

USE OF A SUPERCRITICAL WATER-COOLED REACTOR FOR PROCESS HEAT TO SUPPORT THERMOCHEMICAL HYDROGEN PRODUCTION

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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 production. The Copper-Chlorine (Cu-Cl) cycle is a prospective thermochemical cycle with a maximum temperature requirement of ~530°C. Thermalhydraulic calculations are presented for a double-pipe counter-flow heat exchanger with smooth pipe conditions and enhanced local heat transfer coefficients of 25%, 50% and 75% above smooth pipe cases.

1. Introduction

Hydrogen has been identified as an energy carrier which could supply a portion of the world's future energy requirements. The drive to find an alternative energy source replacing carbon-based fuels is due in part to reducing greenhouse gas emissions which contribute to global warming and preparing for a future global economy unwilling to rely on high-cost and scarce energy sources. As developing countries industrialize, their energy demand adds to the ever-increasing demand from current industrialized nations and drives energy prices upward.

Due to the low cost and available production methods, carbon-based hydrogen production via Steam Methane Reforming (SMR) or gasification is the most feasible hydrogen production process currently available. Furthermore, the majority of hydrogen produced is 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. One of the challenges associated with the development of thermochemical cycles is identifying a sufficient source of energy with an appropriate thermal transportation network that can supply the necessary reaction steps. Nuclear-based hydrogen production can be achieved by linking a Generation IV SuperCritical Water-cooled Reactor (SCWR) with a Cu-Cl cycle based hydrogen production facility. An intermediate process loop would be required with a Heat exchanger (HX) transferring thermal energy from the SCWR coolant to the Cu-Cl cycle. One possible design that may be used to provide the thermal energy transfer is a counter flow double-pipe HX. To optimize the size of the HX, heat transfer enhancement techniques can also be implemented in the form of corrugated piping which can increase local Heat Transfer Coefficients (HTCs) and reduce the HX's physical dimensions.

2. Thermochemical cycles

Thermochemical cycles decompose water into hydrogen and oxygen through a set of reactions that require thermal energy input. In hybridized cycles, an electrolysis step supports the decomposition process. Over 200 thermochemical cycles have been identified in literature, however, only few are technologically or economically feasible [1]. Many cycles face limitations due to high temperature requirements, low efficiencies or complex material/construction demands rendering the cycles unfeasible for development beyond theoretical calculations. Operating at temperatures of 870°C, the Sulphur-Iodine (SI) cycle is one of only several thermochemical cycle currently under investigation which have progressed to demonstrative pilot facility stages. The high temperature requirements of the cycle would make it suitable to link to a High-Temperature gas-cooled Reactor (HTR) which has a core coolant outlet temperature of up to 1000°C [2].

Compared to other cycles the Copper Chlorine (Cu-Cl) cycle operates at lower maximum temperatures of approximately 530°C. The cycle was chosen to be further investigated through research part of the United States Department of Energy's Nuclear Hydrogen Initiative (NHI). The objective of the NHI is to develop a cost competitive nuclear-heat based hydrogen production facility by 2019 [3]. Of the cycles evaluated, the Cu-Cl cycle had several strengths including the low temperature requirement, successful laboratory tests, international support and favourable economic targets [3]. Wang et al. have also shown that the SI and Cu-Cl cycles have similar hydrogen production costs and provided effective internal heat recycling they have an efficiency advantage over conventional electrolysis methods [4].

2.1 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 [5]. Research into the Cu-Cl cycle started in the 1970's when Dokiya and Kotera proposed a hybrid 2-step process [6]. All Cu-Cl cycle variations are based on different combinations of the 5-step cycle having different characteristics with associated advantages/disadvantages [3],[7],[8],[9]. Several strengths of the cycle include a relatively low maximum temperature requirement (~530°C), favourable reaction kinetics and the opportunity for internal heat recycling (5-step cycle) [7]. The 5-step cycle is characterized by an exothermic hydrogen-production step, three endothermic processes and an electrolysis step. Naterer et al. conducted thermodynamic analysis of the 5-step cycle and found the thermal energy requirements to be 277.4 kJ/g of H₂ produced with no heat recycling available and 31.3 kJ/g of H₂ of electrical energy [8]. The hydrogen production step, shown in Table 1, Reaction 1a) is an exothermic reaction operating at 450°C providing a source of thermal energy that could be redirected to the endothermic reactions in the cycle. A disadvantage associated with this step, however, is that it processes solid copper reactant which requires additional drying processes adding to the complexity of the system.

