HEAT-TRANSFER ANALYSIS OF SCW TO SCW DOUBLE-PIPE HEAT EXCHANGER FOR INDIRECT-CYCLE SCW NPPS

H. Thind, S. Gupta, I. Pioro, and G. Harvel
Faculty of Energy Systems and Nuclear Science
University of Ontario Institute of Technology
2000 Simcoe St. North, Oshawa, Ontario, L1H 7K4 Canada
harwinder.thind@uoit.ca; sahil.uoit@gmail.com; igor.pioro@uoit.ca; glenn.harvel@uoit.ca

Abstract

This paper presents the heat transfer analysis of an intermediate Heat eXchanger (HX) design for indirect-cycle concepts of Pressure-Tube (PT) and Pressure-Vessel (PV) SuperCritical Water-cooled Reactors (SCWRs). Thermodynamic configurations with an intermediate HX give a possibility to have a single-reheat option for PT and PV SCWRs without introducing steam-reheat channels into a reactor. Similar to the current CANDU and Pressurized Water Reactor (PWR) Nuclear Power Plants (NPPs), steam generators separate the primary loop from the secondary loop. In this way, the primary loop can be completely enclosed in a reactor containment building.

This paper analyzes the heat transfer from a SuperCritical Water (SCW) reactor loop to SCW turbine loop using double-pipe intermediate HX. The numerical model is developed with MATLAB and NIST REFPROP software. Pipes wall thickness of the HX are sized for the design pressure with a safety factor of +25% on operating pressure and divided into several nodes for the analysis. Water from the primary (reactor) loop flows throw the inner pipe, and water from the secondary (turbine) loop flows through the annulus in counter direction of the double-pipe HX. The analysis on the double-pipe HX shows temperature and thermophysical properties profiles along the heated length of the HX.

It was found that the pseudocritical region has a significant effect on the temperature profiles and heat-transfer area of the HX. An analysis shows the effect of variation in pressure, pipe size, and temperatures on pseudocritical region and heat-transfer area of the HX. The results from the numerical model can be used to optimize the heat-transfer area of the HX. The higher pressure difference on the hot side and higher temperature difference between the hot and cold sides reduces the pseudocritical-region duration. This decreases the heat-transfer surface area of the HX.

1. Introduction

At present, research activities are conducted around the world to develop Generation-IV nuclear reactors concepts, and a SuperCritical Water-cooled nuclear Reactor (SCWR) is one of them. Existing nuclear-reactor designs, which are denoted as Generation-II and -III reactors, provide a reliable, economical and publicly acceptable supply of electricity in existing markets. However, further advances in nuclear-power industry require systems with higher efficiency and low-cost electrical energy. The thermal efficiency of existing Nuclear Power Plants (NPPs) is not very high just about 30-35%; whereas the thermal efficiency of thermal power plants reached a level of 45-55%.

SuperCritical Water (SCW) NPPs will have much higher operating parameters compared to those of current NPPs (i.e., pressures of about 25 MPa and outlet temperatures up to 625°C) (see Figure 1). Due to higher operating temperatures, SCWRs can facilitate an economical co-generation of hydrogen through thermochemical cycles [1].

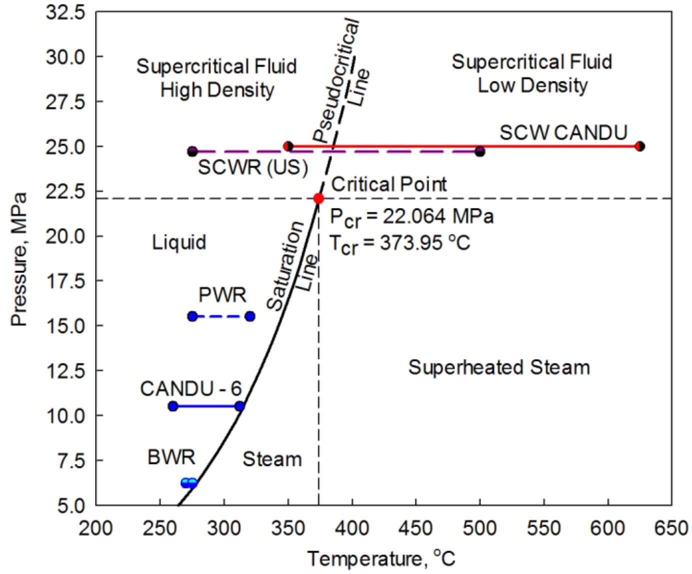


Figure 1: Pressure-Temperature diagram of water for typical operating conditions of SCWRs, PWRs, CANDU-6 reactors and BWRs.

The SCWR concepts follow two main types [2]: (a) A large reactor Pressure-Vessel (PV) with a wall thickness of about 0.5 m to contain the reactor-core heat source, analogous to conventional Light Water Reactors (LWRs); or (b) Pressure-Tubes (PTs) or fuel channels analogous to conventional Heavy Water Reactors (HWRs). Within these two main classes (PV and PT), PT reactors are more flexible with respect to flow, flux and density changes than the PV reactors. Also as compared to PV reactors, the PT reactor design gives the flexibility of accommodating a single-reheat option, which will include the addition of nuclear steam reheat to the reactor. However, the addition of the steam-reheat option will increase the complexity of the reactor-core design.

Note that single-steam-reheat cycles are widely used in both supercritical and subcritical steam cycles in fossil-fueled power plants as an economical way to improve cycle efficiency. As a side benefit, it reduces the steam flow required for a given power output (and hence, reduces equipment size), and moreover, it reduces the steam moisture content in the Low-Pressure (LP) turbine(s) and eliminates the need for moisture-removal equipment [3]. Also the vast majority of the modern and upcoming supercritical turbines are single-reheat-cycle turbines. Due to the maturity and high efficiency of a single-reheat steam cycle in modern thermal power plants, the option of using similar technology in SCWR appears to be quite practical. Also, other thermodynamic cycles such as dual and indirect cycles are being evaluated for SCW NPPs to help optimize these concepts on a basis of increased safety, economics, and efficiency.

