THERMAL INTEGRATION OF SCWR NUCLEAR AND THERMOCHEMICAL HYDROGEN PLANTS

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Abstract

In this paper, the intermediate heat exchange between a Generation IV supercritical water-cooled nuclear reactor (SCWR) and a thermochemical hydrogen production cycle is discussed. It is found that the maximum and range of temperatures of a thermochemical cycle are the dominant parameters that affect the design of its coupling with SCWR. The copper-chlorine (Cu-Cl) thermochemical cycle is a promising cycle that can link with SCWRs. The location of extracting heat from a SCWR to a thermochemical cycle is investigated in this paper. Steam bypass lines downstream of the SCWR core are suggested for supplying heat to the Cu-Cl hydrogen production cycle. The stream extraction location is strongly dependent on the temperature requirements of the chemical steps of the thermochemical cycle. The available quantity of heat exchange at different hours of a day is also studied. It is found that the available heat at most hours of power demand in a day can support an industrial scale steam methane reforming plant if the SCWR power station is operating at full design capacity.

Keywords: Supercritical water-cooled reactors, Heat exchange, Thermochemical hydrogen production

1. Introduction

The supercritical water reactor (SCWR) is a Generation IV nuclear reactor with a higher thermal efficiency and considerably simplified system configuration, compared with conventional light water reactor (LWR). The working fluid of the SCWR is light water that operates at a supercritical state above the water critical point with a temperature and pressure higher than 375^{o}C and 22.1MPa [1-4], respectively. Since the SCWR uses light water, it can be regarded as a special type of LWR operating at higher pressures and temperatures with a direct, once-through cycle. Therefore, existing relatively mature LWR technology can be adopted since there is already extensive worldwide knowledge of LWRs for engineers to design, construct and operate SCWRs.

To operate on a direct cycle indicates the SCWR is also much like a special type of Boiling Water Reactors (BWR). In addition, steams and liquids can be considered indistinguishable and have the same density at the supercritical state, indicating only one phase present like the Pressurized Water Reactor (PWR). Therefore, it is anticipated that SCWRs would have a combination of advantages of BWRs and PWRs [5, 6].

Since the coolant in SCWRs has a high temperature that does not experience phase change in the reactor and can be directly coupled with energy conversion equipment, this gives SCWRs a higher thermal efficiency and considerable plant simplification. For example, the thermal efficiency of an SCWR could reach 45%, while in comparison, 30-35% are typical values for current LWRs [7-9].

The enhanced power generation efficiency of SCWRs does not imply that SCWRs can reduce the challenges of load balancing. The required load in the power grid changes with the power demand of end users. A typical example is the significant gap between peak and off-peak hour power demands [10]. The frequent adjustment of nuclear power output brings issues of safety, reliability and stability into the design, operation and maintenance of a power station. To address these challenges, hydrogen production, either by conventional electrolysis or thermochemical water splitting, can be effectively integrated with power generation to buffer the load adjustment, especially at off-peak hours. In this way, SCWRs can operate at a constant power load or at invariable maximum power, independent of the power demand changes on the grid, i.e., power load fluctuations throughout a day or year. When the power load decreases, the SCWR will produce more hydrogen. Another benefit to couple SCWRs with thermochemical water splitting, rather than steam methane reforming (SMR) to produce hydrogen, is the reduction of greenhouse gases emitted from SMR. It is also anticipated that hydrogen as a clean energy carrier will be a significant driving force for sustainable energy demand in the future [11, 12].

Since thermochemical water splitting can provide much higher thermal efficiency than conventional electrolysis, thermochemical hydrogen production is an emerging technology of growing importance. Currently, the University of Ontario Institute of Technology (UOIT) in collaboration with Atomic Energy of Canada Limited (AECL) and other university and industry partners is developing the Cu-Cl cycle for nuclear hydrogen production. The energy required by thermochemical hydrogen production cycles to split water is predominantly heat, with a lesser portion of electricity if the thermochemical cycle is hybrid [11-13]. From this aspect, therefore, heat exchange between a thermochemical hydrogen production cycle and a SCWR power plant will be studied in this paper in terms of the factors such as the heat extraction location, method, quantity, and hydrogen production scale.