The 4-step hybrid cycle removes the requirement for solid copper processing but also loses the exothermic hydrogen production resulting in less thermal energy for recycling. The 4-step cycle, shown in Table 1, is derived by combining steps 1a) and 1b) of the 5-step cycle into a single electrolysis step operating at near-ambient temperatures to produce hydrogen electrolytically. This step is analogous to that proposed by Dokiya and Kotera [6]. Teams at several institutions

Table 1. Reaction steps in the hybrid 4-step Cu-Cl cycle [7],[10],[11].

The diagram illustrates a chemical process involving four main units: Unit 1 (Electrochemical Cell, 70°C), Unit 2 (Spray Dryer, 70°C), Unit 3 (HCl (g) Prod. (Fluidized Bed, 400°C)), and Unit 4 (O2 Prod. (Molten Salt Rx, 530°C)).

Inputs:

- Input: H_2O (to Unit 3)
- Input: Waste Heat (to Unit 2)
- Input: Heat (to Unit 1)

Outputs:

- Output: H_2Gas (from Unit 1)
- Output: $\text{O}_2\text{ Gas}$ (from Unit 4)

Internal Flows:

- Unit 1 produces HCl (aq) , which is heated and sent to Unit 3.
- Unit 3 produces HCl (g) , which is heated and sent to Unit 4.
- Unit 4 produces CuCl (l) , which is heated and sent to Unit 1.
- Unit 1 produces CuCl (s) , which is heated and sent to Unit 2.
- Unit 2 produces $\text{CuCl}_2\text{ (aq)}$, which is heated and sent to Unit 3.
- Unit 3 produces $\text{CuO} \cdot \text{CuCl}_2\text{ (s)}$, which is heated and sent to Unit 4.
- Unit 4 produces H_2O , which is heated and sent to Unit 1.

There are two reaction steps in the Cu-Cl cycle which require high temperature thermal energy: hydrolysis (Step 3) and decomposition (oxygen production) (Step 4). Since the temperature requirement of the hydrolysis reaction is bounded by the oxygen production step any heat source supplying the Cu-Cl cycle must be assessed against a temperature of 530°C. A direct or indirect heat supply could be integrated from an external source, however, in relation to an SCWR link,

an indirect cycle would be required to lower the probability of any radioactive material being released to the external environment (Cu-Cl cycle processes). Due to the temperature requirements of the two reaction steps a series piping arrangement could be used to supply the thermal energy. SuperHeated Steam (SHS), or an alternative fluid, could be delivered to the oxygen production step and then be fed downstream to the hydrolysis reactor. Alternatively, two separate heating streams could be supplied to the individual reactions in a parallel configuration.

The 4-step cycle has less recoverable thermal energy compared to the 5-step cycle, some of which is low grade. Wang et al. have reported that approximately 50% of the heat released within the 5-step cycle can be recycled [12]. As a result, the net heat input required by the 4-step cycle is 247 kJ/g of hydrogen with 46 kJ/g available for recycling [4]. Accounting for the recoverable fraction, the net thermal energy requirement of the cycle is 224 kJ/g of hydrogen.

3. Potential SCWR layouts

Currently in the conceptual design phase, the SCWR is a Generation IV nuclear-reactor-design having two main objectives: 1) increase the thermal efficiency of current NPPs from 30-35% to ranges of 45-50%; 2) decrease capital, operational and unit-energy costs. The operating conditions of the SCWR further present the opportunity for process heating applications involving thermochemical cycles. Due to the nature of the technology, NPPs provide baseload electricity and typically do not load follow. A process heating application would allow a reactor to operate at constant power with varied electrical output. Hydrogen production via the Cu-Cl cycle could be maximized during periods of off-peak electrical demand.

There are several design layouts for a SCW NPP based on no-reheat and single reheat “steam” cycles. The SCWR design operates with light water coolant at pressures of 25 MPa and temperatures of up to 625°C. As the coolant travels through the reactor it passes through the *pseudocritical point* which is defined as a point at a given temperature and pressure above the critical point where the specific heat of the liquid is at its maximum value. The pseudocritical temperature for water at a pressure of 25 MPa is approximately 384.9°C. Water at this state is termed SuperCritical (SC) and possesses an immense amount of thermal energy which can be used as input to the Cu-Cl cycle. A fraction of high temperature SCW coolant from the primary SCWR loop would be diverted to an HX where it could transfer heat to an intermediate fluid (e.g., steam or helium) and then be returned to a suitable location on the coolant circuit. Studies have shown that to meet the thermal demand of the 5-step Cu-Cl cycle through a 1200 MW_{el} NPP, 12% of the total SCWR thermal energy would need to be diverted to the HX [13]. This requirement would change based on the variation of Cu-Cl cycle used, the amount of heat loss/recovery within the cycle and the thermal losses associated with transporting the intermediate coolant to the required reactions in the hydrogen production facility.