In direct-cycle SCWR concept the supercritical "steam" is fed directly into the turbines. This option is the simplest approach from the thermodynamic point of view to reach higher thermal efficiency and lower capital costs. This approach is also used in current Boiling Water Reactor (BWR) NPPs. However, the safety can be compromised.

In general, both the dual and indirect cycles provide increased safety in terms of an extra barrier between the reactor primary coolant, which may contain a certain level of radioactivity, and clean NPP equipment such as the turbines, feedwater heaters, circulation pumps, etc., but have slightly lower thermal efficiency compared to that of the direct cycle. In addition, the primary coolant may contain unwanted substances, which will deposit on turbine blades and other equipment. Therefore, in the current paper an intermediate SCW Heat eXchanger (HX) is investigated in support of indirect cycles, as it allows using the single-reheat option in both PV and PT reactors. Also, it will reduce further complexity of the reactor-core design in case of implementing nuclear steam reheat.

As SCW NPPs will have much higher operating parameters, it is necessary to analyze technical challenges and higher costs associated with SCW HXs, for example, a material to be used for the HX, hydraulic resistance, heat-transfer-surface area, size of the HX and number of units required. The higher cost and larger size of the HX might make it impractical to implement the indirect cycle in SCW NPPs. It is important to determine if added safety and advantages of the indirect cycle outweigh the cost and implications attached to it.

2. SCWR NPP Layouts – Indirect Cycles

There are four different indirect layouts studied for SCWR reactors in this paper.

2.1 Indirect single-reheat cycle for PT and PV reactors

A SCW NPP indirect single-reheat-cycle arrangement is shown in Figure 2. The SCW from the reactor at a pressure of 25 MPa and temperature of 625°C transfers the heat through a heat exchanger (HX1) to the secondary loop. The supercritical "steam" from the secondary loop is expanded inside a single-flow High-Pressure (HP) turbine from the supercritical pressure of 25 MPa and temperature 550°C (Point 3) to an intermediate pressure of 4.9 MPa and temperature of 330°C (Point 4). The subcritical steam from the HP turbine is sent to the second heat exchanger (HX2), where the SCW from the reactor at a pressure of 25 MPa and a temperature of 625°C raises the steam temperature in the secondary loop to superheated conditions.

Then Super-Heated Steam (SHS) at a subcritical pressure of 4.5 MPa and temperature 550°C (Point 5) is expanded in the Intermediate-Pressure (IP) turbine and transferred through a cross-over pipe and expanded in the LP turbine to a pressure of 6.77 kPa and temperature of 38.4°C (Point 6).

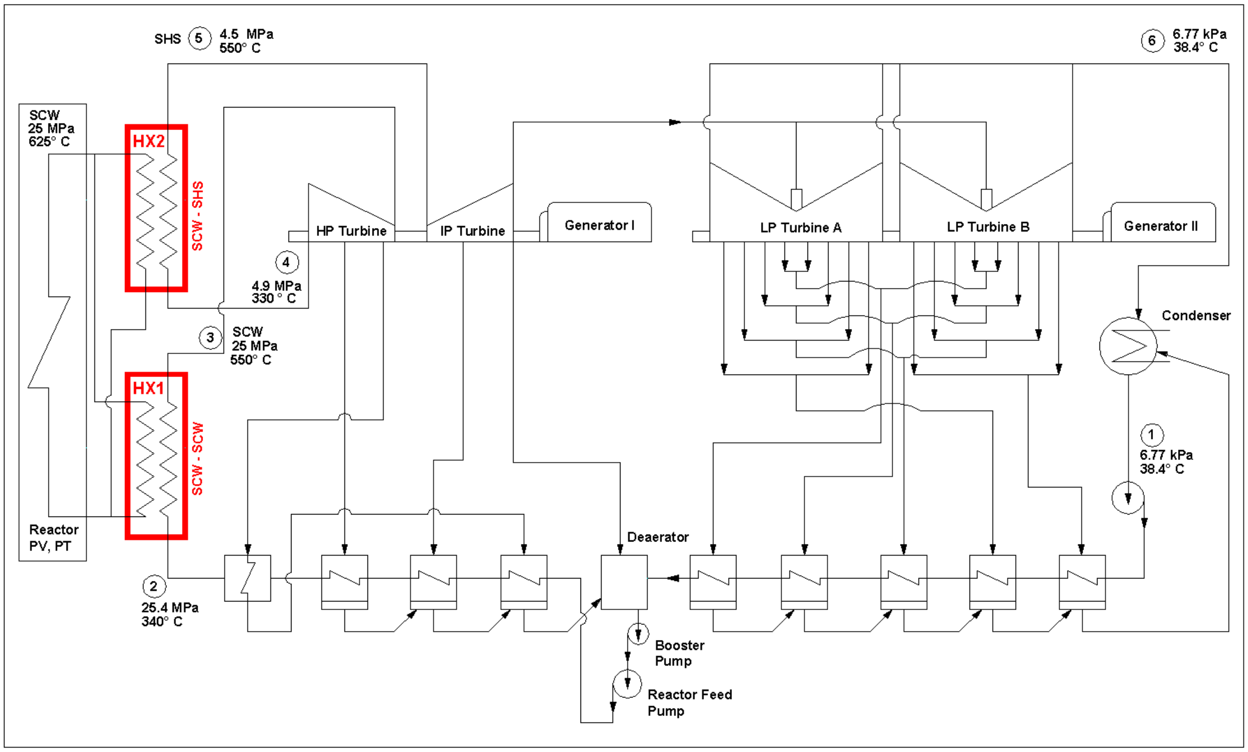


Figure 2: SCWR NPP indirect single-reheat cycle for PT and PV reactors.

