HEAT-LOSS CALCULATIONS FOR PRESSURE-CHANNEL SCWRS

W. Peiman[1], K. Gabriel[2] and I. Pioro[1]
[1]Faculty of Energy Systems and Nuclear Science
[2]Faculty of Engineering and Applied Science
University of Ontario Institute of Technology (UOIT)
2000 Simcoe St. N., Oshawa ON L1H 7K4 Canada
wargha.peiman@gmail.com, Kamiel.Gabriel@uoit.ca, Igor.Pioro@uoit.ca

Abstract

This paper focuses on two fuel channel options for SuperCritical Water-cooled Reactors (SCWRs). One fuel channel design utilizes a ceramic insulator while another uses a gaseous insulator— similar to the CANDU-6 fuel channel design. The objective of this paper is to estimate heat losses from the coolant to the moderator from these two fuel channel designs at SuperCritical Water (SCW) and Steam-Re-Heat (SRH) conditions. In order to fulfill the objective, MATLAB and NIST REFPROP software were utilized for programming and calculation of thermophysical properties as needed, respectively.

Steady-state one-dimensional heat transfer analysis was conducted to calculate heat losses from the fuel channels to a liquid moderator. The convective heat loss of the ceramic-insulated fuel channel and convective and radiative heat losses of the CANDU-6-type fuel channel were calculated. The total heat losses from the ceramic-insulated and CANDU-6 type fuel channel were approximately 105 and 30 kW per fuel channel at SCW conditions. The corresponding total heat losses per fuel channel at SRH conditions were approximately 112 and 43 kW, respectively.

1. Introduction

Currently, six reactor concepts have been selected to be studied under the Generation-IV nuclear reactors program, one of which is an SCWR concept. In general, SCW Nuclear Power Plants (NPPs) will operate at higher efficiencies of about 45 − 48%, which are comparable to those of modern SCW coal-fired power plants [1]. Additionally, high coolant outlet temperatures will allow for a co-generation of hydrogen, which can be achieved through thermo-chemical cycles or through high-temperature electrolysis.

A pressure boundary of a SCWR can be classified into two categories: (a) Pressure Vessel (PV), and (b) distributed Pressure Channels (PChs) or Pressure Tubes (PTs). Canada and Russia are the main developers of the latter design. In general, PT reactors are more suitable for SCW than PV reactors, because of a better control of the flow and density variations. Significant variations in the coolant density pose a challenge to the SCWR design especially for PV reactors. In PT

SCWRs, the coolant flow in two adjacent fuel channels is bi-directionally interlaced, which significantly enhances the uniformity of the coolant density within the reactor core [2].

Several fuel channel designs are available for SCWRs including the ceramic-insulated, gaseous insulated (CANDU-6 type), and re-entrant options, which in general, were proposed by Atomic Energy of Canada Limited (AECL) [1−3]. The ceramic-insulated fuel channel design utilizes a ceramic insulator. The heat loss from the coolant to the liquid moderator from this fuel channel is approximately 104 kW. A CANDU-6 fuel channel consists of a PT, a Calandria Tube (CT), and a gap in between them. The gap is filled with a gas, which significantly reduces the heat losses from a fuel channel to the moderator. However, this fuel channel design needs to be modified based on the operating conditions of SCWRs.

One of the best layouts of SCW NPPs is a single-reheat cycle. In this option, the reactor core consists of 220 SCW and 80 SRH fuel channels. The efficiency of the plant is demonstrated to be approximately 52% [4]. This paper presents the calculated heat losses of the ceramic-insulated and CANDU-6-type fuel channel designs at SCW and SRH conditions.

2. Heat loss from a CANDU-6 type fuel channel

In general, one of the advantages of the CANDU-6 fuel channel is that the heat loss from the coolant to the moderator is quite low, approximately 5% of the total heat generated inside the moderator [5, 6]. The small amount of heat loss is due to effective use of gaseous insulator. The heat losses from the coolant to the moderator are calculated in Sections 2.2 and 2.3. Table 1 shows operating parameters of a generic PCh-SCWR, which were used for the heat loss analysis.