For a no-reheat NPP layout with a total coolant flowrate of approximately 1200 kg/s, the sole candidate location for an HX is at the reactor outlet. This is also one of the two locations available on the single reheat cycle which is shown in Figure 2. A double-pipe HX at this location, termed “HX A” would operate with SCW flowing through the inner pipe and SHS in the annulus. For a single-reheat NPP layout with a total flow rate of 960 kg/s, there are two candidate locations under consideration, however, only one should be integrated per station [14].

Following expansion of the SCW through a High Pressure (HP) turbine with coolant extraction the lower pressure SHS would return to the reactor at a flow of 780 kg/s and be heated to a temperature of 625°C and pressure of 5.7 MPa. Flow exiting the reactor could then be diverted to an HX, “HX B” operating with an SHS/SHS interface.

The HXs under consideration would need to be located inside the containment structure for the SCWR to provide a barrier to prevent external radioactive releases. The intermediate coolant loop between the two facilities would act as the containment boundary between the NPP and the external environment. 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.

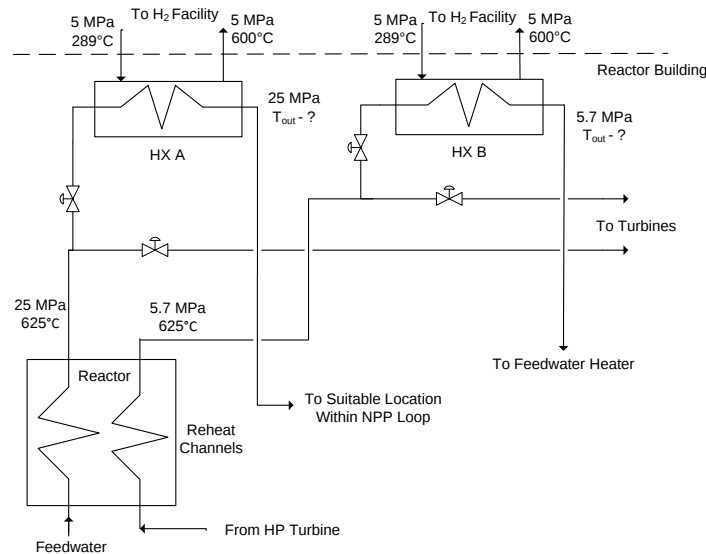


Figure 2. Potential HX location for a single-reheat SCW NPP layout.

4. Heat-exchanger thermalhydraulic analysis

The objective of performing thermalhydraulic calculations was to assess combinations of HX design parameters and determine which of them produced feasible operating conditions that could be further investigated in future work. The focus of this research was the HX A arrangement as it involves more complex design due to the SCW/SHS interface. A hydrogen production rate of 1 kg/s was assumed on the Cu-Cl facility side and steady state operating conditions were assumed for the HX. Additional assumptions for the analysis included no heat loss through the outer pipe outer wall, no pressure losses, no radiation effects and no fouling on HX pipe walls. A script was developed using MATLAB computational software that would iteratively calculate thermophysical properties and perform energy balance for the HX operating fluids across the HX pipe length.

The heat-transfer correlation selected for the analysis was the Mokry et al. correlation [17], shown as Equation (1). The correlation was developed from an experimental dataset for heated upward flow of SCW in vertical bare tubes. It is dependent on both bulk-fluid and wall-fluid properties similar to correlations based on the Bishop et al. correlation [18]. Although the

correlation was developed for water at supercritical conditions it was also been applied to the SHS flow in the annulus gap. This was based on conclusions of researchers at the University of Ottawa (UO) specifying the Mokry et al. (earlier termed “Gospodinov et al.”) correlation showing the best agreement with available experimental data for the SHS and SCW regions [19].

$$\text{Nu}_b = 0.0061 \text{Re}_b^{0.904} \text{Pr}_b^{0.684} \left(\frac{\rho_w}{\rho_b} \right)^{0.564} \quad (1)$$

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

Since the Mokry et al. correlation requires evaluation of thermophysical properties at the pipe wall, the wall temperature, $T_{w,x}$, for each Control Volume (CV) was calculated iteratively using Equation 2. An initial wall temperature was assumed and used to calculate thermophysical properties and HTC's which were then used as inputs into Equation 2 to generate a calculated value. If a discrepancy existed then the assumed wall temperature was increased or decreased by half of the difference of the assumed and calculated wall temperatures. Once the wall temperature was obtained, the overall HTC was calculated using Equation 3. Iterations were performed until the change in wall temperature was less than 0.001 K. This typically required less than 80 iterations for more demanding solutions.