2.2 Indirect single-reheat cycle for PT reactors

A SCW NPP indirect single-reheat cycle for PT reactors is shown in Figure 3. This arrangement is possible in PT reactors only, due to flexibility of the PT design to accommodate SCW and SHS cycles in reactor core design simultaneously. The SCW from the reactor at a pressure of 25 MPa and temperature of 625°C transfers the heat through a heat exchanger (HX1) to the secondary loop. The supercritical "steam" from the secondary loop is expanded inside a single-flow HP turbine from the supercritical pressure of 25 MPa and temperature 550°C (Point 3) to an intermediate pressure of 4.9 MPa and temperature of 330°C (Point 4). The subcritical steam from the HP turbine is sent to the second heat exchanger (HX2), where SHS from the reactor at a pressure of 6.3 MPa and a temperature of 625°C raises the steam temperature in the secondary loop to superheated conditions through HX2. Then the SHS at a subcritical pressure of 4.5 MPa and temperature 550^{o}C (Point 5) is expanded in the IP turbine and transferred through a cross-over pipe and expanded in the LP turbine to a pressure of 6.77 kPa and temperature of 38.4°C (Point 6).

2.3 No-reheat indirect cycle for PT and PV reactors

A SCWR NPP no-reheat indirect cycle arrangement for PT and PV reactors is shown in Figure 4. In this arrangement the SCW from a reactor at a pressure of 25 MPa and temperature of 625°C transfers the heat through a heat exchanger (HX1) to the secondary loop. The supercritical "steam" from the secondary loop is expanded inside an HP turbine from the supercritical pressure of 25 MPa and temperature 550°C (Point 3) to an intermediate pressure of 4.9 MPa and temperature of 330°C (Point 4). The subcritical steam from the HP turbine is transferred through a cross-over pipe and expanded in the IP/LP turbines to a pressure of 6.77 kPa and temperature of 38.4°C (Point 5).

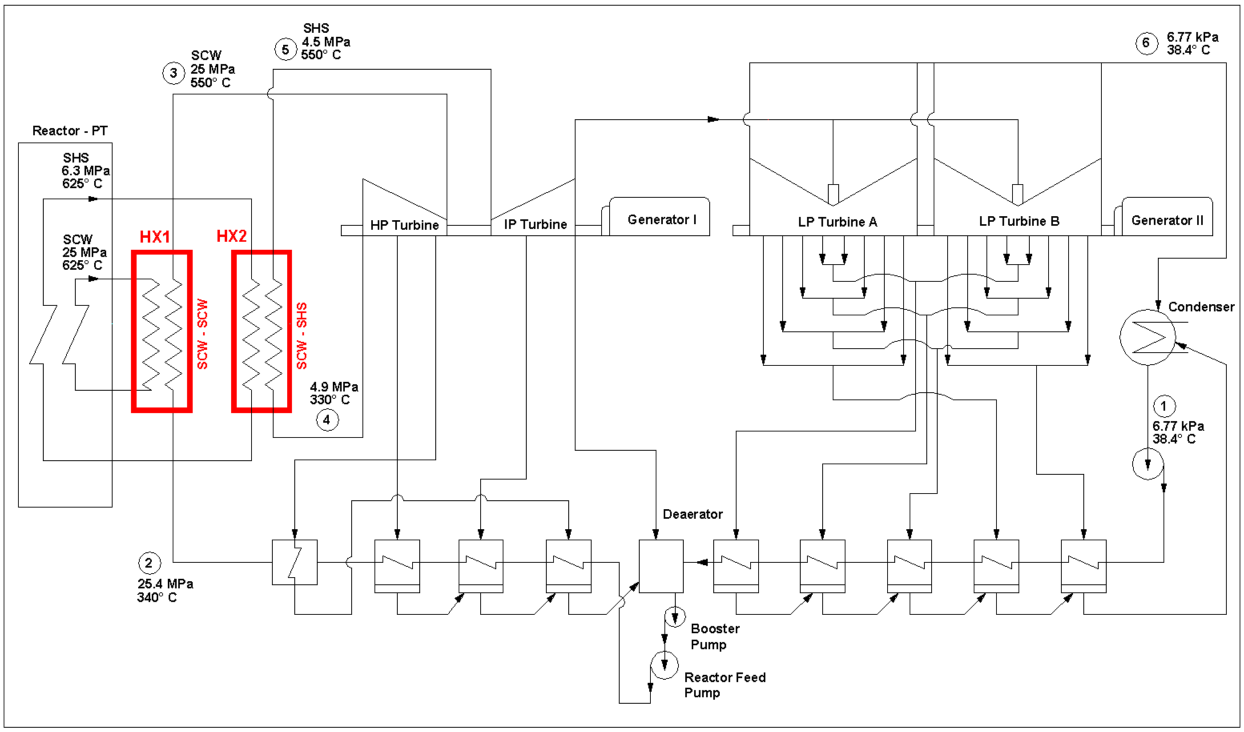


Figure 3: SCW NPP indirect single-reheat cycle for PT reactor.

2.4 Indirect dual cycle for PT and PV reactors

SCWR NPP indirect dual-cycle arrangement for PT and PV reactors is shown in Figure 5. The SCW from the reactor at a pressure of 25 MPa and temperature of 625°C transfers the heat through a heat exchanger (HX1) to the secondary loop. The supercritical "steam" from the secondary loop is split into two flows: the first portion is expanded inside a single-flow HP turbine from the supercritical pressure of 25 MPa and temperature 550°C (Point 3) to an intermediate pressure of 4.9 MPa and temperature of 275°C (Point 4). The second portion of the supercritical "steam" (Point 3) from the heat exchanger (HX1) at the pressure of 25 MPa and temperature of 550°C goes to the second heat exchanger (HX2), where it raises the subcritical steam temperature (Point 5) to 500°C at a pressure of 4.5 MPa (Point 6). Then SHS at a subcritical pressure of 4.5 MPa and temperature of 500°C (Point 6) is expanded in the IP turbine and transferred through a cross-over pipe and expanded in the LP turbine to a pressure of 6.77 kPa and temperature of 38.4°C (Point 7).

