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SYSTEM ANALYSES OF HIGH AND LOW-TEMPERATURE INTERFACE DESIGNS FOR A NUCLEAR-DRIVEN HIGH-TEMPERATURE ELECTROLYSIS HYDROGEN PRODUCTION PLANT

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ABSTRACT

As part of the Next Generation Nuclear Plant (NGNP) project, an evaluation of a low-temperature heat-pump interface design for a nuclear-driven high-temperature electrolysis (HTE) hydrogen production plant was performed using the UniSim process analysis software. The low-temperature interface design is intended to reduce the interface temperature between the reactor power conversion system and the hydrogen production plant by extracting process heat from the low temperature portion of the power cycle rather than from the high-temperature portion of the cycle as is done with the current Idaho National Laboratory (INL) reference design. The intent of this design change is to mitigate the potential for tritium migration from the reactor core to the hydrogen plant, and reduce the potential for high temperature creep in the interface structures. The UniSim model assumed a 600 MW_t Very-High Temperature Reactor (VHTR) operating at a primary system pressure of 7.0 MPa and a reactor outlet temperature of 900°C. The low-temperature heat-pump loop is a water/steam loop that operates between 2.6 MPa and 5.0 MPa. The HTE hydrogen production loop operated at 5 MPa, with plant conditions optimized to maximize plant performance (i.e., 800°C electrolysis operating temperature, area specific resistance (ASR) = 0.4 ohm-cm^2, and a current density of 0.25 amps/cm^2). An air sweep gas system was used to remove oxygen from the anode side of the electrolyzer. Heat was also recovered from the hydrogen and oxygen product streams to maximize hydrogen production efficiencies. The results of the UniSim analysis showed that the low-temperature interface design was an effective heat-pump concept, transferring 31.5 MW_t from the low-temperature leg of the gas turbine power cycle to the HTE process boiler, while consuming 16.0 MW_e of compressor power. However, when this concept was compared with the current INL reference direct Brayton cycle design and with a modification of the reference design to simulate an indirect Brayton cycle (both with heat extracted from the high-temperature portion of the power cycle), the latter two concepts had higher overall hydrogen production rates and efficiencies compared to the low-temperature heat-pump concept, but at the expense of higher interface temperatures. Therefore, the ultimate decision on the viability of the low-temperature heat-pump concept involves a tradeoff between the benefits of a lower-temperature interface between the power conversion system and the hydrogen production plant, and the reduced hydrogen production efficiency of the low-temperature heat-pump concept compared to concepts using high-temperature process heat.

INTRODUCTION

Considerable analyses have been performed at the Idaho National Laboratory (INL) to develop a reference commercial-scale HTE conceptual plant design driven by a helium-cooled Very High Temperature Reactor (VHTR) operating at 600 MW_t with a reactor outlet temperature of 900°C. The advantage of nuclear-driven HTE over conventional electrolysis, which is a well established technology, is that considerably higher overall hydrogen production efficiencies can be achieved at the higher temperatures. This improvement occurs because the power cycle driving the HTE process has high efficiency and because heat can be directly added to the hydrogen production process without the losses associated with the conversion to electricity. Therefore, in high temperature electrolysis some of the energy needed to split the water is added as heat instead of electricity, thereby reducing the total energy required, and improving the overall process efficiency. An additional advantage of the use of nuclear energy for large-scale hydrogen production is that no greenhouse gases are produced. However, high temperature creep in structures at the thermal interface between the nuclear plant and the hydrogen plant, and the migration of tritium from the reactor core through structures in the interface present unique challenges that must be addressed at the high-temperature interfaces.

To address this issue, Argonne National Laboratory (ANL) has proposed a unique low-temperature heat-pump concept [1] in which near-waste heat from the power conversion unit (PCU) is extracted at a point downstream of the turbine generator, for use as a heat pump heat source. The heat-pump concept raises the temperature of the waste heat from the PCU to a temperature sufficient for the evaporation of the water feeding the electrolysis process. The utilization of waste heat at a temperature close to that needed by the process has the potential to improve the overall process efficiencies. In addition, the lower temperatures at the power conversion/process loop interface (~220°C) compared to current interface temperatures near the reactor outlet (~900°C) could mitigate potential tritium migration issues as well as creep of high temperature structures at the primary system interface. These improvements could result in improved plant safety and lower overall plant capital costs.