$$T_{w,x} = \left[\left(\frac{T_{i,x}}{R_{i,x}} \right) + \left(\frac{T_{o,x}}{R_{o,x}} \right) \right] / \left[\left(\frac{1}{R_{i,x}} \right) + \left(\frac{1}{R_{o,x}} \right) \right] \quad (2)$$

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

A second iterative process was used to calculate temperature parameters for each CV. Energy balance Equation 4 was rearranged to solve for SCW outlet temperature, $T_{SCW,out,x}$, while Equation 5 was rearranged for SHS inlet temperature, $T_{SHS,in,x}$. A value for SHS inlet temperature was assumed in Equation 4 to calculate an SCW temperature. Subsequently, using the results of Equation 4, a temperature value for the SHS was calculated using Equation 5. These values were then used to calculate energy balances for both flows. The above procedure was repeated until the difference in thermal energy transferred between the streams was 0.001 J. The typical length for convergence to be achieved was approximately 20 iterations.

$$\text{Inner Pipe: } \dot{m}_{SCW} c_{p,SCW,x} (T_{SCW,in,x} - T_{SCW,out,x}) - U_x A_{inc} \left[\frac{T_{SCW,in,x} + T_{SCW,out,x}}{2} - \frac{T_{SHS,in,x} + T_{SHS,out,x}}{2} \right] = 0 \quad (4)$$

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

The results of these calculations showed that HXs can be integrated at both the SCW channel outlet and steam reheat channel outlet stream locations for a single reheat SCW NPP [15,[16]. For a select number of HX A arrangements the temperature of the SCW flow nearing the HX outlet would approach the *pseudocritical* region for pressures of 25 MPa. The *pseudocritical* temperature at 25 MPa, corresponding to the temperature where the SCW flow would experience a maximum specific heat value, is 384.9°C. For such layouts the thermophysical properties of both the SCW and counter flow SHS flows would change significantly in this region. This required an iterative solution to obtain HX parameters such as pipe length, required number of

pipes and the SCW flow exit temperature. The inlet temperature of SHS into the HX was fixed at approximately 25°C above the saturation temperature for water at 5 MPa to ensure that the flow through the HX entered as SHS and remained a single phase. For an HX A design, results for pipe length varied between 10 m to 50 m with the number of pipes required to provide the total Cu-Cl cycle thermal energy requirements ranging between 2800 and 4400 as shown from several test cases in Table 2 and [16].

Table 2. General design parameters for several test HX A designs.

	Parameter	HX A - 1	HX A - 2	HX A - 3	HX A - 4
Overall Heat Exchanger (HX A)	Heat Transferred per Pipe, kW	55.5	77.7	78.5	54.8
	No. of HX Pipes, N	4043	2890	2857	4095
	Average Overall HTC, U , W/m ² K	764	879	810	826
	Heat Transfer Area per Pipe, m ²	1.04	1.93	3.35	0.83
	Length per Pipe, L , m	12.1	23.0	39.9	9.9
SCW - Inner Pipe Flow	Total Mass Flow Rate, $\dot{m}$, kg/s	340	243	197	424
	Inlet/Outlet Temperatures, T , °C	625/441	625/405	625/391	625/468
	Inner Diameter, d_i , mm	18.9	18.9	21	21
	Outer Diameter, d_o , mm	26.7			
	Pipe Mass Flux, G , kg/m ² s	300	300	200	300
	Maximum Flow Speed, m/s	4	4	3	4
SHS - Annulus Gap Flow	Total Mass Flow Rate, $\dot{m}$, kg/s	287	289	286	287
	Inlet/Outlet Temperature, T , °C	284/600	289/600	287/600	287/600
	Inner Diameter, D_i , mm	30.1			
	Outer Diameter, D_o , mm	33.4			
	Annulus Mass Flux, G , kg/m ² s	462	659	659	462
	Maximum Flow Speed, m/s	36	52	52	36