As such, an intermediate heat exchanger is useful for several different SCW-based thermodynamic configurations. A double-pipe configuration heat exchanger is simulated for a reference set of conditions that will be useful for each concept proposed.

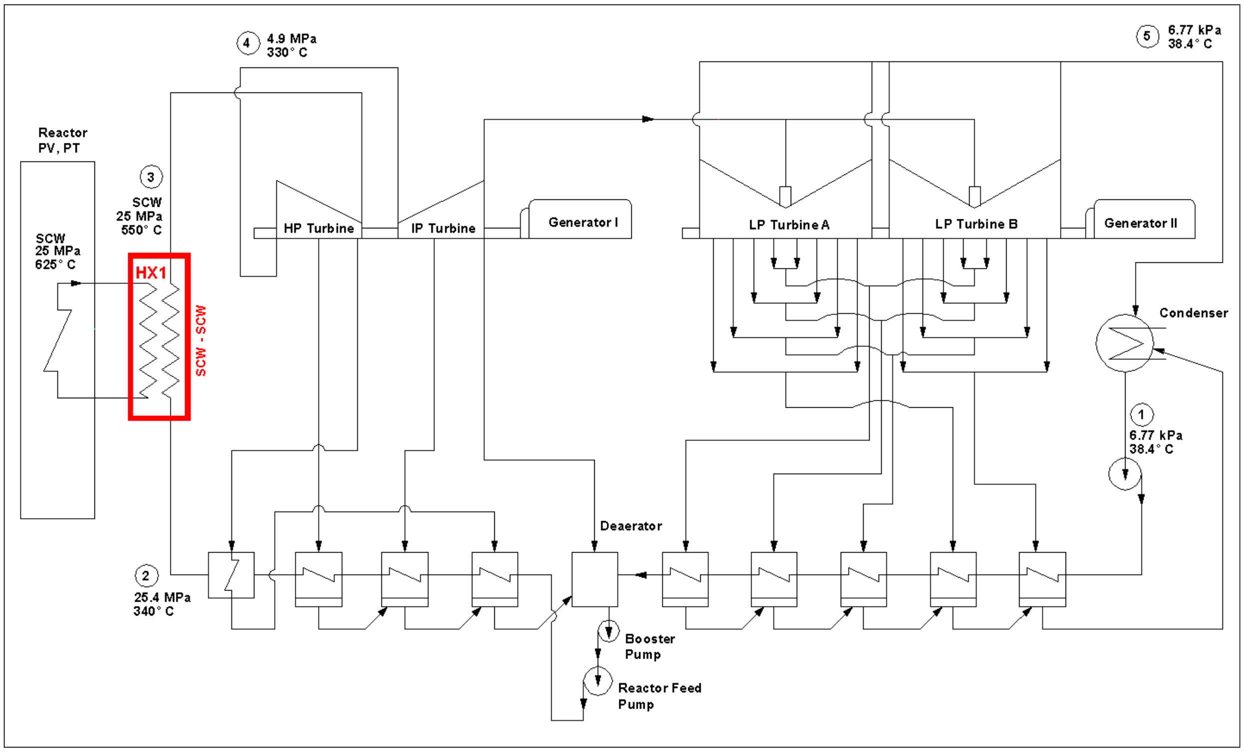


Figure 4: SCW NPP indirect cycle for PT and PV reactors.

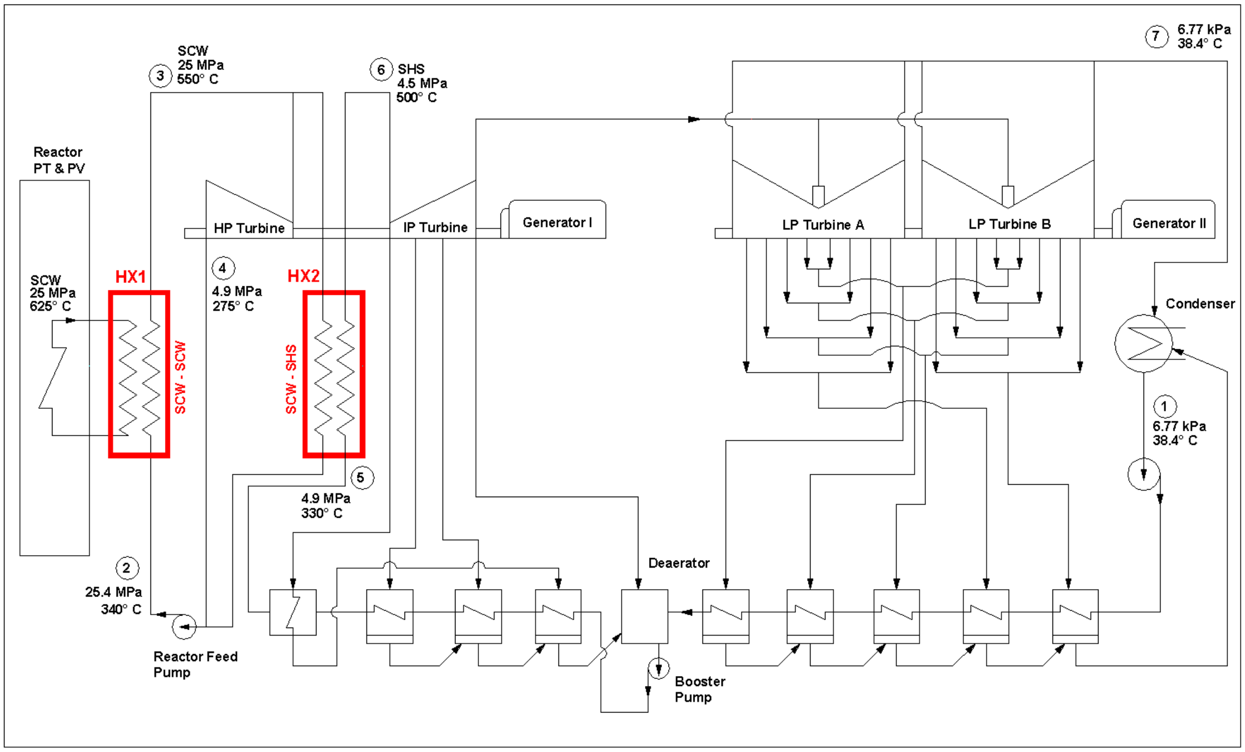
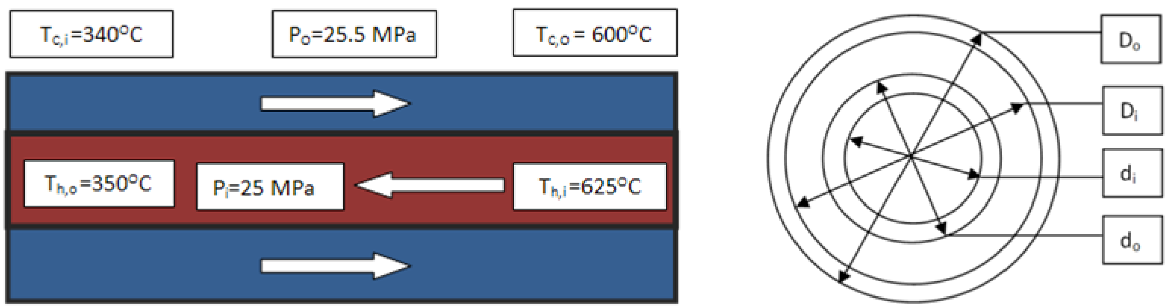


