ and $h_{i,out}$ are the flowrate, inlet and outlet specific heat of corresponding material.

3.43.3 Electric heater

The electric heater can be considered as a special form of heat exchanger that is powered by electrical energy to heat the material on the secondary side. Therefore, ignoring primary side dynamics, the model of the electric heater can be simplified as

$$V_{H_2O3}\rho_{H_2O3}C_{H_2O3}\dot{T}_{EHs} = G_{H_2O}(h_{EHs,in} - h_{EHs,out}) + W, \qquad (22)$$

where W is the electric power consumed by electric power.

4. SIMULATION AND ANALYSIS

In this section, the steady-state operation points and transient characteristics are given by the numerical simulation software based on MATLAB/Simulink platform, which consists of 6 NSSS modules, Cu-Cl cycle module and HTE module.

4.1 Steady State Points

In plant full power operation, each NSSS modules operate at 100%FPL, and the total hydrogen production is 25.6t/h. Specific key process parameters are shown in Table 1.

Table 1. Steady-state values of plant key process variables

Parameter	Value	Unit
Plant		
Thermal power	1522.7	MW
Hydrogen production	25.6	t/h
Electricity consumption	745.7	MW
Main steam temperature	600	°C
Feedwater temperature	205	°C
Hydrogen process		
Hydrogen production	6.46	t/h
Hydrolysis temperature	400	°C
Hydrolysis pressure	0.1	MPa
Decomposition temperature	500	°C
Decomposition pressure	0.1	MPa
Electrolysis pressure	2.5	MPa
HTE temperature	800	°C
HTE pressure	0.13	MPa
Discharge temperature	80	°C

In the hydrogen production plant, the Cu-Cl cycle mainly consumes thermal energy while HTE process consumes elec-

tric energy, therefore, it mainly focuses on the efficiency of
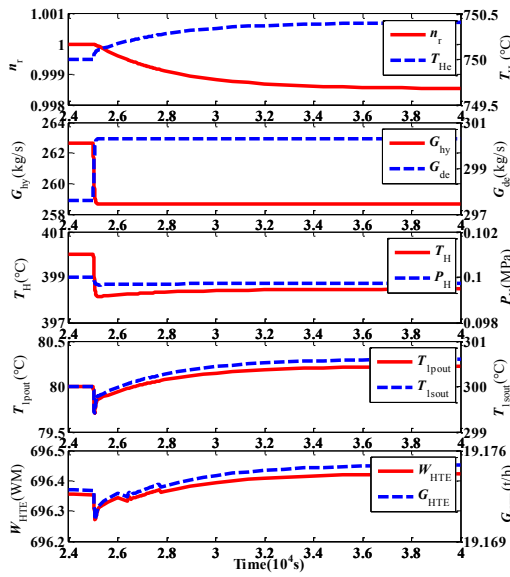
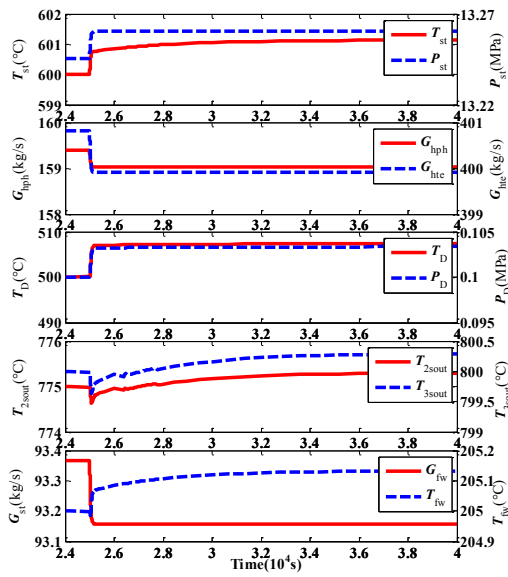Cu-Cl cycle. According to the current international research

Fig. 3 Dynamic responses of hydrogen production plant in case of step decrease of hydrolysis adjust valve opening.
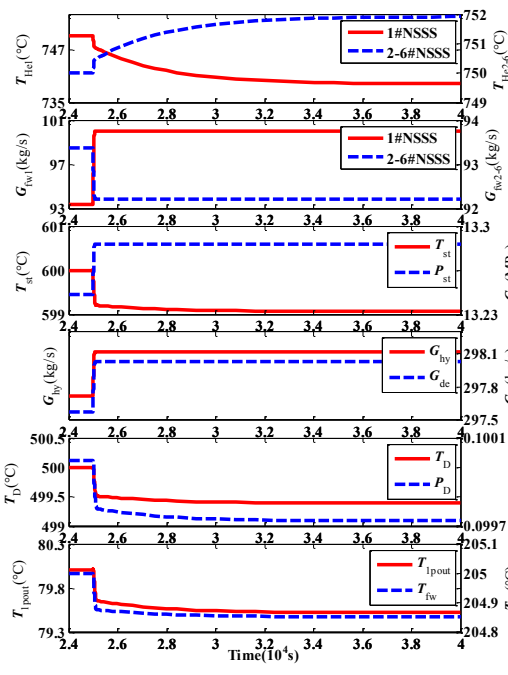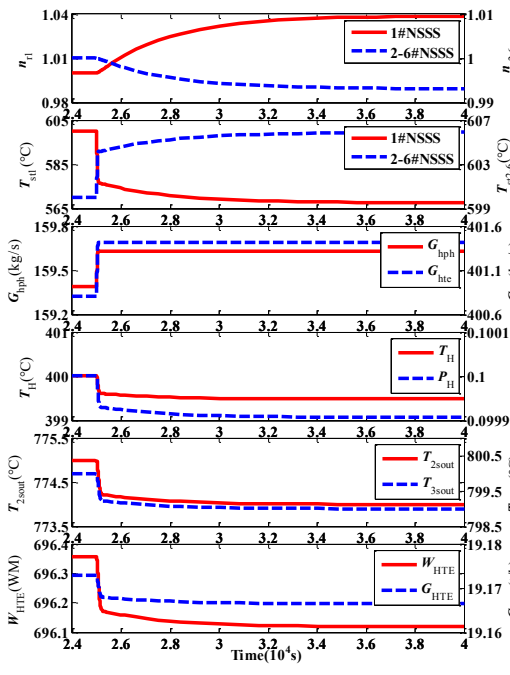