4.1 Heat transfer enhancement

To optimize the size of the HX design used in this application heat transfer enhancement techniques were considered. Enhancement techniques can be used to increase heat transfer area (finned surfaces), a fluid flow's HTC (surface roughness) or a combination of the preceding factors. It is recommended that any augmentation of the heat transfer surface be applied to the fluid stream that has the dominant thermal resistance in the system [20]. Although the SCW thermal resistance was typically dominant in previous analyses, enhancement was applied to both streams. Focus was on a passive enhancement technique in the form of helically corrugated pipes. The use of a helically corrugated pipe for the inner pipe would introduce a rough surface for both the internal and annulus flows promoting improved turbulence and better heat transfer at the pipe wall. Additional benefits of helically corrugated pipes over other types of corrugated pipes include easier fabrication, more effective heat transfer relative to increased friction factors and low levels of fouling [21]. Figure 3 depicts a cross sectional view of a HX pipe with a helically corrugated inner pipe. This type of arrangement causes secondary flows within the piping resulting in better mixing of the working fluid near the pipe wall and a reduction in the boundary layer improving heat transfer [22].

Helically corrugated pipes are characterized by three main parameters: pipe diameter, rib height (depth between inner and outer surface) and helical pitch. Studies by Pethkool et al. [22] investigated various samples of helical pipes in a double-pipe HX and measured enhancement

effects on Nusselt number, friction factor and thermal performance factor. The average increase in heat transfer across the HX in their analysis was up to 232% while Vicente et al. [23] reported Nusselt numbers up to 250% greater for helically corrugated tubes than those for smooth tubes in their experimental analysis of several tube samples.

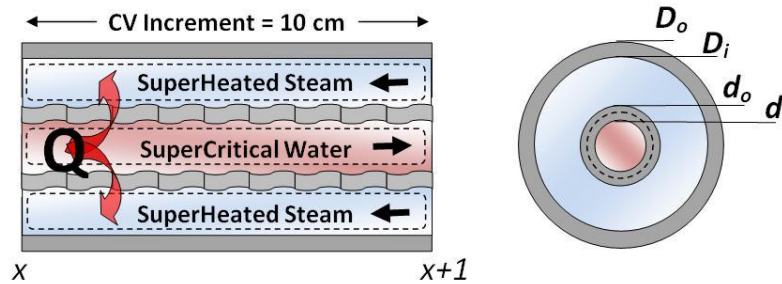


Figure 3. Corrugated inner pipe with smooth outer pipe for a double-pipe HX (not to scale).

This analysis looked to evaluate the impact of heat transfer enhancement on the inside and outside surfaces of the inner pipe of the double-pipe HX. The Mokry et al. correlation was modified to increase the value of the local HTC for both SCW and SHS flows by values of 25%, 50% and 75%. Factors such as modified piping dimensions were not accounted for as the sole objective was to assess the level of enhancement, regardless of the corrugated pipe dimensions used to incorporate it. Results for four test cases are shown in Table 3. The thermal energy transferred for each pipe remained fixed as the flow rates of SCW and SHS remained constant through the HX and only pipe length was allowed to vary. Temperature profiles were obtained for each of the test cases, with examples shown in Figure 4 and Figure 5 for the smooth pipe and 50% local HTC increase case of HX A–2, respectively. Findings show that an increase in the local HTCs by a given fraction did not result in the overall HTC being increased by the same amount as is shown in Table 3 and Figure 6. This is due in part to the wall thermal resistance remaining unchanged by the enhanced heat transfer conditions on the pipe surfaces. Additionally, the relative improvement of the overall HTC decreased as local HTCs were increased suggesting that there is an upper bound for level of enhancement beyond which it would not be economical to pursue for an HX design.

Table 3. HX A heat transfer characteristics for enhanced pipes with local HTCs of 25%, 50% and 75% above values for smooth pipes.

		Heat Transfer per Pipe, kW	No. of HX Pipes, N	Average Overall HTC, U, W/m ² K	Overall HTC Increase, %	Heat Transfer Area per Pipe, m ²	Length per Pipe, L, m
HX 1	25%	~55	4075	917	20	0.86	10.3
	50%		4099	1058	38	0.75	8.9
	75%		4120	1189	56	0.66	7.9
HX 2	25%	~78	2873	1050	19	1.62	19.3
	50%		2879	1205	37	1.41	16.8
	75%		2894	1347	53	1.26	15.0
HX 3	25%	~78	2873	981	21	2.76	32.9
	50%		2826	1146	42	2.37	28.3
	75%		2876	1297	60	2.09	24.9
HX 4	25%	~55	4095	826	21	0.83	9.9
	50%		4040	1004	41	0.69	8.2
	75%		4102	1168	61	0.59	7.0