2. Matching heat flows of SCWRs and thermochemical cycles

2.1 Temperature levels of SCWRs

The thermal energy used by thermochemical hydrogen production cycles is the heat extracted from the supercritical water stream exiting the SCWR core. The temperature difference between SCWR and the thermochemical cycle provides the driving force of the heat exchange. Before entering turbines, the water stream is in the form of supercritical water that has the highest temperature to provide the maximum heat transfer. From this perspective, the temperature of the supercritical water upstream of the turbines greatly influences the practicality of coupling SCWRs with thermochemical hydrogen production cycles.

The minimum temperature of supercritical water is determined by the critical point of water, which is 374^{o}C. To reduce the risk of the fluctuation of temperature (i.e., the fluctuation caused by flow rate variations of water circulation, nuclear heat release, and power demand change), the temperature of the supercritical water is usually much higher than 374^{o}C. The higher temperature can increase the thermal efficiency of SCWRs. However, the maximum outlet temperature of the reactor core is significantly influenced by reactor materials.

The temperature range in Japan [2] for a high-temperature large fast reactor cooled by supercritical water (SCFR-H) is 467-537^{o}C, with blankets cooled by ascending and descending flow. The SCFR-H adopts a radial heterogeneous core with zirconium-hydride layers between the driver core and the blankets for making the coolant void reactivity negative. The highest temperature range cited at the University of Tokyo [14] was 593-600 ^{o}C due to the corrosion and duration of reactor material operation. The design of an SCWR in China was planned to be at a temperature of 500^{o}C [15], using reduced activation ferritic-martensitic steels as the reactor core materials.

The Idaho National Engineering and Environmental Laboratory (INEEL) cited a temperature range of 565-620^{o}C based on the existing engineering experience in supercritical water power plants [16], such as supercritical water turbine technology. AECL is developing an SCWR with an outlet temperature in the range of 625-650 ^{o}C [17, 18]. This temperature allows it to also produce hydrogen by thermochemical water splitting. AECL is collaborating with UOIT (University of Ontario Institute of Technology, Canada) and ANL (Argonne National Laboratory, USA) to develop the technology of coupling the CANDU-SCWR with thermochemical hydrogen production.

2.2 Temperature levels of themochemical hydrogen production cycles.

Around two hundred thermochemical water splitting cycles have been reported in past literature [19, 20]. Among these cycles, the sulfur–iodine (S-I, [12, 22-25]) and coppler-chlorine (Cu-Cl) cycles are two leading examples [19-22]. There are several types of S-I cycles and three-step cycle is commonly accepted as the most typical loop [23-25]. In the three-step loop, steps 2 and 3 are endothermic and the maximum temperature requirement is 850 ^{o}C for step 2 and 450 ^{o}C for step 3.

For the Cu-Cl cycle, there are also several types with various numbers of steps from 2 to 6 depending on reaction types and conditions [20, 21, 24]. Due to a similar reason as for the S-I cycle, the following cycle with 4 steps will be considered in this paper:

Step I: Hydrogen production step (electrolysis)

$2CuCl(aq) + 2HCl(aq.) = 2CuCl_2(aq) + H_2(g)$, in aqueous solution of HCl, 80~100 ^{o}C (1)

Step II: Drying step (endothermic)

$CuCl_2(aq) + n_f H_2O(l) = CuCl_2 \bullet n_h H_2O(s) + (n_f - n_h)H_2O$

n_f>7.5, n_h = 0~4, at 30~80 °C (crystallization) or 100~260°C (spray drying) (2)

Step III: Hydrolysis step (endothermic)

$2CuCl_2 \bullet n_hH_2O(s) + H_2O(g) = CuOCuCl_2(s) + 2HCl(g) + n_hH_2O(g)$, n_h is 0~4, at 375 °C (3)

Step IV: Oxygen production step (endothermic)

$CuOCuCl_2(s) = 2CuCl(molten) + 0.5O_2\ (g)$, at 500~530 °C (4)

Each step in the cycle is sequenced using upper case Roman numbers in order to avoid confusion with the numbers of the S-I cycle.

