Operation and Control Methodology for High-Temperature Steam Electrolysis System with Auxiliary Heating Devices

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1. Introduction

Very high-temperature gas-cooled reactor (VHTR) is one of GEN-IV nuclear reactor concepts using helium as a coolant, and it can be utilized for hydrogen mass-production and industrial applications due to coolant outlet temperature up to 950°C [1]. For an experimental demonstration, Korea Atomic Energy Research Institute (KAERI) is conducting a study in collaboration with Research Institute of Industrial Science and Technology (RIST), generating high-temperature steam using a helium loop and supplying it to Solid Oxide Electrolysis Cell (SOEC) stacks to produce hydrogen through high-temperature steam electrolysis (HTSE) [2].

Plate-type SOEC stack for HTSE has the advantage of being highly manufacturable and having a dense structure with very high hydrogen production efficiency. However, it is very sensitive to thermal shocks and rapid heating or cooling should be avoided during stack operation[3]. During startup and shutdown operation, the temperature change must be kept below 0.5~1.0°C per minute, which leads to unnecessary waste of heat source and increased work time of the operator. Therefore, an auxiliary device that automatically heats or cools the HTSE stack gradually is required [4].

This study introduces auxiliary heating units that can gradually heat up and cool down the HTSE stack and develops a methodology for operating and controlling the stages of operation utilizing these units. The auxiliary heating units have the advantage of conveniently startup or shutdown the stack with less energy than the main heat source. We prepared the units of 30 kW SOEC testable capacity, and a 6 kW SOEC test is currently planned to validate the unit's performance and methodology.

2. Requirements of the HTSE stack operation

Fig. 1 shows a schematic diagram of the HTSE connected to the heat source. An HTSE includes a stack of several single repeat units. The single unit is composed of the three layer cell (cathode/electrolyte/anode) and two half-interconnects [3]. In the cathode, high temperature steam is reduced and decomposed into hydrogen and oxygen ions. The oxygen ion from cathode is transferred to the anode, and the oxygen is produced in the anode by oxidizing oxygen ion. The generated hydrogen flows out of the stack along with the remaining steam and then passes through a condenser to remove the remaining steam.

SOEC stacks that require an operating temperature of 600~900°C are usually installed inside a high-temperature environment furnace to execute electrolysis operation. The SOEC has a steam channel to separate hydrogen and an air channel to blow out oxygen, a by-product, and the steam and air entering the SOEC must be preheated to the SOEC operating temperature for high-temperature operation. The steam supplied by the SOEC requires a constant, high-purity steam supply. An unstable flow rate of steam can cause pressure waves that can damage the sensitive SOEC stack internals.

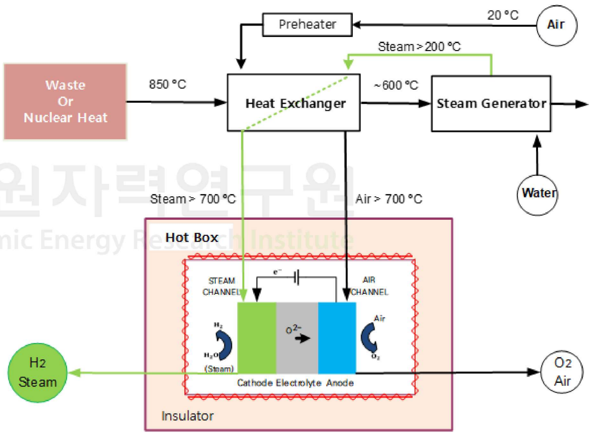

Fig. 1. Schematic diagram of the HTSE connected to the heat source.

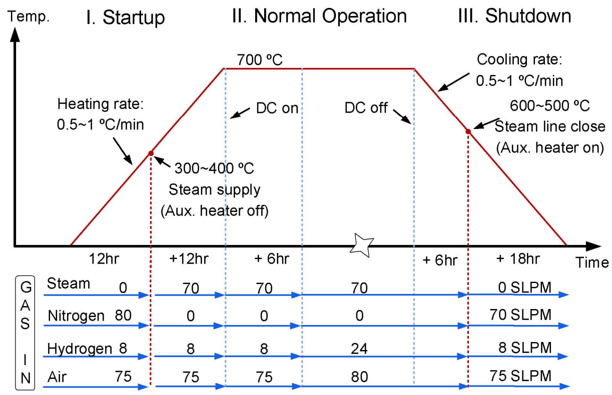

Fig. 2. Example of an operating procedure for a 6.0 kW capacity HTSE system [4].

