HYDROGEN PRODUCTION USING PROCESS HEAT FROM AN SCW NPP VIA A DOUBLE-PIPE HEAT EXCHANGER

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Abstract

The SuperCritical Water-cooled nuclear Reactor (SCWR) is one of six Generation-IV nuclear-reactor concepts currently under development worldwide. It is designed to operate at pressures of 25 MPa and temperatures up to 625°C. These operating conditions make an SCW Nuclear Power Plant (NPP) suitable to support thermochemical-based hydrogen co-generation. The Copper-Chlorine (Cu-Cl) cycle is a prospective thermochemical cycle with a maximum temperature requirement of ~530°C. Preliminary thermalhydraulic calculations are presented for a double-pipe counter-flow heat exchanger located downstream of an SCWR with no-steam-reheat cycle and with SCW coolant flowing through the inner pipe and steam flowing to the Cu-Cl cycle facility through the annulus.

1. Introduction

Global dependence on fossil-fuel energy sources is increasing as demand expands, not only in developed countries, but in developing countries where evolving economies are driving industrialization, integration of improved transportation networks and better living standards. Ongoing volatility in fossil-fuel prices has placed pressure on businesses to optimize operating processes while leading scientists to search for alternative energy resources that can replace or offset the need for the fossil-based energy. Hydrogen has been identified as an energy carrier, which could supply a portion of the world's future energy requirements.

At this time, the use of hydrogen as an energy carrier is mainly embraced in the petroleum, chemical and food industries. Predictions made by the United States' Department of Energy (DOE) estimate annual hydrogen demand for fuel-cell powered automobiles will be 65 Mt by the year 2040 [1]. If such predictions are fulfilled and extend to other countries developing hydrogen programs then it will be necessary to produce the fuel through economic and environmentally-sound methods. Due to the low cost and available production methods, carbon-based hydrogen production via Steam Methane Reforming (SMR) or gasification is the most feasible process currently available. Furthermore, hydrogen is commonly produced and consumed at the same location, and only in the necessary quantities. Using non-carbon-based energy sources such as nuclear or solar power to support thermochemical cycles would facilitate the development of centralized, large-scale hydrogen-production facilities.

In order for a SuperCritical Water-cooled Reactor (SCWR) to support thermochemical hydrogen production through the Cu-Cl cycle, a system to transfer thermal energy between the facilities is required. The use of an inter-facility Heat eXchanger (HX) is required to deliver the necessary thermal energy to the dependent reaction steps in the Cu-Cl cycle. This paper provides an overview of the energy requirements of the Cu-Cl cycle and presents preliminary thermalhydraulic calculations identifying design parameters for a potential HX design to be used as part of a no-reheat SuperCritical Water (SCW) Nuclear Power Plant (NPP).

2. Alternative hydrogen production - thermochemical cycles

Thermochemical cycles represent a form of hydrogen production involving a decomposition of water into its constituent substances using two main inputs: thermal energy and water. Cycles are characterized by reaction steps involving the feed substances and various intermediate compounds attributed to each cycle. Over 200 potential cycles have been identified in literature with no additional processes found in a survey conducted between 2000 and 2005 [2]. A large portion of all cycles identified face limitations due to high temperature requirements, low efficiencies or complex material/construction demands rendering the cycles unfeasible for development beyond theoretical calculations. One of the few cycles having advanced to demonstrative pilot facility status is the Sulphur Iodine (SI) cycle. Operating at temperatures of approximately 870°C, the SI cycle is being investigated by several organizations with the potential to integrate a hydrogen production facility with a High-Temperature gas-cooled Reactor (HTR) [3][4]. As part of the DOE's Nuclear Hydrogen Initiative, 7 cycles in addition to the SI cycle were evaluated against several criteria including efficiency, chemical viability, engineering feasibility and DOE timeline requirements. Of the cycles investigated, the Copper Chlorine (Cu-Cl) cycle was selected for further development based on, among other factors, low temperature requirements, successful laboratory tests, international support and favourable economic targets [5].