2.3 Driving process of heat exchange

Figure 1 shows the temperature levels of SCWRs and temperature requirements of S-I and Cu-Cl cycles. It can be found that most SCWRs can cover the temperature requirements of all steps in

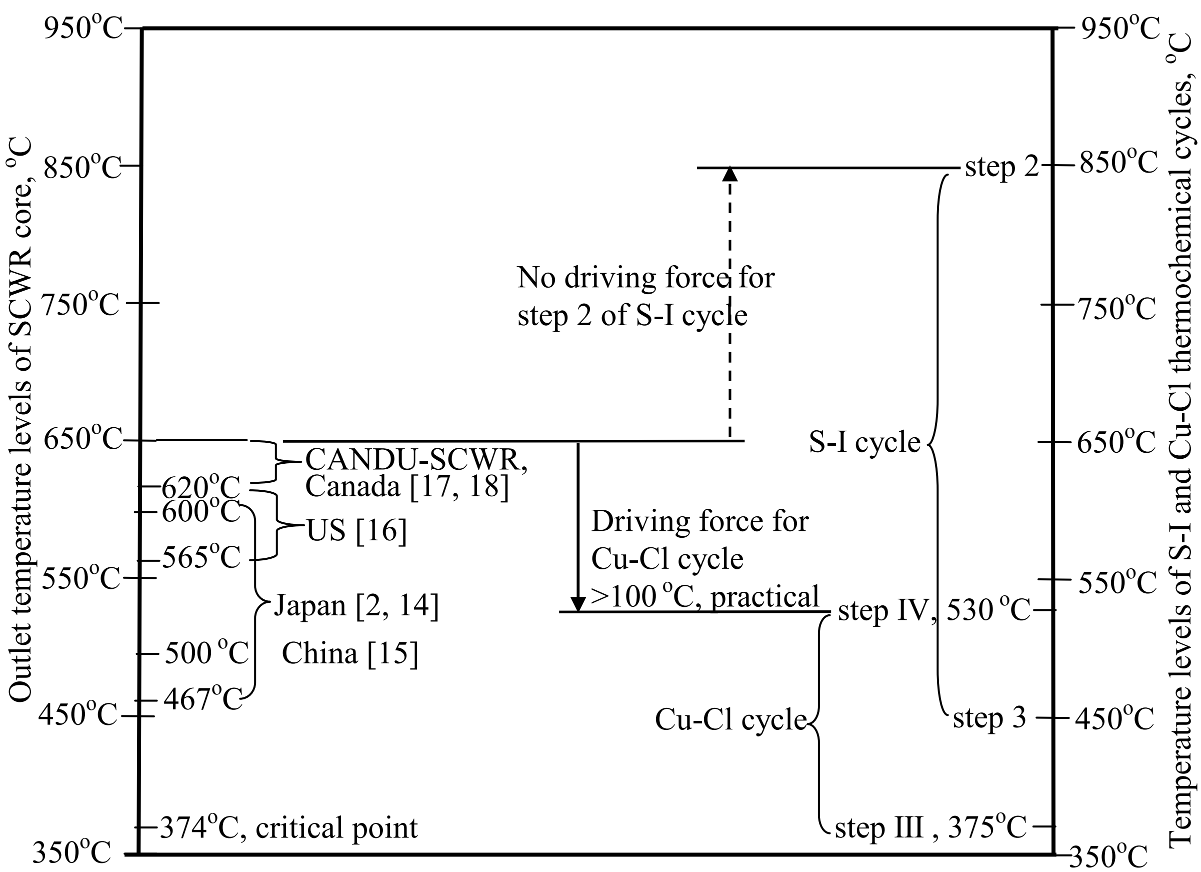

Figure 1 Temperature levels of SCWRs vs. requirements of S-I and Cu-Cl cycles

the Cu-Cl cycle. The driving process for the heat exchange provided by CANDU-SCWR of Canada is larger than 100°C.

For the S-I cycle, step 2 requires 850 °C, which cannot be reached with current technology of SCWRs. Although the temperature of SCWRs can cover step 3, the heat quantity at 450° required by step 3 occupies less than 10% of the total heat required by the S-I cycle. In comparison, the heat quantity required at 850° by step 2 accounts about 90% of the total heat requirement, which will be discussed in the following sections of the paper.

3. Heat extraction from SCWR to Cu-Cl cycle

3.1 Direct and indirect heat supply for the Cu-Cl cycle

In theory, the water stream of the SCWR coolant loop, either in form of supercritical or gaseous state, can be directly extracted as the reactant and heating fluid for the Cu-Cl cycle. However, this extraction method is not suggested due to the consideration of water contamination and safety issues. The chemical reaction pressure is lower than 2.4 MPa in the Cu-Cl cycle [21, 24]. In comparison, water stream exiting the SCWR core is usually higher than 25 MPa if it is supercritical water. This means the water pressure leaving the SCWR must be significantly decreased to the lower pressure of the Cu-Cl cycle. In addition, if the supercritical water stream is open to chemicals of the Cu-Cl cycle, it may lead to chemical contamination. Therefore, indirect heat exchange is suggested, whereby the water stream in the SCWR coolant loop serves as the heat carrier rather than as the reactant source of Cu-Cl cycle. The term “water stream” in this paper refers to the water stream of the SCWR coolant loop.