To evaluate the proposed low-temperature heat-pump concept, INL performed detailed system analyses of three different interface configurations for a nuclear-driven high-temperature electrolysis (HTE) hydrogen production plant. The first configuration, referred to as the reference design, used a direct Brayton power conversion cycle to produce the electricity to drive the HTE hydrogen production process and extracted heat from the high temperature side of the cycle (upstream of the gas turbine) to supply process heat for the hydrogen production process. The second configuration used an indirect Brayton cycle with an intermediate heat exchanger between the reactor primary system and the power conversion system to create an additional separation or barrier between the reactor power source and the hydrogen production plant. This configuration also extracted heat from the high temperature side of the power cycle (upstream of the gas turbine) to supply process heat directly to the hydrogen production process. The third configuration analyzed was the heat-pump concept described above which utilized an indirect Brayton power conversion cycle with heat extracted from the cold side of the power cycle (down stream of the gas turbine) and a steam/water heat-pump loop to transfer heat from the low-temperature power conversion unit (PCU) heat source to the high-temperature water source feeding the electrolysis process. All three concepts assumed a 600 MW_t helium-cooled VHTR operating at a primary system pressure of 7.0 MPa and a reactor outlet temperature of 900°C. The HTE hydrogen production loop for each of the three concepts operated at 5 MPa, with the plant configuration and electrolysis module operating conditions optimized to maximize plant performance (i.e., 800°C electrolysis operating temperature, electrolysis cell area specific resistance (ASR) = 0.4 ohm-cm^2, and a current density of 0.25 amps/cm^2. Detailed descriptions of the modeling of each of these concepts, and comparisons of the results of the system models are presented in subsequent sections of this paper.

NOMENCLATURE

ASR	Area Specific Resistance, ohm-cm^2
HTE	High Temperature Electrolysis
IHX	Intermediate Heat Exchanger
PCU	Power Conversion Unit
SOEC	Solid Oxide Electrolysis Cell
VHTR	Very High Temperature Reactor

REFERENCE DIRECT BRAYTON CYCLE MODEL

UniSim process-analysis software, a derivative of the HYSYS software, was used in the analysis of the INL reference design for the nuclear-driven HTE hydrogen production plant.

The overall process flow diagram for the very high temperature helium-cooled reactor coupled to the direct helium Brayton power cycle and the HTE plant with air sweep is presented in Figure 1. The UniSim power-cycle model was initially described in [2]. The reactor power source shown at the bottom left of Figure 1 supplies 600 MW_t of energy to the electrolysis process. The primary helium coolant exits the reactor at 900°C. This helium flow is split at T1, with more than 85% of the flow directed toward the power cycle and the remainder directed to the intermediate heat exchanger to provide process heat to the HTE loop. Within the power-cycle loop, helium flows through the power turbine where the gas is expanded to produce electric power. The helium, at a reduced pressure and temperature, then passes through a recuperator and precooler where it is further cooled before entering the low-pressure compressor. To improve compression efficiencies, the helium is again cooled in an intercooler heat exchanger before entering the high-pressure compressor. The helium exits the high-pressure compressor at a pressure that is slightly higher than the reactor operating pressure of 7 MPa. The coolant then circulates back through the recuperator where the recovered heat raises its temperature to the reactor inlet temperature of 540°C, completing the cycle.

Process heat for the HTE hydrogen production plant is provided by splitting the reactor coolant outlet flow into two streams, and allowing a fraction (typically less than 15%) of the flow to pass through an intermediate heat exchanger where heat is extracted for use in the hydrogen production process. The cooler helium leaving the intermediate heat exchanger (stream 1 in Figure 1) is then returned through a circulator to the reactor inlet pressure and mixed with the primary coolant returning to the reactor.