2.1 Variations of copper-chlorine cycle

The Cu-Cl cycle has been selected as a prime cycle to be linked with an SCWR for the production of hydrogen [6]. Several strengths of the cycle include a relatively low maximum temperature requirement (~530°C), favourable reaction kinetics for oxygen and hydrogen production steps and opportunity for internal heat recycling [7]. Research into the Cu-Cl cycle was conducted in the 1970's with identification of several forms of the cycle including a 2-step process proposed by Dokiya and Kotera [8]. The typical forms of the Cu-Cl cycle found in recent literature are the 5-step, 4-step hybrid and 3-step cycles [5], [8], [9], [10]. The proposed combinations are based on the 5-step cycle with ranging temperature and energy requirements. The 5-step cycle is comprised of an exothermic hydrogen-production step, three endothermic processes and an electrolysis step. Naterer et al. conducted thermodynamic analysis of the 5-step process determining thermal energy requirements of 277.4 kJ/g of H_2 produced assuming no internal heat recycled and 31.3 kJ/g of H_2 of electrical energy [9]. One advantage of the process is that excess reaction heat may be used internally in the cycle to lower the net external-energy requirements. A major disadvantage associated with the 5-step process is the production and handling of solid copper, which requires additional thermal-energy requirements.

One variation of the 5-step cycle is the 4-step hybrid cycle with reactions outlined in Table 1. This variation combines the hydrogen production and electrolysis (Steps 1a and 1b (Table 1)) processes to a new electrolysis reaction occurring at temperatures of approximately 100°C producing hydrogen and copper chloride electrolytically. This step is analogous to that proposed by Dokiya and Kotera [8]. The grouping of these two reactions avoids the production of intermediate copper simplifying the process configuration. Recent changes have shifted focus away from the 5-step production cycle towards the 4-step hybrid cycle. Teams at several organizations including the University of Ontario Institute of Technology (UOIT), Atomic Energy of Canada Limited (AECL) and Argonne National Laboratory (ANL) are participating in research on the hybrid process. Current work involves scaling up proof of principle experimental set-ups to larger assemblies capable of producing 3 kg of hydrogen per day [10].

Table 1. Reaction steps in the hybrid 4-step Cu-Cl cycle [7], [11], [12].

Step	Reaction		Temp. Range (°C)	Feed/Output	
1	$2CuCl\ (aq) + 2HCl\ (aq) \rightarrow H_2\ (g) + 2CuCl_2\ (aq)$	Electrolysis (Hydrogen Production)	~100	Feed	Aqueous CuCl and HCl + V + Q Electrolytic Cu + dry HCl + Q
				Output	$H_2 + CuCl_2\ (aq)$
2	$CuCl_2\ (aq) \rightarrow CuCl_2\ (s)$	Drying	<100	Feed	Slurry containing HCl and $CuCl_2$ + Q
				Output	Granular $CuCl_2$ + H_2O/HCl vapours
3	$2CuCl_2\ (s) + H_2O\ (g) \rightarrow CuO{*}CuCl_2\ (s) + 2HCl\ (g)$	Hydrolysis	375-400	Feed	Powder/granular $CuCl_2$ +$H_2O(g)$ + Q
				Output	Powder/granular $CuO{*}CuCl_2$ + 2HCl (g)
4	$CuO{*}CuCl_2\ (s) \rightarrow 2CuCl\ (l) + 1/2O_2\ (g)$	Oxygen Production	450-550	Feed	Powder/granular $CuO{*}CuCl_2$ (s) + Q
				Output	Molten CuCl salt + oxygen
Q, thermal energy; V, electrical energy 5-Step Cycle Reaction 1: a) $2Cu\ (s) + 2HCl\ (g) \rightarrow 2CuCl\ (l) + H_2\ (g)$ at 450°C b) $2CuCl\ (aq) = Cu\ (s) + CuCl_2\ (aq)$ in HCl solution at 30-80°C					

The new form of the Cu-Cl cycle has two reaction steps, which require high temperature heating, the hydrolysis (Step 3) and oxygen production (Step 4) reactions. These locations within the cycle must be connected to an external heating source supplying temperatures in excess of 530°C to supply the maximum temperature requirements of the oxygen production step. Measures to reduce external heat supply have been explored by Wang et al. in the form of a proposed modified Cu-Cl cycle demanding lower excess steam for the hydrolysis reaction [10]. An excess of steam is required to progress the hydrolysis reaction to completion such that a high yield of product can be obtained and formation of impurities such as CuCl and Cl_2 can be minimized [11]. Increases in the steam to $CuCl_2$ ratio in the hydrolysis reaction does not reduce the heat required for reaction significantly [10]. The shift in focus toward a 4 step Cu-Cl process has eliminated a large source of exothermic heat from the cycle normally generated in the thermochemical hydrogen production step shown in Table 1. As a result, the net heat input required by the cycle is 247 kJ/g of hydrogen with 46 kJ/g available for recycling [13]. It is assumed that up to 50% of the heat generated within the cycle is recoverable [14]. Therefore, the net external thermal energy, Q, requirement of the new Cu-Cl cycle is 224 kJ/g of hydrogen produced. A commercial scale hydrogen production rate of 1 kg/s is assumed for this analysis.

