Heat Transfer Analysis for the Application of SCWR Process Heat for the Thermochemical Production of Hydrogen

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Summary

The use of SuperCritical Water-cooled Reactor (SCWR) process heat for the thermochemical production of hydrogen is investigated. The objective of this work is to complete a heat transfer analysis on an intermediate counter-flow double-pipe heat exchanger (HX) to be used for hydrogen cogeneration. In this work the thermal energy requirements for the 4-stage thermochemical Copper-Chlorine (Cu-Cl) are identified. A numerical model is developed using MATLAB and a sensitivity analysis is performed. The sensitivity analysis is performed to determine the effect certain parameter changes will have on the overall size of the HX when compared against an initial reference case.

1. Introduction

Carbon based fuel sources will to be the dominant force within the energy landscape for the foreseeable future, however it is unlikely that they will be able to sustain these efforts with depleting resources. Due to this, it is important that viable alternatives be identified. One possible alternative is the non-carbon based production of hydrogen through the use of thermochemical cycles. This can be achieved by using an intermediate heat exchanger (HX) to integrate a Nuclear Power Plant (NPP) with a hydrogen production facility. By integrating a NPP with a hydrogen production facility, the external thermal energy requirement for the cycle can be met without the use of fossil fuels. One thermochemical cycle currently being studied for this application is Copper-Chlorine (Cu-Cl) cycle. Compared with other thermochemical cycles, this cycle is considered a strong candidate due to its relatively low temperature requirements[1]. There are six Generation-IV nuclear reactor concepts currently under development worldwide. Each of these designs looks to improve upon the current nuclear reactor fleet by addressing eight technology specific goals. While not outlined as a specific goal, hydrogen production technologies can be developed within the Gen-IV International Forum (GIF) [1]. For the purpose of this research the SuperCritical Water-cooled Reactor (SCWR) design was investigated.

2. Literature Review

The SCWR is a water-cooled reactor designed to operate above the critical point of water, which is 22.064 MPa and 373.95ºC [2]. There are two designs that currently exist for the SCWR: the Pressure-Tube (PT) and Pressure-Vessel (PV) designs. This paper will focus on the PT-SCWR. The operating conditions of SCWRs are significantly high, with operating pressures of 25 MPa and reactor outlet temperatures up to 625ºC[3]. For this reason SCWRs are being considered for hydrogen cogeneration through the use of thermochemical cycles. The 4-step Cu-Cl cycle has a maximum temperature requirement of approximately 530ºC[1, 4]. There are several variations of the Cu-Cl, however the analysis presented in this paper is based on the requirements of the 4-stage cycle.This variation was selected to its advantages in thermal efficiency and practical viability.

The 4-step Cu-Cl requires a net heat input of 247 kJ/g of hydrogen with approximately 46 kJ/g available for recycling [5]. With an assumption that approximately 50% of the heat being generated within the cycle is recoverable, the net thermal energy requirement, Q, is 224 kJ/g of hydrogen produced. Applying this requirement to a commercial scale hydrogen production rate of 1 kg/s, the power requirement for the cycle becomes 224 MW. In the analysis presented in this paper, a thermal energy requirement of 10% of total SCWR thermal power is investigated.

Integrating an SCWR NPP with a hydrogen production facility will allow for reactor process heat to be used for hydrogen production during off-peak hours. To achieve this, a percentage of the SuperCritical Water (SCW) coolant will be diverted to an intermediate HX where it will transfer its heat to the intermediate working fluid on the cold side. After leaving the HX the SCW coolant would be sent back to the reactor. Based the necessary temperature requirements the ideal extraction point was selected to be at the reactor outlet. It should be noted that while studies determining the ideal extraction point have been conducted on the no-reheat and single-reheat cycle, this paper focuses solely on the no-reheat cycle.

3. Methodology

This section describes the design and operating parameters used in the reference case for the analysis. It also details the heat transfer model and the numerical model that was developed in MATLAB.