Table 1: Operating Parameters of Generic PCh-SCWR [4].

Parameter	Unit	SCWR	
Electric Power	MW	1220	
Thermal Power	MW	2540	
Thermal Efficiency	%	52%	
Coolant	-	H_2O	
Moderator	-	D_2O	
Pressure of SCW at Inlet/Outlet	MPa	25.8	25
Pressure of SHS at Inlet/Outlet	MPa	6.1	5.7
T_{in} / T_{out} Coolant (SCW)	°C	350	625
T_{in} / T_{out} Coolant (SHS)	°C	400	625
Mass Flow Rate per SCW/SRH Channel	kg/s	4.37	10
Thermal Power per SCW/SRH Channel	MW	8.5	5.5
# of SCW/SRH Channels	-	220	80
Heat Flux in SCW/SRH Channel	kW/m^2	970	628
Fuel Bundle		Variant-18*	

*42 elements with an OD of 11.5 mm and one element with an OD of 18 mm.

In the CANDU-SCWR core, there are 220 SCW fuel channels and 80 SRH fuel channels. In SCW fuel channels, the light-water coolant enters the fuel channel with an inlet temperature of 350℃ and leaves it with an outlet temperature of 625℃, at an operating pressure of approximately 25 MPa. In SRH fuel channels, Super-Heated Steam (SHS) enters the fuel channel at 400℃ and reaches an outlet temperature of 625℃, at an operating pressure of approximately 5.7 MPa.

2.1 Fuel channel description

As shown in Fig. 1, the fuel channel consists of a PT, CT, and a gap in between them, which is filled with a gas such as CO_2 [2, 7]. The thickness of the PT was calculated based on an operating pressure of 25 MPa, which is shown in Section 2.2.2. The thicknesses of the annulus gap and the CT were kept unchanged, same as those of the CANDU-6 fuel channel. In this paper, the fuel bundles are assumed to be of Variant-18 fuel bundle, which consists of 42 elements with an outer diameter of 11.5 mm and the central element with an outer diameter of 18 mm [8].