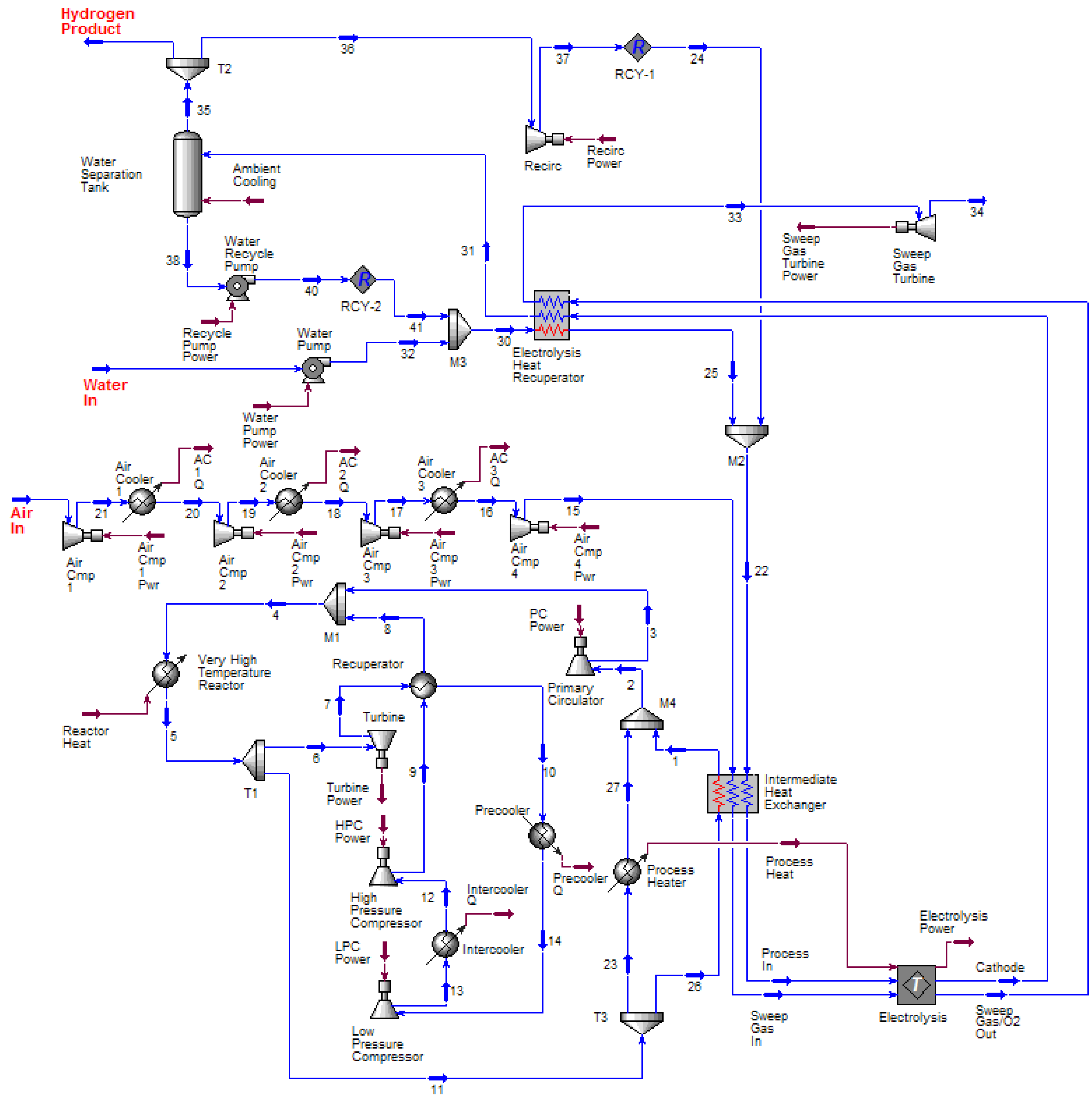

Figure 1. Process flow diagram for helium-cooled reactor/direct Brayton/HTE system with air sweep.

In the hydrogen production process loop, liquid water feedstock enters at the left in the diagram (Water In). The water is then compressed to the HTE process pressure of 5.0 MPa in the liquid phase using a pump. Downstream of the pump, condensate from the water knockout tank is recycled back into the inlet stream at M3. The water stream is then vaporized and pre-heated in the electrolysis recuperator, which recovers heat from the post-electrolyzer process and sweep-gas outlet streams. Downstream of the recuperator, at M2, the steam is mixed with recycled hydrogen product gas. A fraction of the product gas is recycled in this way in order to assure that reducing conditions are maintained on the steam/hydrogen electrodes of the electrolysis cells. Downstream of the mixer, the process gas mixture enters the intermediate heat exchanger (IHX), where final heating to the electrolysis operating temperature occurs, using high-temperature process heat from the nuclear reactor. The process stream then enters the electrolyzer, where oxygen is electrolytically split from the steam, producing hydrogen and oxygen. An additional process heater is used to directly add heat during the electrolysis process to maintain isothermal electrolyzer operating conditions.

Downstream of the electrolyzer, the hydrogen – rich product stream flows through the electrolysis recuperator where the product stream is cooled while preheating the inlet process stream. The product stream is cooled further at the water knockout tank, where the majority of any residual steam is condensed and separated, yielding dry hydrogen product. The cooled product stream is split at T2 and a fraction of the product gas is recycled into the inlet process stream, as discussed previously. A recirculating blower is required to

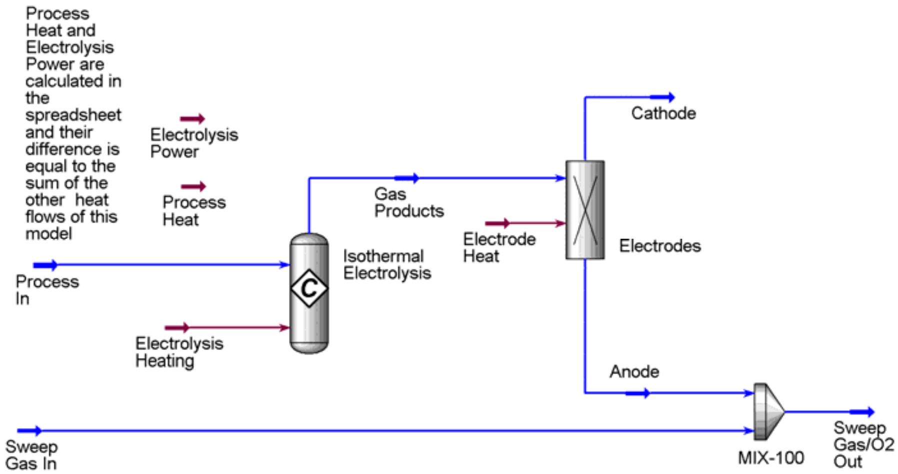

Figure 2. Process flow diagram of electrolyzer model.

repressurize the recycle stream to the upstream pressure at M2.