Figure 5: SCW NPP indirect duel cycle for PT and PV reactors.

3. Major Parameters of Primary and Secondary Loops

The reference case studied is for SCW in the primary loop at a pressure 25 MPa entering the HX at 625°C and exit at 350°C. The pressure on the secondary side is 25.5 MPa. On the secondary side the SCW with counter flow enters into the HX at 340°C in the annulus pipe and exits at 600°C. Mass-flow rates on both primary and secondary sides are assumed to be the same at 1320 kg/s. Figure 6a,b shows a schematic of flow and a cross-section of the double-pipe HX, respectively.



(a) (b)

Figure 6: Hot- and cold-side arrangements of double-pipe heat exchanger: (a) Schematic of flow, and (b) Cross-section of channel.

4. Heat-Transfer Model for Double-Pipe Heat Exchanger

The numerical model is developed in MATLAB, and thermophysical properties of water used in calculations were obtained from the NIST REFPROP software [5]. A generic PT SCWR was used with a thermal power of 2500 MW [1]. A pipe-wall thickness is calculated for a design pressure with a safety factor of +25% on the operating pressure. The design pressure resulted in the minimum wall thickness of ~4 mm to be included in the heat-conduction analysis.

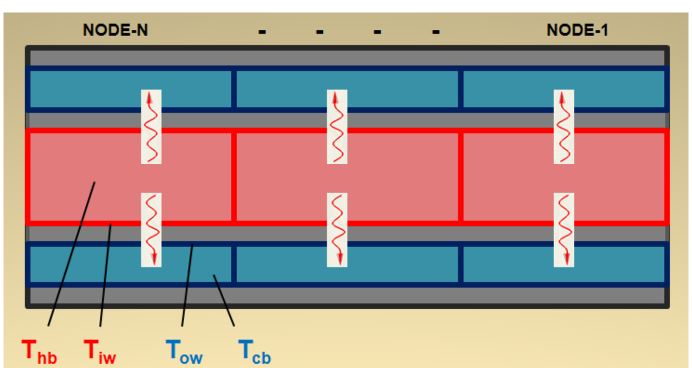


Figure 7: Node diagram of double-pipe heat exchanger.

The length of the HX pipe is divided into 1000 equal nodes. The node layout of the HX is shown in Figure 7. As the inlet temperature and pressure of the hot side are known, the enthalpy of the next node can be obtained using the following equation:

$$H_i = H_{i-1} + \frac{Q}{\dot{m}} \quad (1)$$

The Swenson et al. (1965) [6] correlation is used in the code. This correlation was chosen, because it is valid within the required operating conditions and has a better accuracy when compared with that of Harrison et al. (1976) [7] and Lee et al. (1974) [8] experimental data [9].

$$\mathbf{Nu_w} = 0.00459\ \mathbf{Re_w^{0.923}}\overline{\mathbf{Pr}}_\mathbf{w}^{\mathbf{0.613}} \left(\frac{\rho_w}{\rho_b}\right)^{0.231} \quad (2)$$

The heat transfer coefficient for the hot side is calculated using the following equation:

$$HTC = \frac{Nu_w.k}{d_i} \quad (3)$$

The heat transfer coefficient for the cold side is calculated as

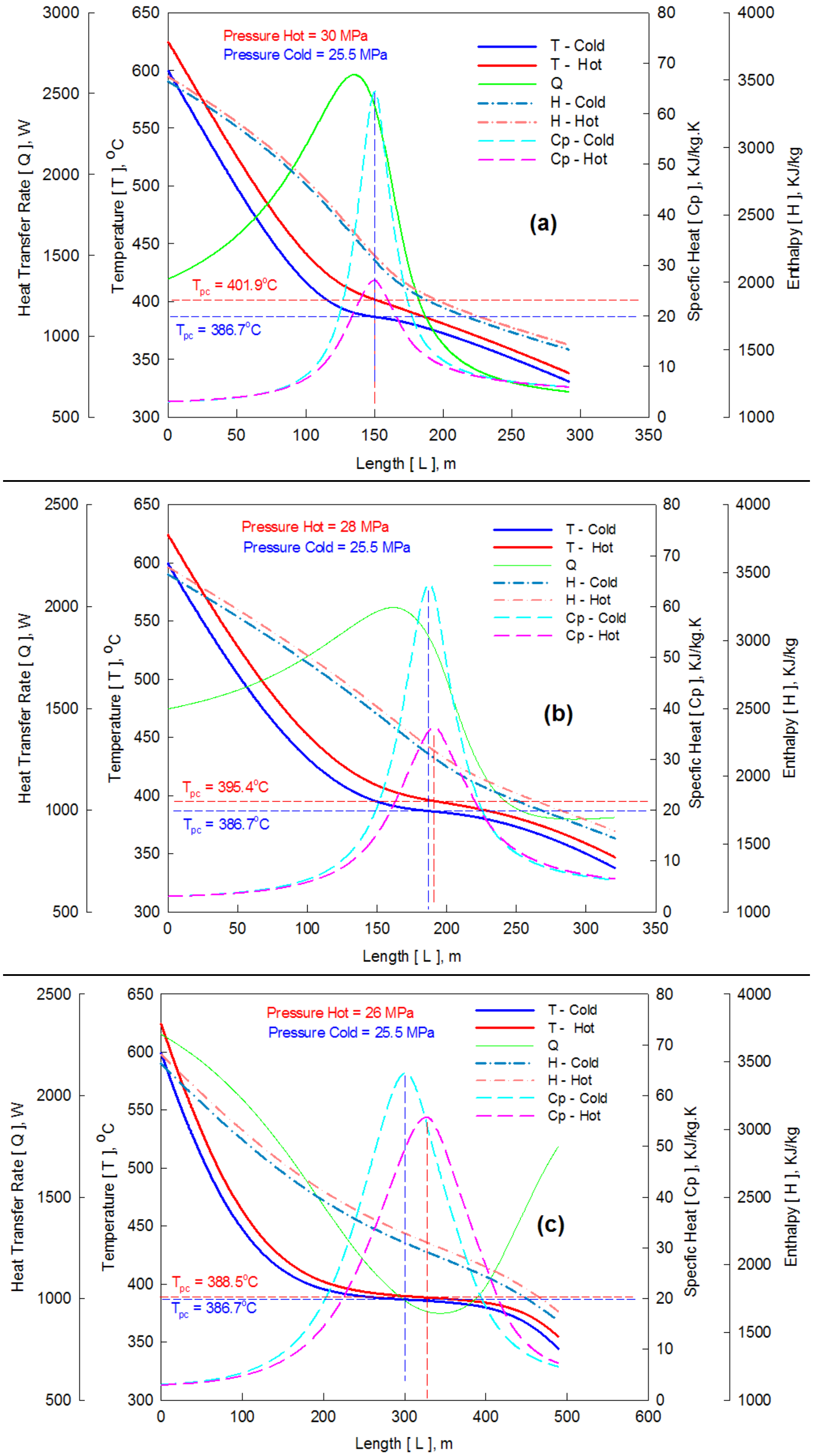
$$HTC = \frac{Nu_w.k}{d_{ht}} \quad (4)$$

The total thermal resistance for heat transfer is calculated, and then the total heat loss for each node can be calculated using the following equation [10]:

$$Q = \frac{T_{hb} - T_{cb}}{R_{total}} \quad (5)$$

5. Analysis and Discussion

Heat-transfer analysis was performed to determine the effect on the heat-transfer-surface area of the HX against various parameteres, i.e., pressure, pipe size, and temperature. Figure 8a-d shows a temperature profile and variations in fluid properties of the hot and cold sides along the length of the double-pipe HX for a variation in the primary-side pressure. The results show that the heat transfer is enhanced or deteriorated due to the change in fluid properties depending on the exact fluid conditions. The heat transfer in the pseudocritical region decreases significantly or is negligible depending on the pressure difference between the hot and cold fluid sides. In Figure 8d, the heat transfer in the pseudocritical range is almost null starting at approximately 300-m length and continuous up to roughly 575 m along the length of HX. After 575 m heat transfer starts again from the hot to cold sides at a very low rate. In Figure 8a when the pressure on the hot side is much higher (30 MPa) than that in the cold side (it is 25.5 MPa), the pseudocritical region is much smaller due to the higher specific heat difference between hot and cold sides in this region. As there is a shorter pseudocritical region in Figure 8a the heat-transfer rate has a much sharper relationship as compared to that in Figure 8b-d. Where as in Figure 8d the value of specific heat on the hot and cold sides is almost the same, which leads to a longer pseudocritical range. In this region the most of the heat is used up due to a higher specific heat capacity of the fluid, resulting in no temperature change between the hot and cold sides.


Pressure Hot = 30 MPa
Pressure Cold = 25.5 MPa
T - Cold
T - Hot
Q
H - Cold
H - Hot
Cp - Cold
Cp - Hot
(a)
T_pc = 401.9°C
T_pc = 386.7°C
Heat Transfer Rate [Q], W
Temperature [T], °C
Specfic Heat [Cp], KJ/kg.K
Enthalpy [H], KJ/kg
Length [L], m
Pressure Hot = 28 MPa
Pressure Cold = 25.5 MPa
(b)
T_pc = 395.4°C
T_pc = 386.7°C
Pressure Hot = 26 MPa
Pressure Cold = 25.5 MPa
(c)
T_pc = 388.5°C
T_pc = 386.7°C