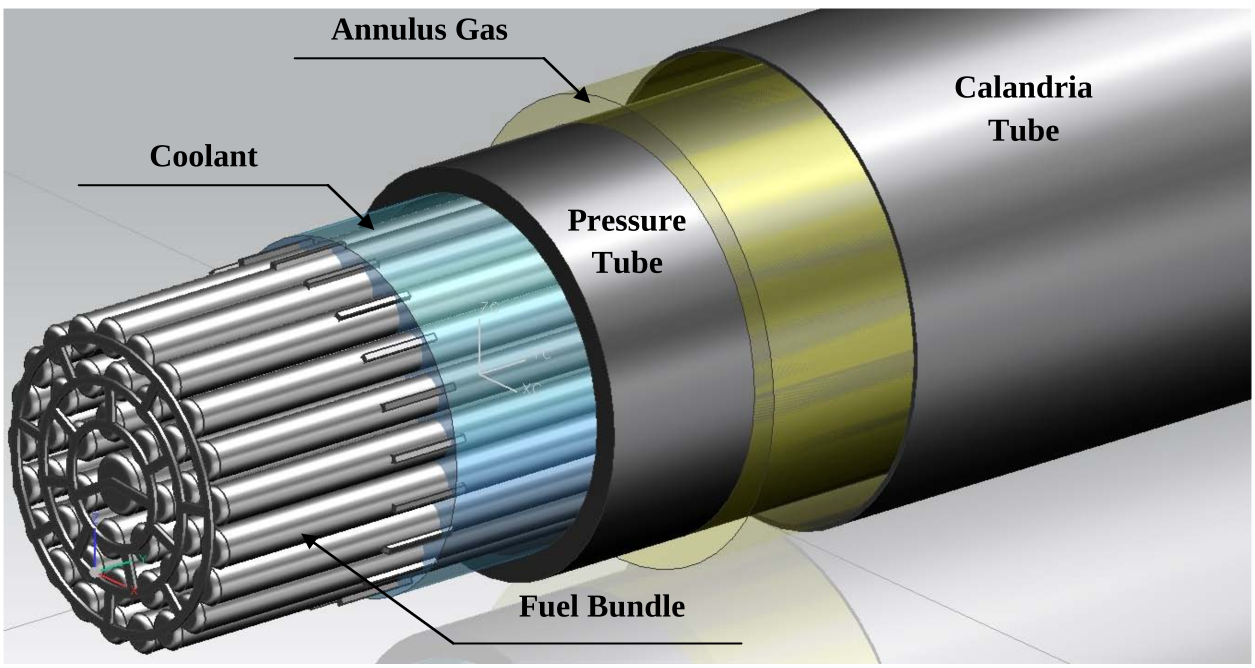

Figure 1: 3-D View of Modified CANDU-6 Fuel Channel for SCWRs [2, 7].

2.2 Convective heat loss

Equation (1) [9] was used to calculate the convective heat loss from the coolant to the moderator. Based on Eq. (1), a heat-loss analysis requires calculation of the thermal resistance network. As shown in Fig. 2, the thermal-resistance network consists of thermal resistances of the coolant, PT, annulus gas, CT, and the moderator, which are calculated in Sections 2.2.1 through 2.2.5.

$$Q = \frac{T_{coolant} - T_{moderator}}{R_{total}} \quad (1)$$

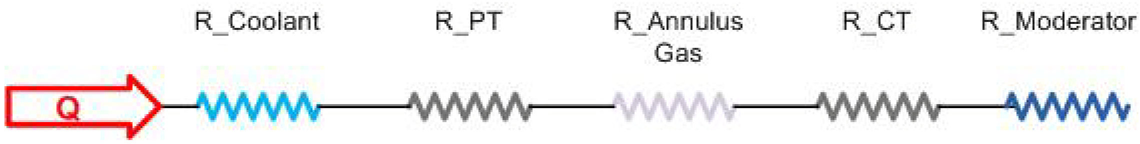

Figure 2: Thermal-Resistance Network.

2.2.1 Coolant thermal resistance

The thermal resistance of the coolant was calculated using Eq. (2), which required the calculation of the convective Heat Transfer Coefficient (HTC). Equation (3) [9] provides a relationship between the Nusselt number and that HTC. Recently, Mokry et al. [10] have proposed a correlation shown as Eq. (4) for calculation of the Nusselt number at SCW conditions. The experimental data, on which the correlation was developed, were obtained within conditions similar to those of proposed SCWR concepts. The experimental dataset was obtained in supercritical water flowing upward in a 4-m-long vertical bare tube. These data were collected at a pressure of approximately 24 MPa for several combinations of wall and bulk fluid temperatures, which were below, at, or above the pseudocritical temperature. The mass flux ranged from 200− 1500 kg/m^{2}s; coolant inlet temperature varied from 320℃ to 350℃ for heat flux up to 1250 kW/m^2 [10].

$$R_{conv} = \frac{1}{hA} \quad (2)$$

$$h = \frac{\mathbf{Nu}_D \cdot k}{D} \quad (3)$$

$$\mathbf{Nu}_x = 0.0061\, \mathbf{Re}_x^{0.904}\, \overline{\mathbf{Pr}}_x^{0.684} \left(\frac{\rho_w}{\rho_b}\right)_x^{0.564} \quad (4)$$

The Reynolds number in Eq. (4) was calculated using Eq. (5). In Eq. (5), D_{hy} is the hydraulic-equivalent diameter, which was calculated using Eq. (6). Equations (7) and (8) were used to calculate the average Prandtl number and average specific heat. Figure 3 shows the coolant and cladding temperatures and HTC profiles along the heated length of the fuel channel. Thermophysical properties were calculated using NIST REFPROP [11].