Fig. 4 Dynamic responses of hydrogen production plant in case of step increase of NSSS feedwater valve opening.

(Farrukh et al., 2018, Wu et al., 2017), the efficiency of different kinds of Cu–Cl cycle for nuclear-based hydrogen production are about from 32% to 55%. In this paper, Cu-Cl cycle efficiency is about 43.6%, which is at the same level as most of the current studies, and further proves the feasibility and correctness of the scheme proposed in this paper.

4.2 Transient State

The transient characteristics are given in open-loop. The initial operation condition is as shown in the section 4.1 and Table 1.

4.2.1 Step decrease of hydrolysis adjust valve opening

At 25000s, the hydrolysis adjust valve opening steps down so that the steam flowrate at the primary side of the hydrolysis reaction decreases with amplitude about 4 kg/s., and the temperature and pressure of the hydrolysis reaction decreased accordingly. The reduction of the hydrolysis steam flowrate

increases that of the decomposition, and the corresponding reaction temperature and pressure increase. The decrease of valve opening results in the increase of equivalent flow resistance of fluid network and the total feedwater and steam flowrate decrease. Therefore, the feedwater flowrate of each NSSS module, the extraction steam flowrate of feedwater heater and the primary side steam flowrate of 1#heat exchanger in HTE are also reduced. Accordingly, the secondary side outlet and reaction temperature of each heat exchanger and solid oxide electrolyser in HTE firstly decreased. As the pressure head of the feedwater pump remains unchanged, the pressure drops of the pump branch and the OTSG secondary side branch decreases, and result in the main steam pressure increase. The decrease of NSSS module feedwater flowrate enhances the thermal resistance on both sides of OTSG, which leads to the temperature increase of helium at inlet and outlet. Due to the negative feedback of core temperature, the reactor neutron flux decrease. Because the thermal power of the reactor is stable, the decrease of feedwater flowrate makes the steam temperature rise. Furthermore, the steam temperature at the outlet of Cu-Cl cycle increases, so the secondary side outlet temperature of each heat exchanger and solid oxide electrolyser temperature in HTE then increases, and the hydrogen production and electric power consumed also decreases firstly and then increases. Due to the decrease of feedwater flowrate and the increase of extraction temperature, the feedwater temperature also increases.

4.2.2 Step increase of NSSS feedwater valve opening

At 25000s, the feedwater valve opening of steps up so that the feedwater flowrate increases with amplitude about 7 kg/s, which weaken the thermal resistance of both sides of OTSG, resulting in the decrease of helium temperature and the increase of reactor neutron flux. Due to that the reactor thermal power unchanged, the steam temperature of 1#NSSS module decreases. With the increasing opening of 1#NSSS feedwater valve, the flow resistance between the main steam and feedwater pump outlets decreases rapidly. Since the pressure head of the feedwater pump and the opening of the main steam regulating valve do not change, the main steam pressure increases, and the feedwater flowrate of the other NSSS modules decreases, so the corresponding dynamic characteristics of helium temperature, steam temperature and neutron flux are opposite to those of 1#NSSS. As other modules are less affected by 1#NSSS, the main steam flowrate increases and the temperature decreases, so the temperature and pressure of hydrolysis and decomposition reaction decrease, and the steam temperature at the outlet of Cu-Cl cycle decrease, which further makes the feedwater temperature and all heat exchangers of HTE and the reaction temperature drop, so the corresponding hydrogen production and electric power consumption also decrease.

5. CONCLUSION

In this paper, a lumped-parameter dynamic model of hydrogen production plant is proposed based on conservation laws of mass, energy and momentum, which is composed of MHTGR, Cu-Cl cycle, HTE and FFN. The plant model is

programmed on MATLAB/Simulink as a numerical software and both steady and transient state validations are carried out, which shows the plant can product hydrogen of 25.6t/h and verifies the correctness and feasibility of model. It lays a foundation for the further work of the control system design.

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Appendix A. SYMBOL DESCRIPTION

n_r	Normalized nuclear power	T_{He}	Helium temperature
T_{st}	Steam temperature	P_{st}	Main steam pressure
T_H	Hydrolysis temperature	P_H	Hydrolysis pressure
T_D	Decomposition temperature	P_D	Decomposition pressure
T_{1pout}	Discharge temperature	T_{3s}	HTE temperature
G_{hv}	Hydrolysis steam flow	G_d	Decomposition steam flow
G_{hph}	Extraction flow	G_{ht}	Steam flow heating HTE
G_{fw}	Feedwater flow	T_{fw}	Feedwater temperature
W_{HT}	HTE electricity consumption	G_H	HTE hydrogen production
T_{1sout}	1#HE temperature	T_{2s}	2#HE temperature