3. SCWR layout – no-reheat cycle

Currently in the conceptual design phase, the Generation IV nuclear-reactor-design concept SCWR has two main objectives: 1) Raise the thermal efficiency of current NPPs from 30-35% to ranges of 45-50%; 2) Decrease capital, operational and unit-energy costs. Integrating an SCW NPP into a process heating application through an interface with a hydrogen production facility based on the Cu-Cl cycle enables hydrogen production during off-peak electrical demand hours. A fraction of high temperature SCW coolant may be diverted to a HX, where it exchanges heat with an intermediate fluid (e.g., steam or helium) and is then returned to a location on the feedwater heating line or reactor inlet. Studies have shown that to meet the heat demand of the 5-step Cu-Cl cycle 12% of the total SCWR thermal energy would need to be diverted [15]. For a 1200 MW_{el} SCW NPP with an HX inlet of 625°C and outlet of 350°C this would correspond to a flowrate of approximately 143 kg/s. Changes in demanded flowrate are dependent on the variation of Cu-Cl cycle used (i.e., 5-step/4-step), the amount of internal heat recycled in the Cu-Cl cycle and the heat losses associated with transport of the intermediate fluid from the SCW NPP to the hydrogen production facility.

For a no-reheat NPP layout with the total flowrate of approximately 1200 kg/s, the single candidate location under consideration which provides a source of high temperature SCW is the reactor outlet, as shown in Figure 1. This HX would be located inside the containment structure to provide a barrier to radioactivity release to the external environment. A double-pipe HX at this location would operate with SCW flowing through the inner pipe and SuperHeated Steam (SHS) in the annulus, as shown in Figure 2. Alternate locations have been proposed in previous studies and suggest a possible link downstream of the High Pressure (HP) turbine with SCWR coolant loop conditions at 9.2 MPa and 460°C [16], [17]. Since this temperature is below the maximum Cu-Cl cycle temperature of 530°C it is not be suitable as a sole source of theraml energy for the hydrogen-production facility. Therefore, this location was not assessed further. For a single-reheat NPP layout, there are two candidate locations under consideration [17]. The first is identical to the no-reheat NPP layout found immediately downstream of the reactor and the second is downstream of the reheat channels. Analysis of HX integration with alternative NPP layouts will also be considered in future investigations. Assessments on the economic impact of adding such an HX into containment are not considered in this analysis, but will be required in the future to measure the increased capital costs associated with its inclusion.

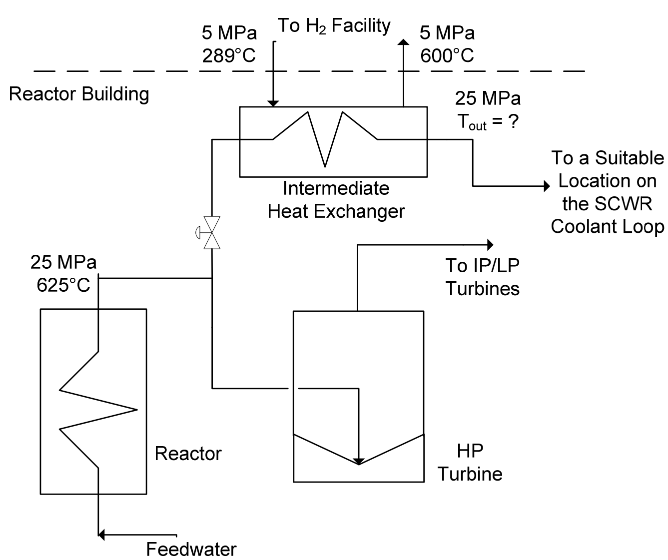

Figure 1. Potential HX location for a no-reheat SCWR NPP layout.