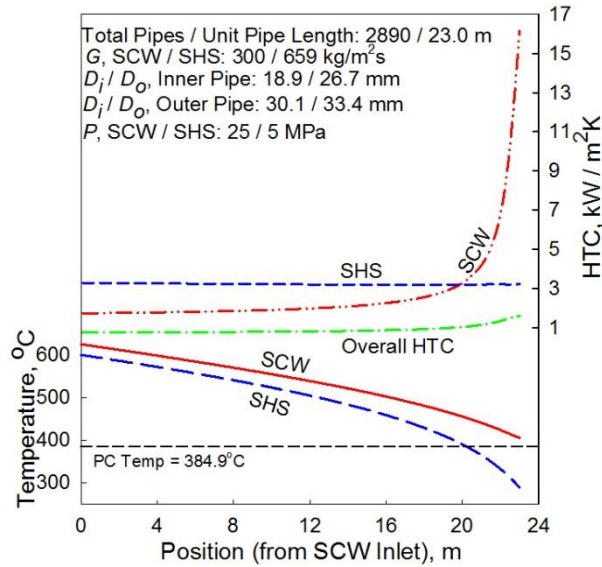


Figure 4. Temperature profiles and overall HTC for HX A-2 for smooth pipe scenario.

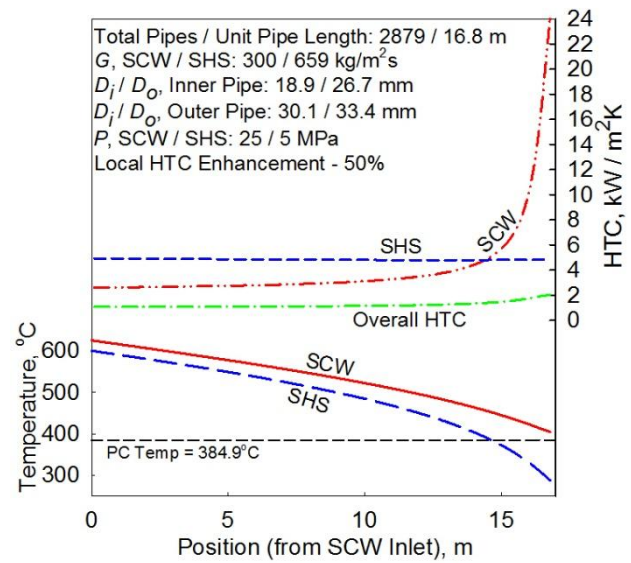


Figure 5. Temperature profiles and overall HTC for HX A-2 for 50% increased local HTCs.

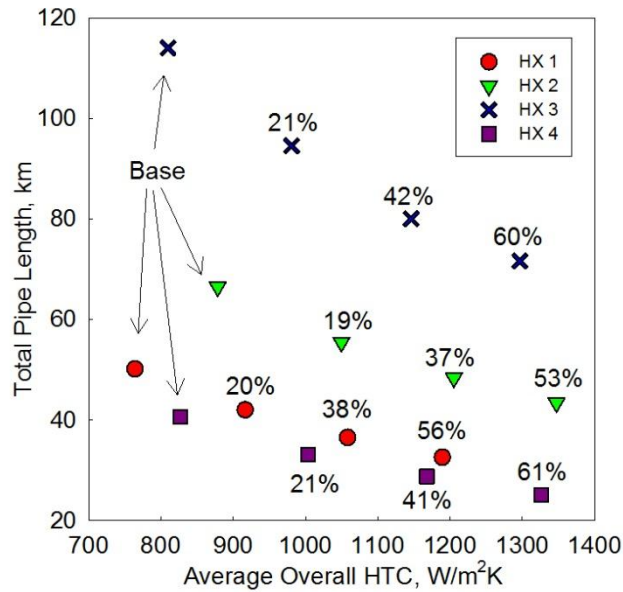


Figure 6. Predicted total HX-A pipe length for augmented pipes versus overall HTC dependent on increased local HTCs of 25%, 50% and 75%.

5. Conclusions

Nuclear-based process heating from an SCWR in support thermochemical hydrogen production via the Cu-Cl cycle was discussed. A counter flow, double-pipe HX would be integrated into the SCW NPP primary SCW coolant loop downstream of the reactor outlet operating at inlet conditions of 625°C and 25 MPa. The HX would transfer approximately 224 MW of thermal

energy as SHS at 600°C and 5 MPa flowing in an isolated intermediate loop to reactions within the Cu-Cl cycle requiring temperatures of up to 530°C.