Fig. 2 shows an example of an operating procedure for a 6.0 kW capacity HTSE system with the auxiliary heater units [4]. As shown in the Fig. 2, a small amount of hydrogen (safe gas) is injected into the steam channel as a reducing agent. This is to address the issue that steam can oxidize SOEC electrode materials at high temperatures, slowly degrading SOEC performance over long periods of operation. SOEC utilizes nitrogen instead of steam for heating or cooling. In addition, a trace amount of hydrogen is always introduced into the cathode (steam channel) to reduce the oxidized surface with steam.

On the other hand, the sealant of the SOEC stack is a glass material that is sensitive to high temperature thermal expansion [3]. The high temperature difference between cells can cause cracks in the glass material, which is the main cause of steam leakage, so controlling the temperature difference during cooling and heating is very important. Therefore, the balance-of-plant configuration of a HTSE that can meet these various operating requirements is necessary for stable SOEC operation. We summarized these requirements in Table I and quantify an approximate value for each.

Table I. Requirements of the HTSE stack operation

Requirement	Value	Prevent
Purified water	MΩ level	Oxidation, Contamination
Purified air	Moisture & oil free	Contamination
Hydrogen injection	Max. 25% (Volume ratio)	Oxidation (Cathode)
Stack heating rate	0.5~1.0°C /min (Plate type)	Leakage, Sealant failure
Hot box temp.	700~1000°C	Heat loss
Outlet temp. of Auxiliary heater	< 600°C	Heater failure
Dynamic pressure	< 50 kPa	Leakage, Sealant failure

3. HTSE experimental facility

An experimental facility is designed and constructed at KAERI for 30kW HTSE test using solid-oxide electrolyte cell (SOEC) stacks [2]. Fig. 3 describes a schematic of the experiment facility for 30kW HTSE system with helium loop as a heat source. The facility is composed of the major components such as a helium loop (lab-scale loop electrically simulating a VHTR), air and purified water supply system, HTSE including SOEC, steam generator, multi-stream heat exchanger (MHX), gas supply system and two auxiliary heating units(Unit-A for the steam line, Unit-B for the airline).

The experiment facility equipped a 77 kW heating system to heat the helium up to 1000℃, and a shell and helical-tube type steam generator and a MHX are manufactured to heat both the steam and air up to 800℃ with the heated helium. Purified water is evaporated via the steam generator and the steam is superheated through the MHX. Air is heated up through the MHX also, and it is used as sweep gas of anode side in SOEC stacks.

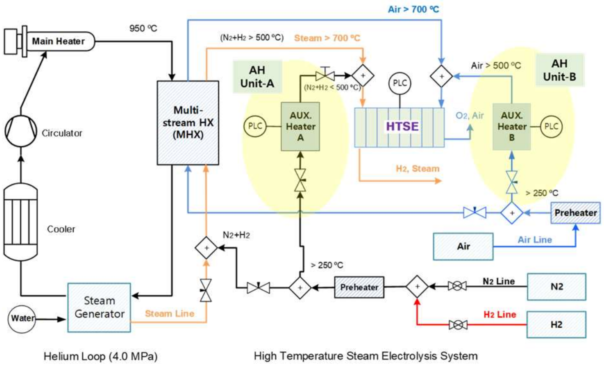

Fig. 3. Layout of the 30kW HTSE experimental facility.

4. Stack operation and control logic

The control logic of the stack must be configured to meet the requirements of the stack operation. To achieve this, we first configured the system and wrote the control logic for mixed gas and air based on the example operating procedure in Fig. 2.

4.1 Mixed gas line with auxiliary heater-A

The SOEC steam channel supplies nitrogen and hydrogen gas to mitigate oxidation during operation. For this purpose, both nitrogen gas line and hydrogen gas line are prepared as shown in Fig. 4, and MFC (Mass Flow Controller) are installed in each line to supply the required flow rate to the SOEC steam channel. These two lines merge at the front of the preheater to form the mixed gas line. The four valves and four junctions in Fig. 4 are to control the path of the gas, which changes according to the control logic of the mixed gas line for each stage of SOEC operation.

The preheater heats the atmospheric nitrogen/hydrogen mixture to close to the steam temperature of the steam line. The heating temperature of the gas mixture is automatically controlled by a PLC (Program Logic Controller), and when the temperature of the gas mixture reaches the maximum setting (ex. 250°C), the maximum setting is kept constant.

The AH-A (Auxiliary Heater-A) is intended to supply the HTSE with a nitrogen/hydrogen mixture instead of steam after heating. According to the control logic of each operation step, the gas mixture heated above 250°C in the preheater is introduced into the AH-A. The AH-A is equipped with a PLC to gradually heat up and cool down the incoming gas at a set rate (ex. 1.0°C /min).

A heating jacket is provided between Junction-2 and Junction-4, where the auxiliary heater is connected, to keep the temperature of the piping at a high temperature of 350°C or more until just before the auxiliary heater is started. This is to minimize the temperature imbalance that may occur at the beginning of the transition. It also suppresses the condensation of steam that may occur between the high temperature valve (MV03) and Junction-4.