4. Heat-exchanger thermalhydraulic analysis

For the proposed HX, a Log Mean Temperature Difference (LMTD) method was initially selected to determine the HX's average overall Heat Transfer Coefficient (HTC), *U*, heat transfer area, *A*, and associated individual pipe length, *L*. Similar analysis has been found in literature for an intermediate HX used to transfer heat from a primary SCW loop to a secondary SCW loop as part of an indirect, single-reheat SCW NPP [18]. To supply an adequate steam temperature to the hydrogen production facility a counter-flow design was selected to allow for the SHS outlet temperature to exceed the HX SCW outlet temperature. Thus, a parallel flow design would not be feasible. Single-phase conditions were assumed for both flows, while pressure losses were neglected. Additionally, the HX was assumed to be insulated from its surroundings with energy transfer only between the two fluids. Following initial analysis using the LMTD method it was identified that in the case of flows experiencing large thermophysical property variations an iterative solution is required on individual Control Volumes (CVs) across the length of the HX. This is due to the temperature profile across the HX not following a logarithmic form. Different test scenarios were developed for combinations of flow conditions and HX tube dimensions and a potential design is presented in the sections below.

Table 2 lists fixed parameters that were assumed for the HX analysis. The pressure and temperature of the SCW flowing into the HX corresponds to conditions at the SCWR outlet header. The desired outlet temperature of the SCW flow from the HX was selected to be 350°C, which is suitable to be redirected back into the inlet stream for the SCWR. As discussed in the sections below, this condition could not be met for the analysis conducted. In the annulus gap, the SHS flow enters the HX at a pressure of 5.0 MPa and a temperature of 15°C above the saturation temperature at the corresponding pressure. The SHS exits the HX at a temperature of approximately 600°C, sufficient for transport to a hydrogen production facility a some distance away. The piping between the two facilities would be subject to varying heat losses when exposed to different environmental conditions and would require assessment to ensure that the minimum temperature requirements of the Cu-Cl cycle would still be met through the SHS flow.

Table 2. Bounding operating parameters for the counter-flow double-pipe HX.

Operating Parameter	Inner Pipe (SCW)	Annulus Gap (SHS)
Pressure, *P*, MPa	25	5.0
Inlet Temperature, T_{in}, °C	625	289
Outlet Temperature, $T_{out,}$ °C	350*	600

*Desired Outlet Condition

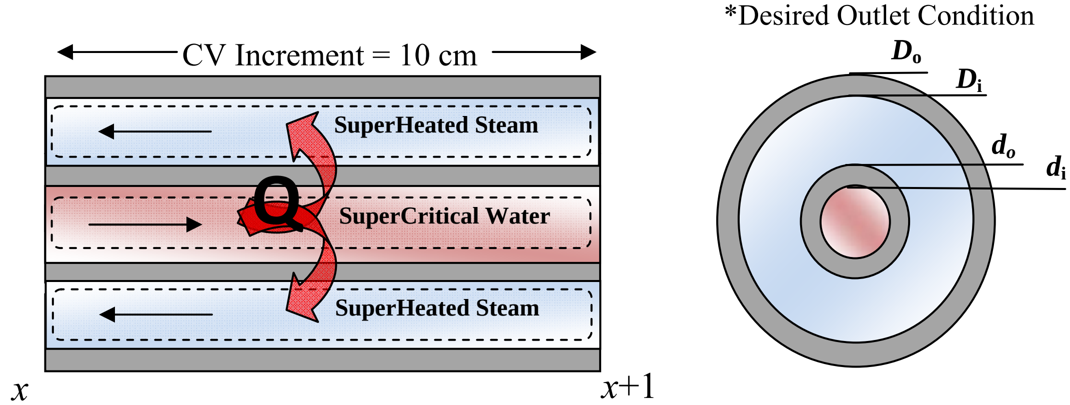

Figure 2. Inner and outer pipes arrangement for a double-pipe HX (not to scale).

For construction of the HX, SS-304 was selected as a choice pipe material for both the inner and outer pipes given its widespread application in the industry. Standard ANSI pipe sizes for outer diameter were used with modified thicknesses to accommodate fluid flow characteristics, namely limiting the SHS flow through the annulus. Additionally, pipe dimensions were selected similar in size to those identified by Ornatskiy et al. [19] for use in supercritical-steam generators. Equation (1), documented by Speigel and Limbrunner, was used to calculate the burst pressure, p, for selected dimensions of piping for both the inner and outer pipes [20].

$$p = \frac{2S \cdot \delta}{d_o} \qquad (1)$$

To be considered acceptable, the calculated burst pressure of the pipe was required to be at least 25% greater than the operating pressure of the pipe, as used in previous studies related to HXs with SCW as a working fluid [18]. This corresponded to a minimum burst pressure of 31.25 MPa. The process of obtaining reasonable flowrates and HTCs in the analyzed piping produced burst pressures which considerably exceeded the minimum safety margin. Values are listed in Table 3.