3.2 Location of heat extraction and flowchart of water stream flows

The temperature levels of SCWR and the Cu-Cl cycle also have significant influence on the location of the heat extraction from an SCWR, and the Cu-Cl cycle in turn will influence the water flow arrangement of the SCWR.

Figure 2 shows the arrangement of the SCWR coolant stream with hydrogen co-generation of the Cu-Cl thermochemicl cycle. The flowchart is based on existing fossil fuel power plants that use a supercritical water turbine after changing the fossil fuel combustion chamber and supercritical water tank to SCWR. The values of temperatures and pressures were calculated according to the water stream enthalpy change and expansion ratio that were reported previously [3, 26].

The water stream circulation illustrated in Figure 2 has the typical features of a single-reheat system that uses a preheater and two types of turbines, i.e., high pressure (HP) turbine and low pressure (LP) turbine. From the temperatures shown in Figure 2, it can be found that point A, i.e., the location downstream of the nuclear reactor but upstream of the turbines, can provide around 100 °C heat exchange of a driving temperature difference for step IV of the Cu-Cl cycle that requires 530 °C. At this location, a bypass line of the supercritical water stream passing points A and J of Figure 2 can be designed for the heat extraction from supercritical water to the Cu-Cl hydrogen production cycle.

An extra bypass line on the HP turbine chamber can be opened for heat extraction, i.e., similar to the extraction line passing point B for heat regeneration in the preheater, but this arrangement is not recommended since the water stream temperature will be lowered to decrease the heat exchange, and challenges arise with the resulting design of turbine chambers. In addition, more openings on the chamber increase the risks of turbine operation.

For step III of the Cu-Cl cycle, the temperature requirement is 375 ^{o}C. The heat for this step can be supplied either directly from another supercritical bypass line passing points A and K, or from the stream at 530^{o}C passing point H after leaving step IV. The latter is preferable since this arrangement can reduce the number of bypass lines of supercritical water and use heat more efficiently. The same consideration is for step IV, an extra bypass line on the HP turbine chamber, passing points B and N, which is not recommended for step III.

The water stream exiting the Cu-Cl cycle still has a temperature higher than 375^{o}C, but the pressure has strong dependence on the dimensions and structures of heat exchangers inside the Cu-Cl cycle. Figures 3 and 4 illustrate two typical types of heat exchangers that are chemical reactors for step IV of the Cu-Cl cycle. The configuration of the heat exchangers for step III could be similar to the types for step IV. The water stream exiting the Cu-Cl cycle can be directed to a steam turbine, heat regenerator, or the nuclear reactor core, depending on the pressure. Detailed studies of the pressure drops of the supercritical water passing through the chemical reactors will be performed in future research.

The water stream can also be arranged to pass through HP and LP turbines in parallel, as shown in Figure 5. In this type of layout, the water stream directly flows back to the SCWR core after leaving the HP turbine, rather than entering the LP turbine. Therefore, there are two water streams at 625-650^{o}C leaving the core of the SCWR. This provides multiple choices for the heat extraction bypass lines and the water stream circulation layout.

The line passing points A_{HPT} and J is the supercritical water line at a high pressure of 25 MPa. The line connecting A_{LPT} and J is the superheated steam line with a low pressure of 5 MPa. Although both lines can be used for the heat supply of the Cu-Cl cycle, it is better to use one line only, as this can simplify the design and operation of the water stream.

The layout of the water stream leaving the Cu-Cl cycle after heat exchange has strong dependence on the pressure that varies with dimensions and structures of heat exchangers inside the Cu-Cl cycle, which is similar to the arrangement discussed for the layout of Figure 2.

In Figures 2 and 5, there could be a number of preheaters, or the water stream circulation could be designed as a multiple reheat cycle, or no reheat. The details of these layouts will not be discussed in this paper since a single heat cycle layout, including its steam turbines and generator, is most widely employed.