An iterative program was developed to perform energy balances across the HX using the Mokry et al. correlation as the heat transfer correlation. Input parameters included HX pipe dimensions, operating pressures and mass flow rates of the fluid flows. Several combinations of test inputs were developed and typical individual pipe lengths for the HX ranged between 10 m and 50 m with the number of pipes required ranging between 2800 and 4400. For all test scenarios, the outlet temperature of SCW for the HX was above the *pseudocritical* temperature.

Heat transfer enhancement effects were also investigated with proposed helically corrugated pipes used for the inner pipe of the HX pipe unit. Increases in local HTC's of 25%, 50% and 75% produced overall HTC increases between 20% and 61% for investigated test cases and reduced the total length of piping required for the HX. The relative improvement in heat transfer decreased as HTC values increased indicating that exceeding an upper bounding percentage of HTC enhancement would result in a smaller reduction in total HX pipe length.

6. Acknowledgements

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7. Nomenclature

A :	Area, m ²	<i>Greek symbols</i>	
$\bar{c}_p$:	Average specific heat, J/kgK $\left(\frac{H_w - H_b}{T_w - T_b}\right)$	ρ :	Density, kg/m ³
D, d :	Diameter, m	μ :	Viscosity, Pa·s
G :	Mass flux, kg/m ² s	<i>Subscripts</i>	
H :	Enthalpy, kJ/kg	b :	Bulk
h :	Heat transfer coefficient, W/m ² K	el :	Electrical
k :	Thermal conductivity, W/mK	hy :	Hydraulic
L :	Length of pipe, m	i :	Inner
$\dot{m}$:	Mass flow rate, kg/s	inc :	Increment
N :	Number of pipes in HX	o :	Outer
P, p :	Pressure, Pa	s :	Surface
Q :	Thermal energy, J	x :	Increment position
q' :	Heat flux, W/m ²	w :	Wall
R :	Thermal resistance, K/W		
T :	Temperature, °C/K		
U :	Overall heat transfer coefficient, W/m ² K		
V :	Electrical Energy, J		

Dimensionless Numbers

Nu:	Nusselt Number	$\left(\frac{h \cdot D_{hy}}{k}\right)$	
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, $\left(\frac{4\dot{m}}{\pi(d_o + D_i) \mu}\right)$ Annulus Gap

Acronyms

AECL	Atomic Energy of Canada Limited	NPP	Nuclear Power Plant
ANL	Argonne National Laboratory	SC	SuperCritical
CV	Control Volume	SCW	SuperCritical Water
Cu-Cl	Copper Chlorine	SCWR	SuperCritical Water Reactor
HP	High Pressure	SHS	SuperHeated Steam
HTC	Heat Transfer Coefficient	SI	Sulphur-Iodine
HTR	High-Temperature gas-cooled Reactor	SMR	Steam Methane Reforming
HX	Heat eXchanger	UO	University of Ottawa
NHI	Nuclear Hydrogen Initiative	UOIT	University of Ontario Institute of Technology

8. References

- [1] Lewis, M., and Taylor, A., "High temperature thermochemical processes", DOE Hydrogen Program, 2006.
- [2] Leybros, J., Carles, P. and Borgard, J-M., "Countercurrent reactor design and flowsheet for iodine-sulfur thermochemical water splitting process", *International Journal of Hydrogen Energy*, Vol. 34, Iss. 22, 2009. pp. 9060-9075.
- [3] Lewis, M.A. and Masin, J.G., "The evaluation of alternative thermochemical cycles-part II: the down-selection process", *International Journal of Hydrogen Energy*, Vol. 34, Iss. 9, 2009. pp. 4125-4135.
- [4] Wang, Z.L., Naterer, G.F., Gabriel, K.S. et al., "Comparison of sulfur-iodine and copper-chlorine thermochemical hydrogen production cycles", *International Journal of Hydrogen Energy*, Vol. 35, Iss. 10, 2010. pp. 4820-4830.
- [5] Naidin, M., Mokry, S., Baig, F., et al., "Thermal design options for pressure-channel SCWRs with cogeneration of hydrogen", *Journal of Engineering for Gas Turbines and Power*, Vol. 131, 2009. pp. 012901-1-8.
- [6] Dokiya, D., Kotera, Y. "Hybrid cycle with electrolysis using a Cu-Cl system," *International Journal of Hydrogen Production and Applications*, Vol. 1, Iss. 6, 1976. pp. 144-153.
- [7] Naterer, G., Suppiah, S., Lewis, M. et al., "Recent Canadian advances in nuclear-based hydrogen production and the thermochemical Cu-Cl cycle", *International Journal of Hydrogen Energy*, Vol. 34, Iss. 7, 2009. pp. 2901-2917.
- [8] Naterer, G.F, Gabriel, K., Wang Z.L. et al., "Thermochemical hydrogen production with a copper-chlorine cycle. I: Oxygen release from copper oxychloride decomposition", *International Journal of Hydrogen Energy*, Vol. 33, Iss. 20, 2008. pp. 5439-5450.
- [9] Wang, Z.L., Naterer, G.F., Gabriel, K. et al., "New Cu-Cl thermochemical cycle for hydrogen production with reduced excess steam requirements," *International Journal of Green Energy*, Vol. 6, Iss. 6, 2009, pp. 616-626.