The heat-transfer correlation selected for this analysis was the Mokry et al. correlation [21], shown as Equation (2), developed from an experimental dataset for heated upward flow of supercritical water in vertical bare tubes. It is dependent on both bulk-fluid and wall properties. When compared to experimental data it has shown good agreement with uncertainty of ±25% for HTC values and ±15% for calculated wall temperature [21]. Although the correlation was developed for water at supercritical conditions it has also been applied to the SHS flow in the outer pipe. This selection was based on conclusions of researchers at the University of Ottawa, which identified the Mokry et al. (earlier called "Gospodinov et al.") correlation as showing the best agreement with available experimental data for the SHS and SCW regions [22]. The layout and orientation of the HX has yet to be determined, and so the Mokry et al. correlation was applied to a generic HX design without accounting for flow direction, and other heat-transfer effects, such as heating and cooling flows. No entrance effects were accounted for in the analysis.

$$\mathbf{Nu}_b = 0.0061\mathbf{Re}_b^{0.904}\overline{\mathbf{Pr}}_b^{0.684}\left(\frac{\rho_w}{\rho_b}\right)^{0.564} \qquad (2)$$

Pressure (P): 22.8-29.4 MPa Heat Flux (q''): 70-1250 MW/m^2
Mass Flux (G): 200-1500 kg/m^{2}s Diameter (D): 0.003-0.038 m

The overall HTC, U, was defined in terms of the inner-pipe wall in contact with the SHS, according to Equation (3). Individual HTCs on both sides of the inner-pipe wall were calculated for successive CVs of 10 cm length as shown in Figure 2. Iterations used to calculate HX parameters could begin at either end of the HX, but were selected to start at the SCW inlet stream/SHS outlet stream. Thermophysical properties were evaluated at the same position within the HX, i.e., position x. Thus, for a counter-flow design, properties of SCW were evaluated at the entry to a CV, while SHS properties were evaluated at the exit of a CV. Iterations were used to calculate the wall temperature, T_w, shown in Equation (4), for each consecutive control volume. Knowing T_w, the thermal conductivity, k, of the SS-304 was calculated from available literature and the HTCs were subsequently calculated. It was assumed that the wall temperature was constant across the pipe wall given that the wall thermal-resistance contribution was negligible compared to the SCW and SHS thermal resistances.

$$\frac{1}{U} = \frac{d_o}{d_i \cdot h_i} + \frac{d_o \cdot ln(d_o/d_i)}{2k} + \frac{1}{h_o} \quad (3)$$

$$T_{w,x} = \frac{\left(\frac{T_{i,x}}{R_{i,x}}\right)+\left(\frac{T_{o,x}}{R_{o,x}}\right)}{\left(\frac{1}{R_{i,x}}\right)+\left(\frac{1}{R_{o,x}}\right)} \quad (4)$$

Once the overall HTC was found for a CV, the outlet temperature of SCW, $T_{\mathrm{SCW,out,x}}$, and inlet temperature of SHS, $T_{\mathrm{SHS,in,x}}$, for the CV were calculated using iterations based on an energy balance across the CV. This numerical approach closely followed the process outlined by Ribando et al. [23] which presented the energy balance equations shown in Equations (5) and (6). This process was repeated until the inlet temperature of SHS reached the lower boundary condition of the saturation temperature at the given pressure. Based on the amount of thermal energy transferred via one pipe, the total number of pipes required to transfer 224 MW was calculated.

$$\text{Inner Pipe: } \dot{m}_{\mathrm{SCW}} c_{\mathrm{p,SCW},x}\left(T_{\mathrm{SCW,in},x} - T_{\mathrm{SCW,out},x}\right) - U_x A_{inc}\left[\frac{T_{\mathrm{SCW,in},x}+T_{\mathrm{SCW,out},x}}{2} - \frac{T_{\mathrm{SHS,in},x}+T_{\mathrm{SHS,out},x}}{2}\right] = 0 \quad (5)$$

$$\text{Annulus Gap: } \dot{m}_{\mathrm{SHS}} c_{\mathrm{p,SHS},x}\left(T_{\mathrm{SHS,in},x} - T_{\mathrm{SHS,out},x}\right) - U_x A_{inc}\left[\frac{T_{\mathrm{SHS,in},x}+T_{\mathrm{SHS,out},x}}{2} - \frac{T_{\mathrm{SCW,in},x}+T_{\mathrm{SCW,out},x}}{2}\right] = 0 \quad (6)$$