4.2 Airline with the auxiliary heater-B

The SOEC air channel supplies air to blow out the oxygen generated during operation. For this purpose, an airline is prepared as shown in Fig. 5 and a gas MFC is placed to supply the required air flow rate. The three valves and one junction in the system are to control the path of the gas, which changes according to the operating logic.

The AH-B (Auxiliary Heater-B) is for heating compressed air and supplying it to the HTSE. According to the control logic of each stage of operation, air heated above 250°C from the preheater is introduced into the AH-B. The AH-B is equipped with a PLC to gradually heat up and cool down the incoming air at a set rate (ex. 1.0°C /min). The function of the preheater and heating jacket is the same as those installed in the mixed gas line.

4.3 HTSE Stack operation and control logic

The stack operation procedure is divided into three stages: startup, normal operation, and shutdown stages. The timing of AH operation and various valve opening and closing is derived based on the operation procedure shown in Fig. 2. Table II describes the control logic for the steam channel and Table III for the air channel. The control logic is written separately for the case with and without auxiliary heater.

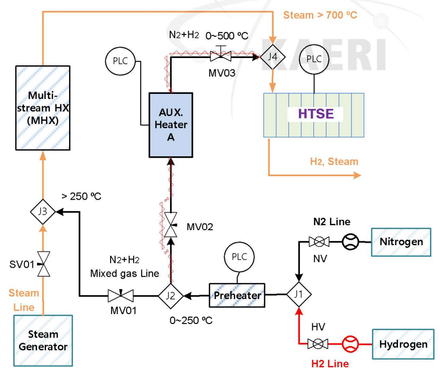

Fig. 4. Configuration of the mixed gas line with auxiliary heater unit-A.

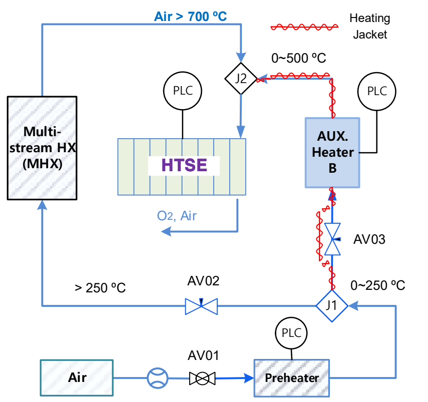

Fig. 5. Configuration of the airline with auxiliary heater unit-B.

Table II. HTSE stack operation and control logic for steam channel

Control device	Startup (°C)			Normal Operation	Shutdown (°C)		
	0~400 AH	0~400 W/O AH	400~700	700	700~500	500~250	250~0
Steam flow	No	←	Yes	←	←	No	←
N2 flow	Yes	←	No	←	←	Yes	←
H2 flow	Yes	←	←	←	←	←	←
SV1 valve	Close	←	**Open**	←	←	Close	←
MV1 valve	Close	**Open**	←	←	←	Close	←
MV2 valve	**Open**	Close	←	←	←	**Open**	←
MV3 valve	**Open**	Close	←	←	←	**Open**	←
Preheater	On	←	←	←	←	←	←
Aux. heater A	On	Off	←	←	←	On	**Off**
Heating jaket	Off	←	←	←	On	Off	←
NV	**Open**	←	**Close**	←	←	**Open**	←
HV	**Open**	←	←	←	←	←	←

Table III. HTSE stack operation and control logic for air channel

Control device	Startup (°C)			Normal Operation	Shutdown (°C)		
	0~400 AH	0~400 W/O AH	400~700	700	700~500	500~250	250~0
Air flow	Yes	←	←	←	←	←	←
AV1 valve	**Open**	←	←	←	←	←	←
AV2 valve	Close	**Open**	←	←	←	Close	←
AV3 valve	Close	Close	←	←	←	**Open**	←
Preheater	On	←	←	←	←	←	←
Aux. heater B	On	Off	←	←	←	On	**Off**
Heating jaket	Off	Off	←	←	On	Off	←

5. Conclusions

Introduced auxiliary heating units to HTSE hydrogen production systems utilizing high-temperature heat sources such as waste heat or nuclear power. Developed a methodology to easily operate and control the HTSE stack after switching the HTSE system from the high-temperature heat source by utilizing the auxiliary heating units.

This methodology can extend the lifetime of the HTSE stack and contribute to increasing the efficiency of hydrogen production by eliminating unnecessary waste of heat sources at the startup and shutdown of a HTSE system and reducing the working time of operators. It also has great potential for industrialization of HTSE systems, which are currently under active development.

ACKNOWLEDGEMENT

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