The process flow diagram shows air in use as a sweep gas to remove the excess oxygen that is evolved on the anode side of the electrolyzer. In the air sweep system, inlet air is compressed to the system operating pressure of 5.0 MPa in a four-stage compressor with intercooling. The final compression stage is not followed by a cooler, so the air enters the IHX at about 171°C. The sweep gas is heated to the electrolyzer operating temperature of 800°C via the IHX which supplies high-temperature nuclear process heat directly to the system. The sweep gas then enters the electrolyzer, where it mixes with product oxygen. Finally, it passes through the electrolysis recuperator to help preheat and vaporize the inlet water. Some of the sweep gas compression work is recovered using the sweep-gas turbine located at the sweep-gas exit.

The custom electrolyzer module developed at INL for direct incorporation into the UniSim system analysis code has been described in detail previously [3]. The electrolyzer model process flow diagram is shown in Figure 2. The electrolyzer inlet process flow consisting of steam and hydrogen (90% and 10% by volume) passes through a conversion reactor where the steam is split into hydrogen and oxygen. The conversion reactor model uses a stoichiometric equation for the splitting of water. Based upon the specified current density and corresponding steam utilization, a known percentage of the steam is converted. UniSim calculates the heat of reaction for this conversion, which is shown as the "Electrolysis Heating" energy stream in Figure 2. The hydrogen, oxygen, and steam enter a component splitter labeled "Electrodes". The product oxygen exits at "Anode" stream. The sweep gas mixes with the anode stream and exits as the "Sweep/Gas O_2 Out" stream. An embedded spreadsheet is used to calculate the Nernst potential, operating voltage, current and electrolysis power. In this reference case, since an isothermal boundary condition is specified, the net heat required to maintain isothermal operation is also calculated. This net heat will be positive if the operating voltage is below the thermal neutral voltage and negative if the operating voltage is above thermal neutral.

For the integrated INL Reference Design configuration shown in Figure 1, which incorporated the electrolysis model shown in Figure 2, the calculated total number of electrolysis cells required was 4,000,900 assuming a cell area of 225 cm^2, a cell current density of 0.25 amperes/cm^2, and a per cell area specific resistance (ASR) of 0.4 ohm-cm^2. The UniSim calculated power cycle efficiency in this case was 53.2% and the calculated overall hydrogen production efficiency was 47.1%.

INDIRECT BRAYTON CYCLE MODEL

The indirect Brayton cycle configuration was modeled using the reference configuration described in the previous section, but replacing the reactor in the power conversion cycle with a primary heat exchanger and adding a separate primary loop and compressor to circulate helium coolant from the reactor to the primary heat exchanger, where the thermal output of the reactor and the heat of compression from the primary circulator are transferred to the indirect Brayton cycle power conversion system. The resultant model is shown in Figure 3.

Helium coolant at approximately 7 MPa and 540°C enters the VHTR, shown at the left in Figure 3. The reactor, operating at 600 MW_t, transfers its heat to the coolant that exits the reactor at 900°C. The coolant then passes through the hot side of the primary heat exchanger where it is cooled and transfers its heat to the indirect Brayton cycle. The coolant is then compressed in the primary circulator and returned to the reactor inlet to complete the primary circuit.

On the secondary side of the primary heat exchanger, the coolant exits at a temperature of about 850°C, is split at T1, with more than 85% of the flow going to the indirect power cycle and the remainder (≤15%) going to the intermediate heat exchanger (IHX) to provide high temperature (850°C) process heat for the HTE loop. The cooler helium leaving the IHX (stream 3 in Figure 3) is then mixed with the bulk of the helium from the power cycle and returned to the cold side inlet of the primary heat exchanger at a temperature and