Various combinations of SCW and SHS mass fluxes were tested along with variations of pipe dimensions in an effort to produce suitable HX parameters, namely desired working fluid inlet/outlet temperatures, HX pipe length and reasonable total number of pipes for the HX. The SCW mass flux and annulus SHS flow rates were treated as the main variables. Design parameters from a given set of test conditions are listed in Table 3.

Table 3. HX design characteristics for a set of test conditions.

Overall HX A Parameters		**SCW - Inner Pipe Flow**		**SHS – Annulus Gap Flow**	
Heat Transferred per Pipe, kW	70	Total Mass Flow Rate, kg/s	224	Total Mass Flow Rate, kg/s	287
No. of HX Pipes, *N*	3205	Inlet Pressure, MPa	25.0	Inlet Pressure, MPa	5.0
Average Overall HTC, W/m^{2}K	426.2	Inlet/Outlet Temperature, °C	625/399	Inlet/Outlet Temperature, °C	289/600
Heat Transfer Surface Area per Pipe, *A*, m^2	4.1	Inner Diameter, d_i, mm	18.9	Inner Diameter, D_i, mm	30.1
Length per Pipe, *L*, m	49.3	Outer Diameter, d_o, mm	26.7	Outer Diameter, D_o, mm	33.4
		Burst Pressure, MPa	124	Burst Pressure, MPa	42
		Pipe Mass Flux, kg/m^{2}s	250	Annulus Mass Flux, kg/m^{2}s	593
		Maximum Flow Speed, m/s	4	Maximum Flow Speed, m/s	47

It is possible to use the results shown in Table 3 as a basis for further HX-design development, however, certain challenges arise. Due to SCW flow entering the PseudoCritical (PC) region as it approaches the exit of the HX there is a large difference between the specific heat capacity of the SCW and the SHS. At a given PC temperature and pressure, the maximum specific heats are observed [24]. This is supported by Figure 3, which shows a significant temperature change of the SHS at the inlet of the HX compared to the small relative change in the SCW flow. At 25 MPa, the PC temperature is approximately 384.9°C. As the SCW reaches the HX outlet it approaches 399°C for this test combination. The temperature gradient of the SHS increases as the SCW progresses further into the PC region, and the calculated allowable entry temperature of the SHS is reached sooner. As a result, it is not feasible to design the HX with the SCW exiting the unit at 350°C as the required temperature difference of the SHS would be incredible. It is then necessary to determine a suitable relocation point on the SCW NPP coolant loop where the flow can be returned. Approximately 19% of the total SCW leaving the reactor would be diverted to such a HX under the presented test conditions. Integrating the fluid back into the cycle would permit more useful energy to be extracted from the flow.