3.1 Design and Operating Parameters

A counter-flow double-pipe HX was selected for the analysis. In this design the hot and cold fluids will enter from opposite ends; the outlet temperature of the cold fluid can then exceed the outlet temperature of the hot fluid[6]. In this design the hot fluid, the SCW coolant coming from the reactor, would flow through the inner pipe. The cold fluid, which is a separate SCW working fluid, would flow through the annulus gap of the HX. The operating parameters used in the reference case are presented in Table 1.

Table 1. Operating parameters for reference case counter-flow double-pipe HX

Operating Parameter	**Inner Pipe (Hot Side)**	**Annulus Gap (Cold Side)**
Fluid	SCW reactor coolant	SCW Working Fluid
Pressure (MPa)	25	25.5
Inlet temp. (°C)	625	350
Outlet temp. (°C)	350	600
Mass flux (kg/m^2·s)	1500	1500
Inner diameter (mm)	20.9	32.5
Outer diameter (mm)	26.7	42.2
Pipe thickness (mm)	2.87	5.80

3.2 Heat Transfer Model

The heat transfer correlation used in the analysis was the Mokry et al. correlation [7]. This correlation does not take entrance region effects into account. However, it is assumed that this will not be hinder the analysis. The Mokry et al. correlation is presented below:

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

A set of thermal energy balance equations for the one-dimensional analysis of HXs was proposed by Ribando et al. [8]. These equations were based on nodalization, where the length of HX is divided into a finite number of Control Volumes (CVs). These equations were used to determine the inlet and outlet temperature of each CV using the overall heat transfer coefficient, U, and heat capacity rate, C.The equations presented below [8]:

$$\text{Hot Side:} \quad C_1(T_{1in} - T_{1out}) - UA_n\left[\frac{T_{1in}+T_{1out}}{2} - \frac{T_{2in}+T_{2out}}{2}\right] = 0 \quad (2)$$

$$\text{Cold Side:} \quad C_2(T_{2in} - T_{2out}) - UA_n\left[\frac{T_{2in}+T_{2out}}{2} - \frac{T_{1in}+T_{1out}}{2}\right] = 0 \quad (3)$$

3.3 Numerical Model

The model that was developed uses nodalization, which divides the HX into a larger number of finite CVs. As a result an iterative solution was used to conduct the heat transfer analysis. This methodology was selected over the more traditional Log Mean Temperature Difference (LMTD) due to the fact that the working fluids are supercritical fluids. A review of their thermophysical properties showed that supercritical fluids undergo significant variation in these properties within the pseudocritical region[9].A diagram of the CV is presented in Figure 1.

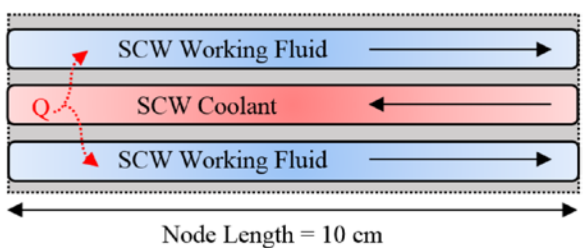

Figure 1. Control volume for counter-flow double-pipe HX

4. Analysis and Discussion

Using the MATLAB programming software, the numerical model to conduct a one-dimensional heat transfer analysis was developed. Fluid properties used in this model were obtained from NIST REFPROP [2]. Using the thermal energy balance equations, a set of iterative calculations were performed to determine the overall size of the HX needed to achieve the required temperature change. The results obtained from the reference case previously shown in Table 1 are presented in Figure 2.