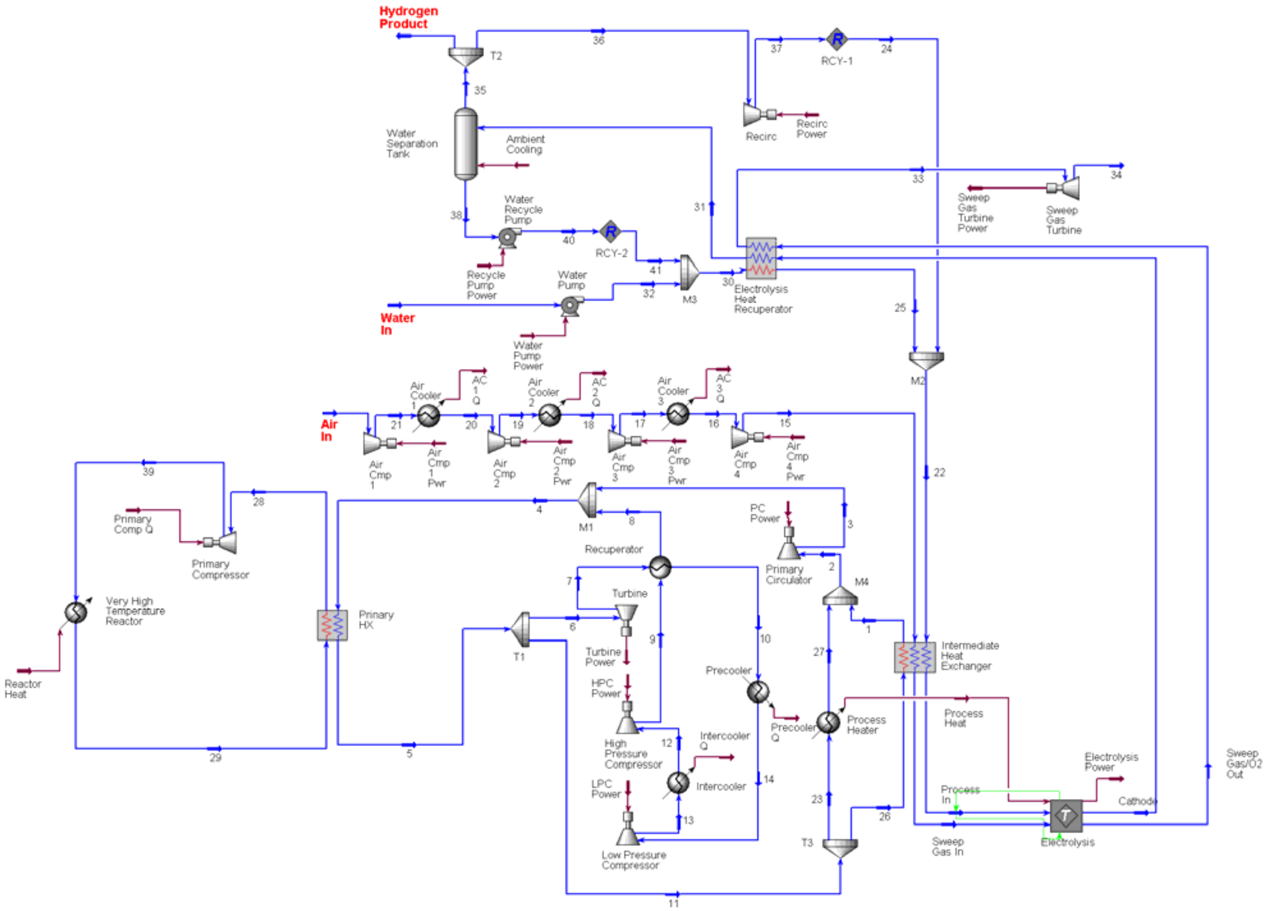

Figure 3. Indirect Brayton cycle model modified from INL reference design.

pressure of 490°C and 7.07 MPa, respectively. The bulk of the helium from T1 (stream 6) passes through the power turbine that supplies electricity for the HTE process. The flow exits from the power turbine at a reduced pressure and temperature, and then passes through a recuperator and precooler where it is further cooled before entering the low-pressure compressor. As described previously, the helium is again cooled in an intercooler before entering the high-pressure compressor. The helium exits the high-pressure compressor and then circulates back through the recuperator where the recovered heat raises its temperature to the primary heat exchanger inlet temperature of 490°C, completing the cycle.

The HTE process loop in Figure 3 is identical to that shown in Figure 1. Therefore, the differences in performance between the two configurations can be attributed to the differences in performance between the direct and indirect Brayton cycles. Because of the temperature drop across the intermediate heat exchanger (~50°C) the indirect Brayton cycle operates at a lower temperature, resulting in a lower power conversion system efficiency and lower overall hydrogen production efficiency than for the direct Brayton cycle reference design. The UniSim model of the INL Reference Design modified to produce an indirect Brayton cycle configuration (Figure 3) resulted in a power cycle efficiency of 48.1% and an overall hydrogen production efficiency of 44.7%. The calculated total number of electrolysis cells required in this case is 3,801,000 assuming a cell area of 225 cm^2, a cell current density of 0.25 amperes/cm^2, and a per cell area specific resistance (ASR) of 0.4 ohm-cm^2. As expected, calculated efficiencies are lower than those previously calculated for the direct Brayton cycle (i.e., 53.2% power cycle efficiency and 47.1% hydrogen production efficiency) because of the added primary loop pumping requirements and the lower process temperatures resulting from the temperature drop across the primary heat exchanger.