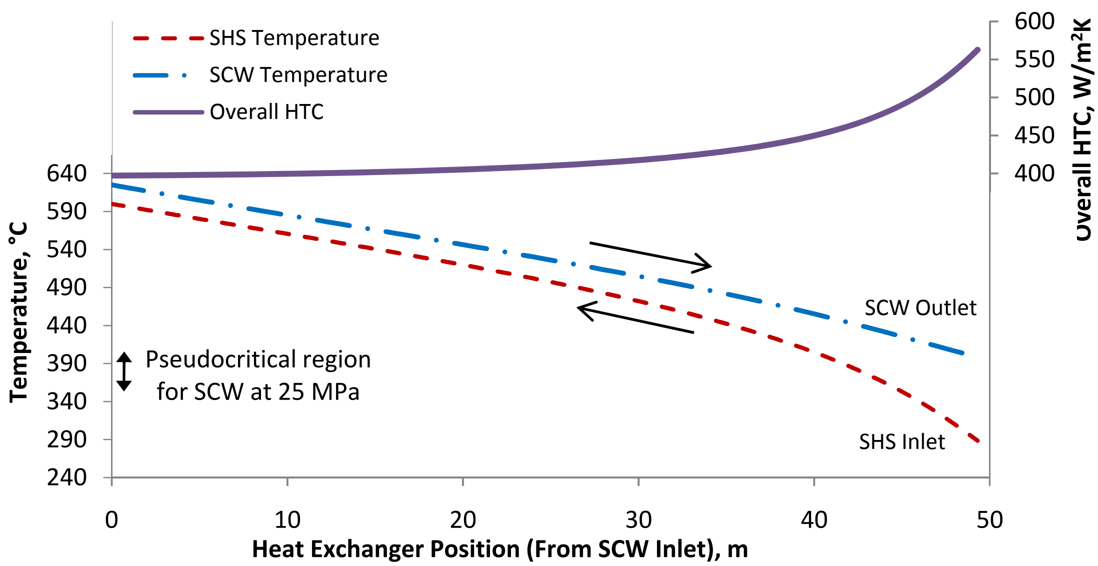

Figure 3. Temperature profiles obtained using the heat balance method.

Reducing the mass flux in the inner pipe increased the number of pipes required for the HX. This, in turn, influenced the mass flux of SHS required in the annulus to produce feasible HX dimensions. While maintaining a high mass flux of SHS in the annulus increases the HTC it also creates high flow velocities, which contribute significantly to pressure losses. Without pressure losses accounted for, the SHS flow velocities were found to vary from 26 to 47 m/s between the inlet and outlet, respectively. The impact of the increase in velocity is partially reflected in the increase in the overall HTC near the HX's SCW outlet shown in Figure 3. For conditions where the flow of SHS is too large, the temperature delta between the two flows becomes very small and the iterative calculations depict a pipe of infinite length required to transfer the total thermal energy, shown in Figure 4. Test conditions must limit the SHS flow to values for which there is a minimum temperature difference between the flows across the entire length of the HX but also above flow rates which produce feasible pipe lengths.

The length of piping used in the HX design must be minimized to reduce the amount of space required within containment. Increasing the overall HTC across the HX by installing flow turbulizers may decrease the length of piping necessary to transfer the total amount of thermal energy. Furthermore, this may reduce the number of tubes required and mass flow rate requiring diversion from the main SCW NPP flow loop. Increasing the inner pipe size would increase the heat transfer surface area, however, it would impact the dimensions of the outer pipe and influence the speed of flow of SCW and SHS. Further refining of operating parameters and HX configuration will be required to obtain a design which adequately satisfies the conditions outlined in this discussion.

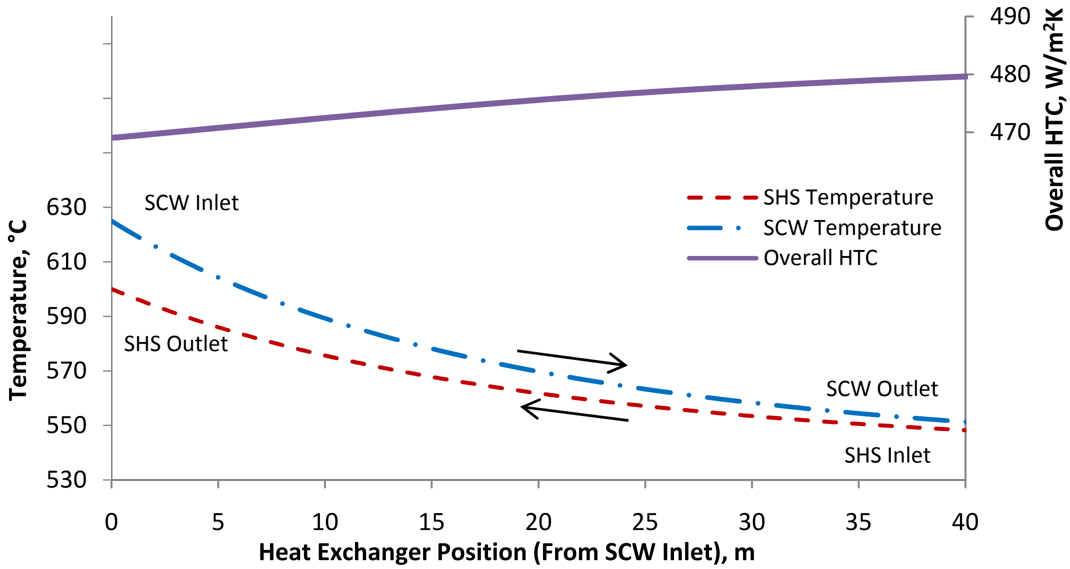

Figure 4. Temperature profiles obtained for excessive SHS flow.