3.3 Hydrogen production scale and available quantity for heat exchange

The hydrogen production scale is significantly influenced by the heat quantity required by the

Cu-Cl cycle, and the heat quantity that can be extracted from the SCWR. Table 1 lists the hydrogen production scale at different times of a day. The calculation is based on the design capacity of 1000 MWe. The ratio of the generated power to its design capacity is assumed to be equal to the ratio of power demand to power supply capacity on the power grid. The ratio is based on data from the provincial Ontario government, Canada [10]. The available heat for hydrogen generation is the difference between the design capacity of the SCWR and the power actually generated in real-time. The SCWR operates at its maximum capacity with cogeneration

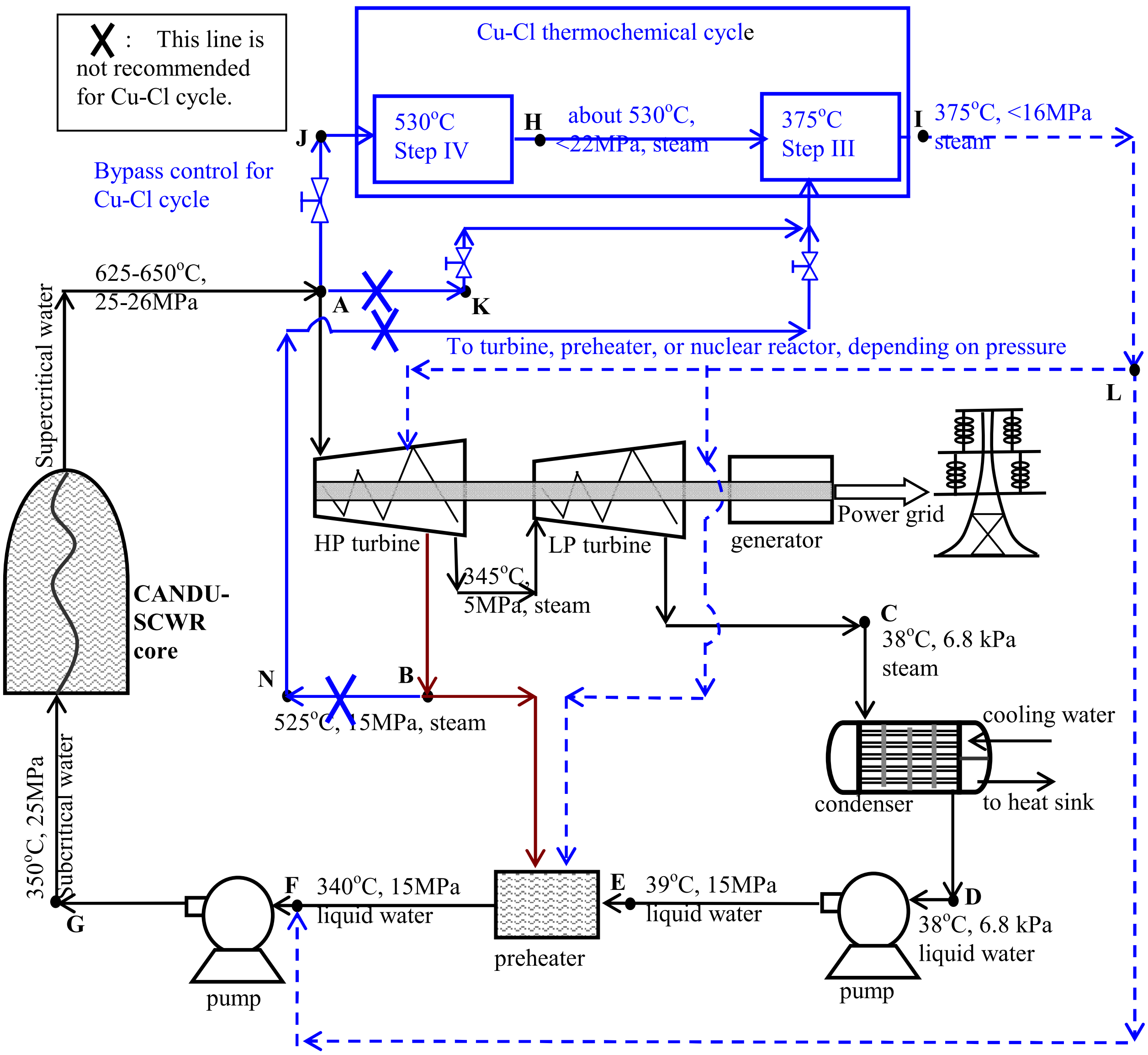

Figure 2 Flowchart of SCWR coolant stream for heat exchange with Cu-Cl cycle (coolant passing through high pressure and low pressure turbines in series)