LOW-TEMPERATURE INTERFACE (HEAT PUMP) MODEL DESCRIPTION

The UniSim model for the low-temperature heat-pump concept was developed to match the configuration and operating conditions of the preceding direct and indirect Brayton cyle concepts so that this concept could be evaluated and its performance compared with the performance of the preceding two designs. The low-temperature heat-pump concept again utilized a 600 MW$_t$ VHTR as the power source, but in this case, heat from the reactor was transferred through

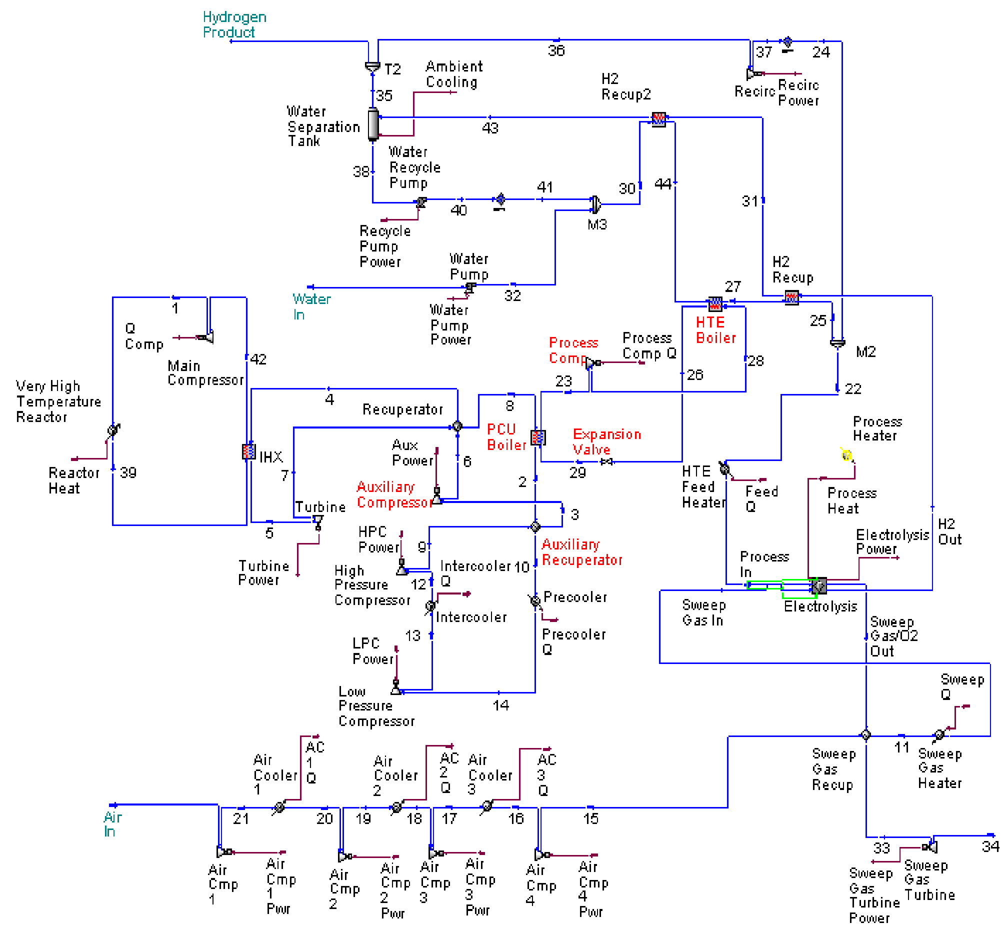

Figure 4. UniSim model of low-temperature heat-pump concept.

an intermediate heat exchanger to a modified indirect Brayton cycle power conversion loop. The UniSim model of this concept, coupled to the hydrogen production loop is shown in Figure 4.

Helium coolant at a pressure of 7.0 MPa and a temperature of 900°C exits the VHTR at the left in Figure 4 (stream 39), and passes through the IHX where its heat is transferred to the indirect power conversion system. The primary coolant exits the IHX (stream 42) and is compressed back to the reactor inlet pressure, completing the primary loop circuit.

The power conversion cycle for the low-temperature heat-pump concept is a modified indirect Brayton power cycle that includes a gas turbine, a recuperator, a precooler to cool the coolant before it enters the low-pressure compressor, and an intercooler to further cool the coolant before entering the high-pressure compressor. However, the model shown in Figure 4 differs from the indirect Brayton cycle shown in Figure 3, in that a low-temperature process loop has been added between the recuperator and the precooler to extract heat from the low-temperature side of the cycle. The intent of this low-temperature process loop is to recover heat from the PCU at a point in the cycle where most of the work potential has already been extracted. To do this requires the addition of three new components to the power conversion system. These new components, indicated in red in Figure 4, are the "PCU Boiler", the "Auxiliary Recuperator", and the "Auxiliary Compressor". The placement and size of the three new components are such that the operating conditions of the other components in the PCU are essentially the same as those in Figure 3 without the low-temperature process loop present. Since the temperature needed for the hot side of the PCU boiler is above the helium inlet temperature to the precooler in the reference plant design, the auxiliary recuperator was added to provide a step up in the temperature. To maintain a constant temperature drop from hot to cold side of the recuperators for maximum efficiency, the auxiliary compressor was introduced. It is intended to provide a rise in temperature that approximately matches the temperature drop across the auxiliary recuperator. To maintain approximately the same flow rate in the PCU, the work done by the high pressure compressor and low pressure compressor is reduced by the amount of work done by the auxiliary compressor. Again, target temperatures and powers in the PCU were deduced by considering heat transfer and work in the new components while at the same time keeping temperatures for the remaining components in the system approximately the same as in the reference design.