5. Conclusions

An SCW NPP is capable of supplying the required high temperature heat for a Cu-Cl based hydrogen-production facility. Feasibility is dependent on selecting a suitable location of the intermediate HX in the SCWR loop and determining appropriate thermodynamic and flow conditions on both the SCW and SHS flow streams. Preliminary analysis was conducted on a double-pipe counter-flow HX with SCW coolant flowing through the inner pipe and superheated steam flowing through the annulus. It is assumed that approximately 50% of the heat generated within the hybrid 4-step Cu-Cl cycle is recycled internally requiring a net external heat input of 224 MW.

The main operating parameters for the HX were found using an iterative heat balance method:
- Inner Pipe Flow (SCW) – T_{in}: 625°C, T_{out}: 399°C, $\dot{m}_{SCW}$: 224 kg/s, P_{SCW}: 25 MPa
- Outer Pipe Flow (SHS) – T_{in}: 289°C, T_{out}: 600°C, $\dot{m}_{SHS}$: 287 kg/s, P_{SHS}: 5.0 MPa

Challenges associated with integrating an HX between the two facilities are numerous and range from thermodynamic considerations to economic concerns. Improvement of the overall HTC or lowering the SHS flow may reduce the size of the HX. Increasing the number of pipes in the system will lower the overall pressure drop of SHS due to lower flow velocities and controlling the SCW flow may reduce the length of HX piping. Iterative calculations are a necessary method to validate analytical calculations and provide indication of anomalies or limitations in calculated data.

Future work will refine the iterative approach used for analysis of HXs of a double-pipe design. Investigations will consider expanding analysis to a shell and pipe HX design for a no-reheat and single-reheat cycles NPP layout and double-pipe design for a single-reheat layout. Based on subsequent results, a design will be proposed for integration with the preferred SCW NPP layout selected. Investigations will also be conducted for single-reheat NPP-layout designs dependent on one of two HX designs located on the SCWR coolant loop. This is to address the potential for a single-reheat cycle NPP layout to be chosen as the optimal Generation-IV SCWR design.

6. Acknowledgements

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7. Nomenclature

A	Area, m^2
$\overline{c_p}$	Average specific heat, J/kgK $\left(\frac{H_w-H_b}{T_w-T_b}\right)$
D, d:	Diameter, m
G:	Mass flux, kg/m^{2}s
H:	Enthalpy, kJ/kg
h:	Heat transfer coefficient, W/m^{2}K
k:	Thermal conductivity, W/mK
L	Length of pipe, m
$\dot{m}$:	Mass flow rate, kg/s
N:	Number of pipes in HX
P,p:	Pressure, Pa
Q:	Thermal energy, J
q''	Heat flux, W/m^2
R:	Thermal resistance, K/W
S:	Tensile strength, MPa
T:	Temperature, °C/K
U:	Overall heat transfer coefficient, W/m^{2}K
V:	Electrical energy, J

Greek symbols

ρ:	Density, kg/m^3
μ:	Viscosity, Pa·s
δ:	Thickness, m

Subscripts

b:	Bulk
el:	Electrical
hy:	Hydraulic
i:	Inner
inc:	Increment
lm:	Log-mean
o:	Outer
s:	Surface
x:	Increment position
w:	Wall

Dimensionless Numbers

Nu: Nusselt Number $\left(\frac{h \cdot D_{hy}}{k}\right)$

$\overline{\text{Pr}}$: Average Prandtl Number $\left(\frac{\mu \cdot \overline{c_p}}{k}\right)$

Re: Reynolds Number $\left(\frac{4\dot{m}}{\pi D_{hy}\mu}\right)$ Inner Pipe, $\left(\frac{4\dot{m}}{\pi(d_o+D_i)\mu}\right)$ Outer Pipe

Acronyms

AECL	Atomic Energy of Canada Limited
ANL	Argonne National Laboratory
CV	Control Volume
Cu-Cl	Copper Chlorine
DOE	Department of Energy
HP	High Pressure
HTC	Heat Transfer Coefficient
HTGR	High-Temperature Gas-cooled Reactor
HX	Heat Exchanger
LMTD	Log Mean Temperature Difference
NPP	Nuclear Power Plant
SC	SuperCritical
SCW	SuperCritical Water
SCWR	SuperCritical Water Reactor
SI	Sulphur-Iodine
SHS	SuperHeated Steam
UOIT	University of Ontario Institute of Technology

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