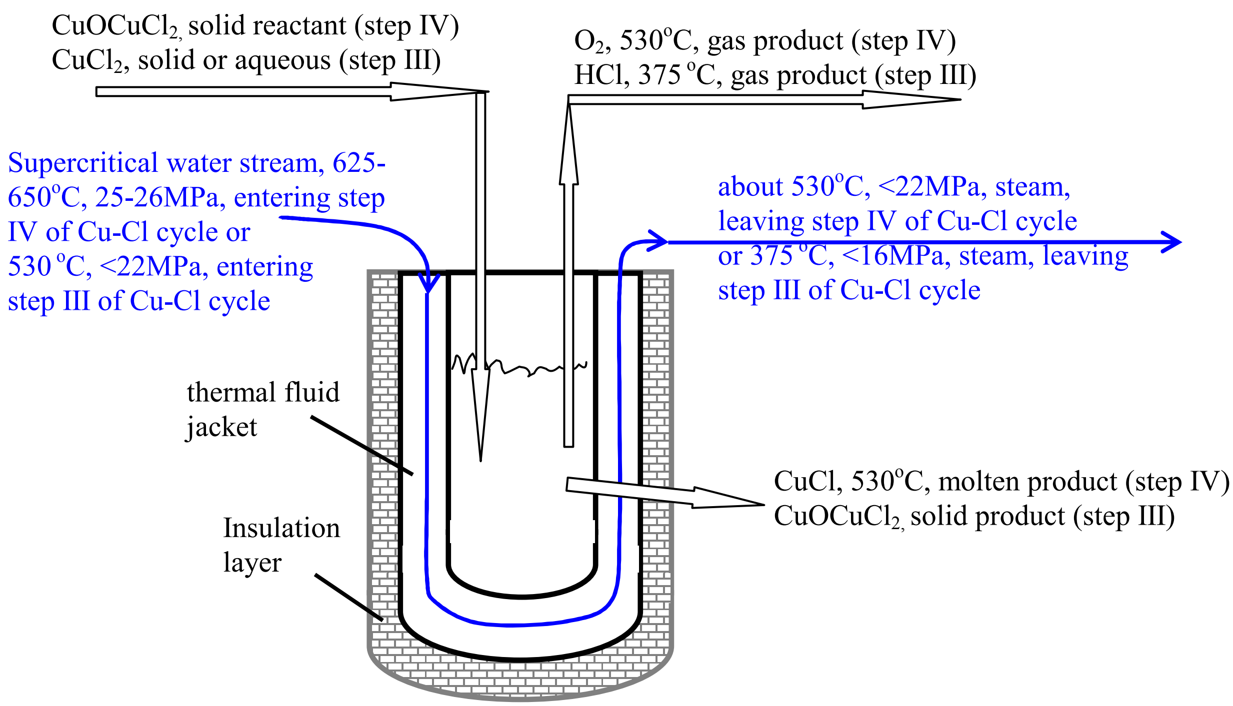

Figure 3 Supercritical water flowing through heating jacket of endothermic chemical reactor of Cu-Cl cycle