The process heat loop on the cold side of the PCU Boiler is a water/steam loop that acts as a vapor-compression heat pump transferring heat from a cold source to a hot sink. The components that make up the process-loop heat pump are also indicated in red in Figure 4. Steam exits the cold side of the PCU boiler at a temperature slightly above saturation (179°C and 0.58 MPa) to ensure that liquid is not present at the inlet to the compressor (Process Comp). The compressor boosts the temperature and pressure of the vapor to approximately 580°C and 7.0 MPa. The circulating flow then passes through the hot side of the HTE Boiler where heat transferred from the superheated steam is used to convert the HTE feed water to steam. The subcooled liquid exiting the hot side of the HTE boiler (stream 26) then passes through a Joule-Thomson expansion valve where the pressure and temperature are reduced to approximately 159°C and 0.59 MPa, respectively (stream 29), resulting in a low quality saturated fluid entering the PCU Boiler to complete the circuit.

The UniSim model of the HTE process loop in Figure 4 was developed to match as closely as possible the reference plant hydrogen production loop operating conditions in Figure 1, but was modified to accommodate the low-temperature (heat-pump) process loop interface design so that the relative performance of the hydrogen production loop in the low-temperature heat-pump and reference plant designs could be compared.

In the UniSim model for the low-temperature heat-pump HTE process shown in Figure 4, the inlet liquid water feedstock at 15.6°C is pressurized to the process pressure of 5.0 MPa. Downstream of the pump, condensate from the water knockout tank is recycled back into the inlet stream at M3. The water stream is then heated (H2 Recup2) using recovered heat from the hydrogen/steam produced in the electrolysis unit to the desired inlet temperature of the HTE Boiler (184°C). The water feedstock is vaporized in the HTE Boiler producing superheated steam at 303.1°C (stream 27). The steam is further heated in another recuperative heat exchanger (H2 Recup) and then mixed with recycled hydrogen product gas at M2. Again, the hydrogen recycle is required to maintain reducing conditions on the steam-hydrogen electrodes in the electrolyzer. The inlet steam-hydrogen (90-10% by volume) mixture is then heated by means of an electrical resistance heater (HTE Feed Heater) to the electrolysis operating temperature of 800°C. The electrical heater is required in this case since no direct high temperature process heat is available.

The steam-hydrogen mixture then enters the solid oxide electrolysis cell (SOEC) stack, where oxygen is electrolytically split from the steam, producing hydrogen and oxygen. The calculated total number of electrolysis cells required in this case is 3,391,000 assuming a cell area of 225 cm^2, a cell current density of 0.25 amperes/cm^2, and a per cell area specific resistance (ASR) of 0.4 ohm-cm^2. Since the electrolyzer is operating slightly below the thermal-neutral voltage, an additional electrical heater (Process Heater) is used to add 30.2 MW of heat directly to the electrolysis process to maintain the electrolyzer operating temperature at 800°C.

Downstream of the electrolyzer, the hydrogen–rich product stream flows through the two recuperative heat exchangers where the product stream is cooled and the inlet process stream is preheated as described earlier. The product stream is cooled further at the water separation tank, where the residual steam is condensed, yielding dry hydrogen product. The cooled product stream is split at T2 and a fraction of the product hydrogen is recycled into the inlet process stream, as discussed previously. A recirculating blower is required to repressurize the recycle stream to the upstream pressure at M2.

As assumed in the previous models, the low-temperature heat-pump design shown in Figure 4 also utilized air as the sweep gas to remove the oxygen that is evolved on the anode side of the electrolyzer. The inlet sweep air is compressed to the system operating pressure of 5.0 MPa in a four-stage compressor with intercooling. After exiting from the final compression stage, the air enters a recuperative heat exchanger where its temperature is raised to 780°C. The air then passes through an electrical heater (Sweep Gas Heater) where its temperature is raised to the electrolyzer operating temperature of 800°C. The sweep air then enters the electrolyzer and exits mixed with the oxygen product gas. Finally, it again passes through the sweep gas recuperator described earlier. Some of the sweep air compression work is then recovered by expanding it in a sweep-air turbine.