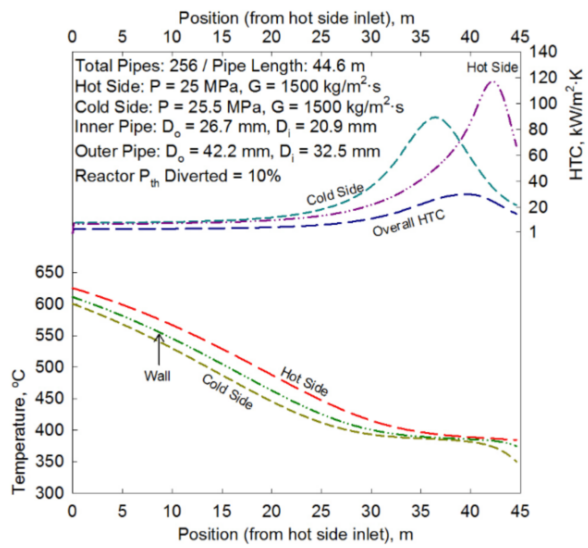

Figure 2. Reference case: hot side, cold side, wall temperatures. Local and overall HTC for HX

It can be seen that to achieve the desired energy transfer to SCW working fluid on the cold side, a total of 256 pipes with a length of 44.6 m per pipe would be needed. It is also demonstrated that at approximately 30 m from the hot side inlet, the temperature profile begins to flatten out. At this point the fluids begin to enter the pseudocritical region. This is demonstrated by the variation in heat transfer coefficient (HTC) profiles after this point. Figure 2 also shows rounded peaks in HTC profile for the both the hot side and cold side. These peaks demonstrate the location of pseudocritical points from the hot side inlet of the HX.

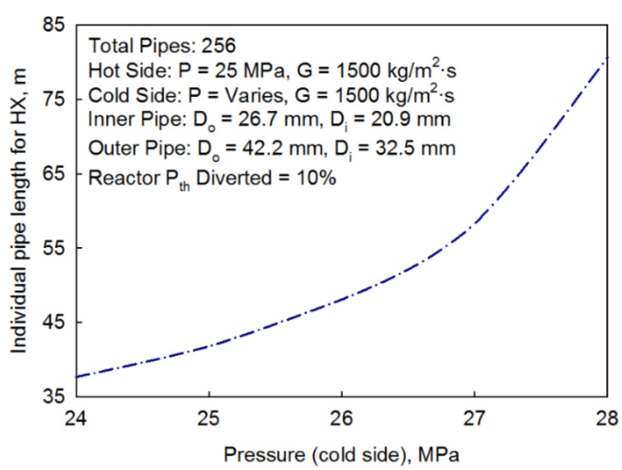

Figure 3. Effect of cold side pressure on HX pipe length

Pressures on the cold side were varied from 24 MPa to 28 MPa in increments of 1 MPa. Figure 3 presents the results of this analysis. The results presented show that when the pressure on the cold side increased, the length of the pipes in HX also increase. This can be attributed to movement of the pseudocritical point. As the pressure of the SCW working fluid increases, so does the pseudocritical point and as a result the pipe length also increases. Therefore, by decreasing the pressure on the cold side, the overall size of the HX can be reduced therein by optimizing the design. However, a potential safety concern arises if the pressure of the cold side is decreased below the pressure of the hot side. If the hot side is set at a higher pressure than the cold side, a leak in the HX would result in the SCW coolant leaking out of the inner pipe. These safety considerations should be taken into account when selecting the final design.

5. Concluding Remarks

A heat transfer analysis on an intermediate HX for an SCWR hydrogen cogeneration plant was conducted. The 4-step Cu-Cl cycle was determined to be the most suitable hydrogen production method due to its relatively low temperature requirements. It was also determined that for a commercial scale hydrogen production rate of 1 kg/s, the power requirement would 224 MW. A methodology using a set of iterative calculations was identified for the study. A one-dimensional heat transfer analysis was conducted on a reference case. Based on the parameters of this reference case, it was determined that for a thermal energy requirement of 10% total reactor thermal power, 256 pipes with a 44.6 m pipe length would be needed for hydrogen production based on the Cu-Cl cycle. It was also determined that decreasing the pressure on the cold side would decrease the overall size of the HX.

6. References

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