- [10] Lewis, M., Ferrandon, M., Tatterson, D., "R&D status for the Cu-Cl thermochemical cycle", DOE Hydrogen Program, 2009.
- [11] Naterer, G., Suppiah, S., Stolberg, L. et al., "Canada's program on nuclear hydrogen production and the thermochemical Cu-Cl cycle", *International Journal of Hydrogen Energy*, Vol. 35, Iss. 20, 2010. pp. 10905-10926.
- [12] Wang, Z., Naterer, G.F., Gabriel, K.S., "Thermal integration of SCWR nuclear and thermochemical hydrogen plants", Proceedings of the 2nd Canada-China Joint Workshop on Supercritical Water-Cooled Reactors (CCSC-2010), Toronto, Ontario, Canada, April 25-28, 2010. 12 pages.
- [13] Lukomski, A., Pioro, I., Gabriel, K., "Aspects of hydrogen co-generation using a thermochemical cycle linked to a supercritical water-cooled nuclear reactor", Proceedings of the 2nd Canada-China Joint Workshop on Supercritical Water-Cooled Reactors (CCSC-2010), Toronto, Ontario, Canada, April 25-28 2010. 12 pages.
- [14] Naidin, M., Mokry, S., Monichan, R. et al., "Thermodynamic analysis of SCW NPP cycles with thermo-chemical co-generation of hydrogen", Proceedings of the International Conference on Hydrogen Production, Oshawa, Ontario, Canada, May 3-6 2009. pp. 178-192.
- [15] Lukomski, A., Gabriel, K., Pioro, I., Naterer, G.F., "Intermediate double-pipe heat exchanger for thermochemical hydrogen co-generation with SCW NPP", Proceedings of the 19th International Conference on Nuclear Engineering, Makuhari, Chiba, Japan, May 16-19, 2011. 9 pages.
- [16] Mokry, S., Lukomski, A., Gabriel, K., et al. "Thermalhydraulic and heat transfer correlations for an intermediate heat exchanger linking a supercritical water-cooled reactor and a copper-chlorine cycle of hydrogen production", Proceedings of the International Conference on Hydrogen Production, Thessaloniki, Greece, June 19-22, 2011. 12 pages.
- [17] Mokry, S., Farah, A., King, K. et al., "Development of supercritical water heat-transfer correlation for vertical bare tubes", Proceedings of the Nuclear Energy for New Europe 2009 International Conference, Bled, Slovenia, September 14-17, 2009. 14 pages.
- [18] Bishop, A., Sandberg, R., and Tong, L. "Forced convection heat transfer to water at near-critical temperatures and super-critical pressures", Atomic Power Division. Pittsburgh, PA., USA: Westinghouse Electric Corporation. 1964.
- [19] Zahlan, H., Groeneveld, D.C., Tavoularis, S., "Look-up table for trans-critical heat transfer", Proceedings of the 2nd Canada-China Joint Workshop on Supercritical Water-Cooled Reactors (CCSC-2010), Toronto, Ontario, Canada, April 25-28, 2010. 18 pages.
- [20] Kuppan, T., "Heat Exchange Design Handbook" Marcel Dekker: New York, NY. 2000. 1119 pages.
- [21] Sethumadhavan, R. and Rao, R., "Turbulent flow friction and heat transfer characteristics of single and multistart spirally enhanced tubes", Trans. ASME, *Journal of Heat Transfer*, 108, 1986, pp. 55-61.
- [22] Pethkool, S., Eiamsa-ard, S., Kwankaomeng, S., Promvonge, P., "Turbulent heat transfer enhancement in a heat exchanger using helically corrugated tube", *International Communications in Heat and Mass Transfer*, Vol. 38, Iss. 3, 2011. pp 340-347.
- [23] Vicente, P.G, Garcia, A., Viedma, A., "Experimental investigation on heat transfer and frictional characteristics of spirally corrugated tubes in turbulent flow at different Prandtl numbers" *International Journal of Heat and Mass Transfer*, Vol. 47 (2004). pp. 671-681.