The UniSim model of the low-temperature heat-pump concept (Figure 4) predicted a power cycle efficiency of 46.4% and an overall hydrogen production efficiency of 39.9%. The reasons for these lower calculated efficiencies for the low-temperature heat-pump concept, compared with the other two concepts are discussed in the following section.

COMPARISON OF ANALYSIS RESULTS

Table 1 summarizes the results of the UniSim calculated temperatures and performance characteristics for the three configurations analyzed. The UniSim calculated results for the low-temperature heat-pump concept shown in column 2 indicate that the interface temperatures are significantly lower than those calculated for the indirect Brayton cycle and the reference direct Brayton cycle designs (columns 3 and 4, respectively). Therefore, the low-temperature heat-pump design concept could reduce the potential for tritium migration and high temperature creep of structures that would otherwise exist at the high-temperature system interface.

The calculated heat duties at the HTE process heat exchanger for the different concepts are shown in the third row of Table 1. The calculated process heat duty for the heat-pump concept in column 2 is considerably lower than those calculated for the indirect and direct cycles shown in columns 3 and 4. This lower process heat value for the heat-pump concept is a result of the fact that electrical heaters are used in this concept to provide the high-temperature heat required to

Table 1. Comparison of temperature and performance of different HTE designs.

	Low-Temperature Heat-Pump Concept	Indirect Brayton Cycle Concept	Reference Direct Brayton Cycle Concept
Maximum Hot Side Temperature at PCU/Process Loop Interface, °C	220	850	900
Process Heat Exchanger Duty at HTE Interface, MW_t	47.5	105.8[a]	82.0[b]
Power Conversion System Efficiency, %	46.4	48.1	53.2
Hydrogen Production Efficiency, %	39.9	44.7	47.1
Hydrogen Production Rate, kg/s	1.99	2.23	2.36

[a] Includes IHX heat duty (74.7 MW) and Electrolysis Process Heater duty (31.1 MW)
[b] Includes IHX heat duty (49.0 MW) and Electrolysis Process Heater duty (33.0 MW)

boost the temperature of the steam feeding the electrolyzer to the final desired electrolysis temperature of 800°C.

The calculated power conversion cycle thermal efficiencies for each of the three concepts are shown in row 4 of Table 1. In each case, an assumed 96% AC-to-DC conversion efficiency was used to calculate the electric power required for the electrolysis stack. The results show that the heat-pump concept has the lowest power cycle efficiency because of the additional pumping requirements associated with the heat pump loop and the modified Brayton power conversion cycle. The indirect Brayton cycle power conversion system efficiency (row 4, column 3 of Table 1) is higher than that of the heat-pump concept because of the lower associated pumping requirements for this concept. However, the direct Brayton cycle reference design (row 4, column 4 of Table 1) has the highest power conversion system efficiency (53.2%) because of the higher turbine inlet temperature that can be achieved which the direct cycle (without the intermediate heat exchanger and associated temperature drop between the reactor primary system and the power conversion loop).

The UniSim calculated overall hydrogen production efficiencies and hydrogen production rates shown in rows 5 and 6, respectively indicate that the reference direct Brayton cycle design had the highest overall hydrogen production efficiency (47.1%) and hydrogen production rate (2.36 kg/s). The indirect Brayton cycle concept has a slightly lower overall hydrogen production efficiency and rate (44.7% and 2.23 kg/s, respectively), and the heat-pump concept had the lowest overall hydrogen production efficiency and rate (39.9% and 1.99 kg/s, respectively). However, despite its lower hydrogen production efficiency, the latter design was an effective heat-pump concept, transferring 31.5 MW_t from the low-temperature leg of the gas turbine power cycle to the HTE process boiler, while generating 16.0 MW_e of compressor power, which is also added to the system as process heat (heat of compression). The resulting total process heat transferred to the hydrogen production loop of 47.5 MW_t (row 3, column 2 of Table 1), however is still lower than the total process heat transferred by the two high temperature process heat concepts. Therefore, the heat-pump concept must provide the additional heat using less efficient electrical heaters, resulting in a lower overall hydrogen production efficiency for this concept.

CONCLUSIONS

The results presented in this paper indicate that the use of a low-temperature heat-pump concept could be an effective method of transferring heat between the power conversion loop and hydrogen production plant in a nuclear-driven HTE hydrogen production plant using a VHTR as the power source. However, the increased electrical power required by the low-temperature heat-pump concept, compared to the electrical power requirements of the direct and indirect power cycle concepts using high temperature process heat, results in overall lower hydrogen production rates and efficiencies. Therefore, the ultimate decision on the viability of the low-temperature heat-pump concept involves a tradeoff between the benefits of lower structural temperatures at the process interface, and the reduced hydrogen production efficiency of the low-temperature heat-pump concept compared to the high-temperature process heat concepts.

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of this manuscript, or allow others to do so, for United States Government purposes.

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