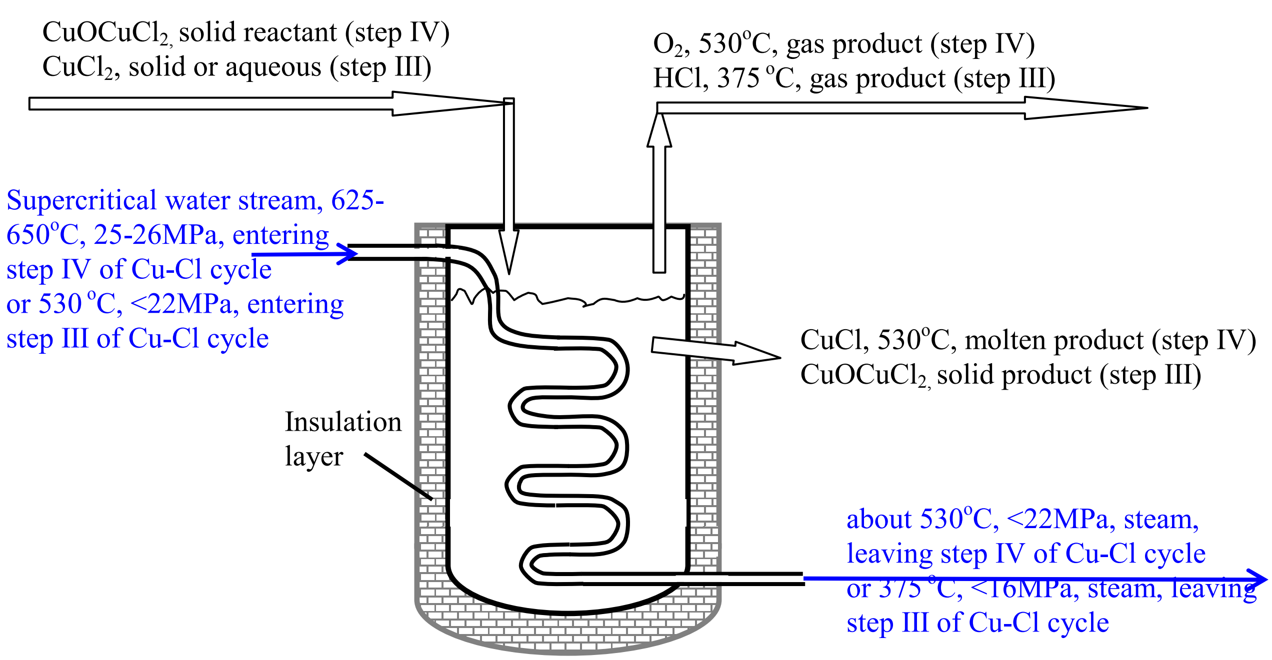

Figure 4 Supercritical water flowing through serpentine heating pipe of endothermic chemical reactor of Cu-Cl cycle