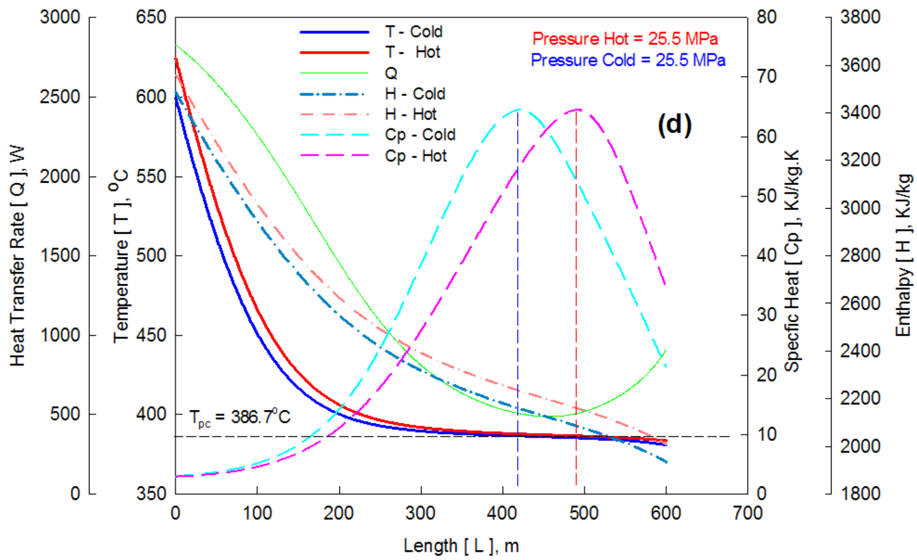


Figure 8: Effect of pressure temperature profile and fluid properties along length of double-pipe HX: P_{hot} = (a) 30 MPa, (b) 28 MPa, (c) 26 MPa, and (d) 25.5 MPa.

Figure 9 shows the effect of change in primary-side pressure. The heat-transfer-surface area decreases almost by ~35% with a pressure increase from 26 to 30 MPa. Thermophysical properties of water go through a significant change within the pseudocritical region. Figure 10 shows the variation of Nusset, Reynolds and average Prandtl numbers for the hot (inner pipe) and cold (annulus pipe) sides along the length. The Nusset number and average Prandtl number peak in the pseudocritical region. These sudden changes in thermophysical properties are affecting the heat transfer.

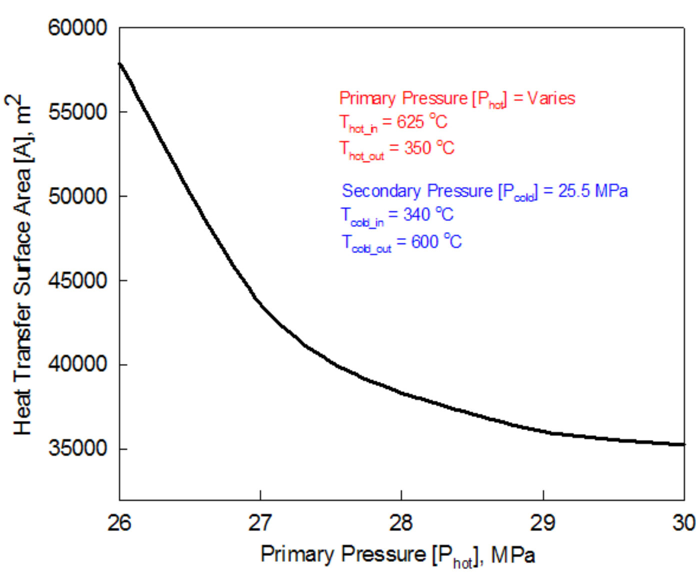


Figure 9: Effect of primary pressure on heat-transfer-surface area of HX.

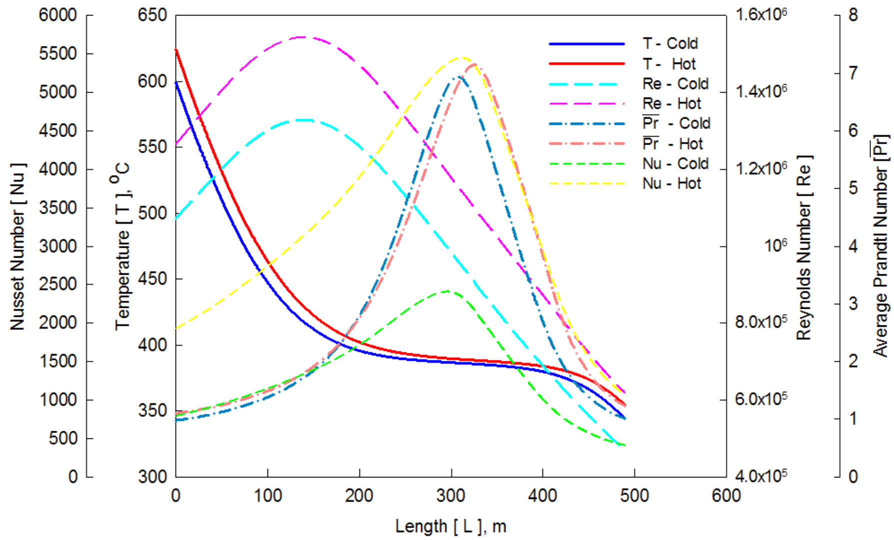


Figure 10: Variation of Nusset, Reynolds and Average Prandtl numbers.

Figure 11 shows the effect of the inner-pipe diameter change on the heat-transfer-surface area and pumping power required for the inner and annulus pipes of the double-pipe HX. The heat-transfer-surface area increases linearly with the increase of the inner-pipe diameter. The pumping power shows the similar effect as heat-transfer-surface area with the increase of inner-pipe diameter except between 20 to 30 mm range, where it show a modest drop. It appears the decrease is at an optimized value at 26 mm (approximately 1" pipe diameter). Figure 12 shows the variation in the heat-transfer-surface area with the change in the outlet temperature of the HX on the secondary side. The heat-transfer-surface area almost decreases by ~40% with secondary-side outlet-temperature changes from 600 to 550°C.