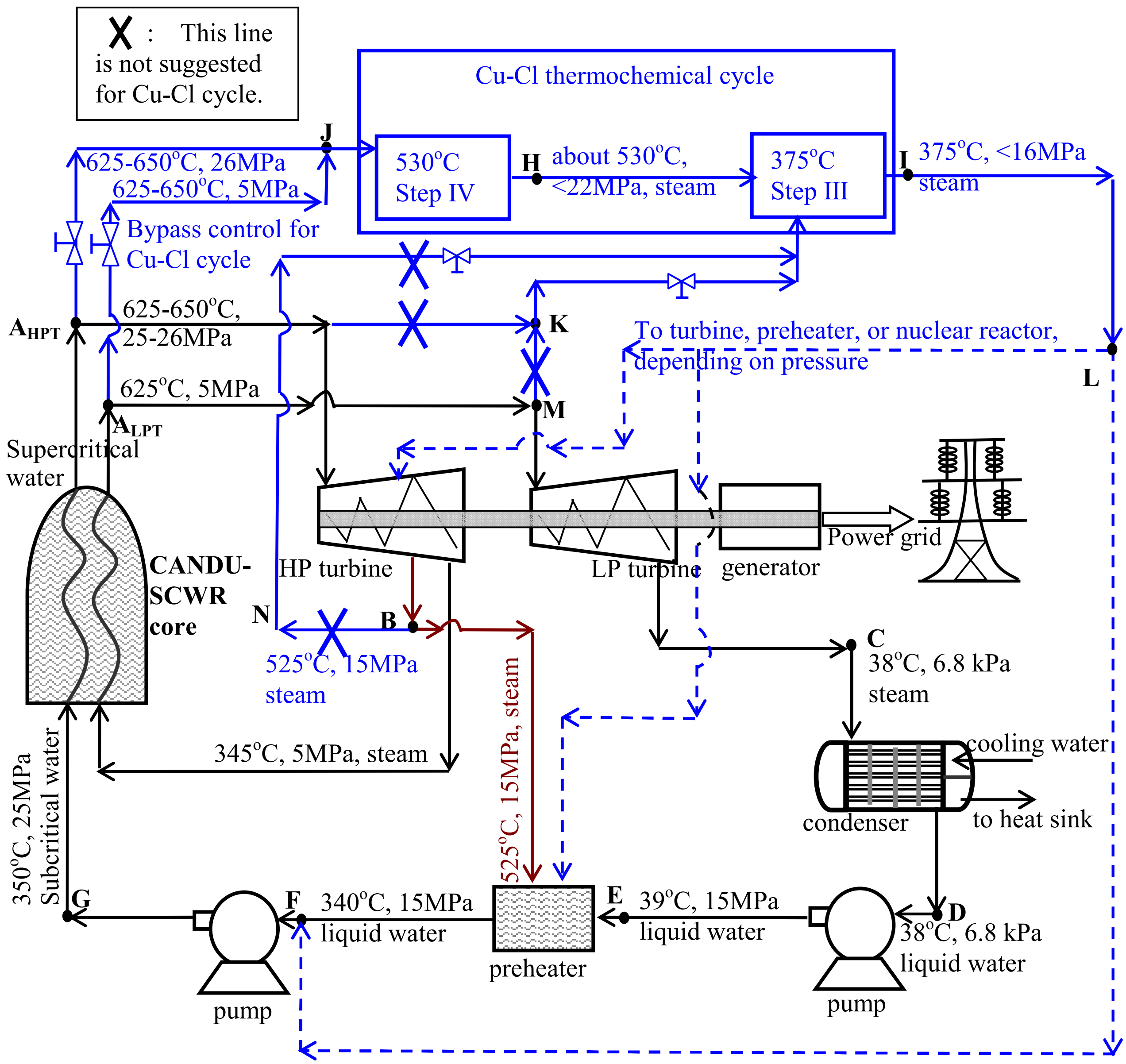

Figure 5 Flowchart of SCWR coolant stream for heat exchange with Cu-Cl cycle (coolant passing through high pressure and low pressure turbines in series)

of hydrogen. The heat transferred to the Cu-Cl cycle from SCWR is assumed to have a loss of 40%, and only 50% of the heat released by exothermic reactions of the Cu-Cl cycle is reused inside the cycle. Table 1 shows that a single SCWR can produce 70-160 tons of hydrogen each day, depending on the peak and off-peak power demand hours of the grid. This hydrogen production scale is equivalent to that of an industrial plant of steam methane reforming [27].

4. Conclusions

This paper examines the heat exchange between Generation IV supercritical water-cooled nuclear reactors (SCWRs) and thermochemical hydrogen production cycles. It is found that the maximum temperature requirement of a thermochemical cycle determines the available driving process for the heat exchange. The Cu-Cl thermochemical cycle can obtain a maximum driving process due to its lower temperature requirement than other cycles. The location of extracting heat from SCWR to the thermochemical cycle is discussed and its influence on the water stream layout is investigated. It is suggested that extra water stream bypass lines immediately downstream of the SCWR core should be prepared for extracting heat to the thermochemical hydrogen production cycle. The available heat quantity for heat exchange at peak and off-peak power demand hours is also discussed, and its influence on the hydrogen production scale is approximated. It is concluded that regardless of peak and off-peak hours, the hydrogen cogeneration design of an SCWR can reach the hydrogen production scale of an industrial steam methane reforming plant.

Table 1 H_2 production scale and available quantity for heat exchange at various hours

Time	**Energy used for power generation**			**Available heat for hydrogen production**		**Heat loss when entering Cu-Cl cycle**	**H_2 production scale**
hour	**% of peak hour** (*)	**% of full design capacity of power generation** (*)	**Power generated** **MW_e** (**)	**Unused power capacity** **MW_e**	**Unused heat quantity (45% thermal efficiency)** **MW_t**	**%**	**324MJ/kgH_2** **Tons/day** (***)
1-5am	66%	53%	530	472	1049	40%	168
5-6am	70%	56%	560	440	978	40%	156
6-7am	77%	62%	620	384	853	40%	137
7-8m	83%	66%	660	336	747	40%	119
8-9am	87%	70%	700	304	676	40%	108
9am-16pm (high demand)	92%	74%	740	264	587	40%	94
16-17pm	94%	75%	750	248	551	40%	88
17-18pm	97%	78%	780	224	498	40%	80
18-20pm (peak demand)	100%	80%	800	200	444	40%	71
20-21pm	97%	78%	780	224	498	40%	80
20-21pm	92%	74%	740	264	587	40%	94
21-22pm	82%	66%	660	344	764	40%	122
22-23pm	75%	60%	600	400	889	40%	142
23pm-1 am	68%	54%	540	456	1013	40%	162

* This percentage was calculated from the statistic power consumption of Ontario, Canada [10].

** The designed full power capacity for a single SCWR is assumed as 1,000 MW_e.

*** 162MJ/kgH_2 is the net heat input required by the Cu-Cl cycle, assuming that 50% of the heat released by exothermic reactions is reused inside the Cu-Cl cycle [24, 28].

5. Acknowledgements

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6. References

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