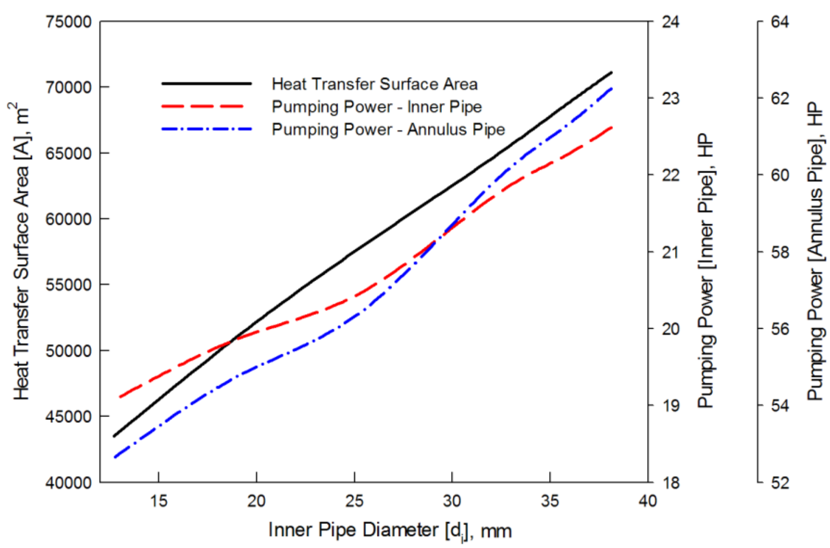


Figure 11: Effect of inner pipe diameter on heat-transfer-surface area and pumping power required for double-pipe HX.

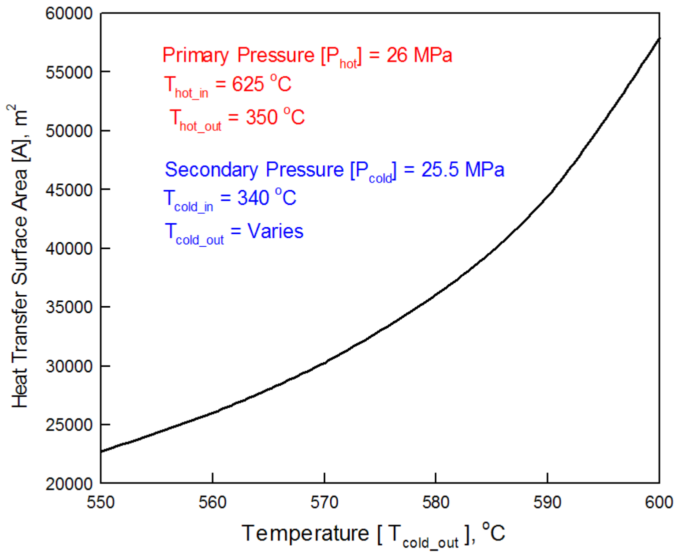


Figure 12: Effect of cold outlet temperature on heat-transfer-surface area.

6. Concluding Remarks

Various indirect-cycle thermodynamic configurations are proposed for PT and PV reactors to keep the nuclear activities within the reactor-containment building and to reduce probability for radioactive contamination of equipment in the turbine building, thus reducing the chances of human interaction with radioactive materials.

A double-pipe HX can be used to operate the indirect-cycle configuration.

The change in thermophysical properties of water within the pseudocritical region has significant effect on the required heat-transfer-surface area of HX.

The higher pressure difference between the hot and cold sides reduces significantly a length of the pseudocritical region, thus decreasing the heat-transfer-surface area of the HX. Although it looks obvious to increase the pressure on the primary (reactor) side to reduce the heat-transfer-surface area of the HX, it might add complexity to the reactor core design.

Heat-transfer-surface area can be reduced significantly by optimizing temperature difference between the primary and secondary sides.

7. Acknowledgements

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8. Nomenclature

A	area, m^2
c_p	specific heat, J/kg K
$\bar{c}_p$	average specific heat, J/kg K $\left(\frac{H_w - H_b}{T_w - T_b}\right)$
D	outside-tube diameter, m
d	inside-tube diameter, m
G	mass flux, kg/m^2.s
h	heat transfer coefficient, W/m^2 K
H	enthalpy, J/kg
k	thermal conductivity, W/m K
L	length, m
$\dot{m}$	mass flow rate, kg/s
P	pressure, MPa
T	temperature, ^{o}C
Q	heat-transfer rate, W

Greek letters

ρ	density, kg/m^3
μ	viscosity, Pa·s

Dimensionless numbers

Nu	Nusselt number $\left(\frac{h \cdot D}{k}\right)$
Pr	Prandtl number $\left(\frac{\mu \cdot c_p}{k}\right)$
$\overline{\textbf{Pr}}$	average Prandtl number $\left(\frac{\mu \cdot \bar{c}_p}{k}\right)$
Re	Reynolds number $\left(\frac{G \cdot D}{\mu}\right)$

Subscripts

b	bulk
c	cold
cr	critical
h	hot
ht	heated
i	inside
o	outside
pc	pseudocritical
w	wall

Acronyms:

AECL	Atomic Energy of Canada Limited
BWR	Boiling Water Reactor
CANDU	CANada Deuterium Uranium (reactor)
HP	High Pressure (turbine)
HTC	Heat Transfer Coefficient
HWR	Heavy Water Reactor
HX	Heat eXchanger
IP	Intermediate Pressure (turbine)
LP	Low Pressure (turbine)
LWR	Light Water Reactors
NPP	Nuclear Power Plant
PT	Pressure-Tube (reactor)
PV	Pressure-Vessel (reactor)
PWR	Pressurized Water Reactor
SC	SuperCritical
SCW	SuperCritical Water
SCWR	SuperCritical Water Reactor
SG	Steam Generator
SHS	Super Heated Steam
UOIT	University of Ontario Institute of Technology
US	United States

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