$$\mathbf{Re}_D = \frac{G\, D_{hy}}{\mu} \quad (5)$$

$$D_{hy} = \frac{4\, A_{fl}}{P} \quad (6)$$

$$\overline{\mathbf{Pr}} = \mu \cdot \bar{c}_p / k \quad (7)$$

$$\bar{c}_p = \frac{H_w - H_b}{T_w - T_b} \quad (8)$$

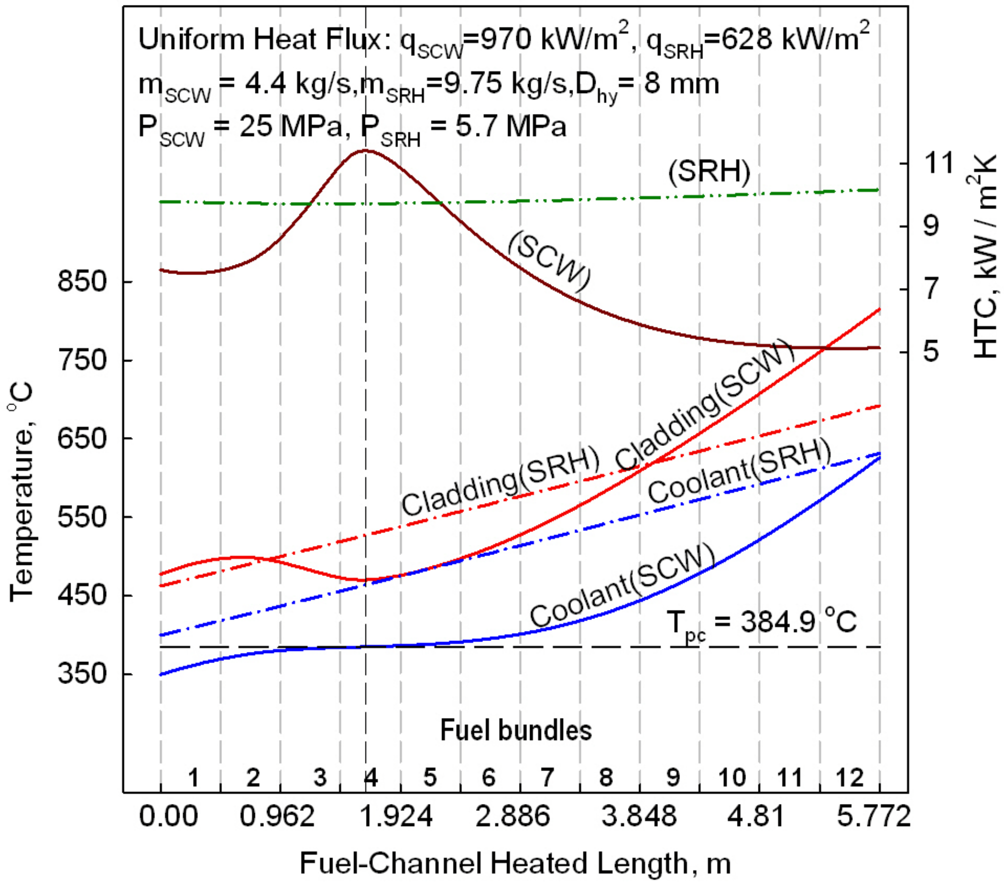

Figure 3: Coolant and Cladding Temperatures and HTC Profiles.

2.2.2 Pressure-tube thermal resistance

As mentioned in Section 2, the thickness of the PT was calculated using Eq. (9) [12] based on the operating conditions specified in Table 1. Since the maximum coolant temperature in normal operation is 625°C, Zr-2.5%Nb could not be selected as the material of choice. Inconel-718 was chosen as the PT material. In Eq. (9), *S* is the permissible design stress. In this case, the rupture strength of Inconel-718 at 760°C was used as the value of *S*, which is 195 MPa [13].

The thermal resistance of the PT was calculated using Eq. (10), which required calculation of the thermal conductivity of the PT [9]. The thermal conductivity was calculated using Eq. (11), where *T* indicates temperature in Kelvin [14]. The thermal resistance of the PT varies from 0.001 to 0.0007 K/W along the heated length of the fuel channel.

$$t = \frac{P \cdot D_o}{2 \cdot S} \tag{9}$$

$$R_{cond} = \frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi L k} \tag{10}$$

$$k = 11.45 + 1.156 \cdot 10^{-2} T + 7.72 \cdot 10^{-6} T^2 \tag{11}$$

2.2.3 Annulus-gas thermal resistance

The thermal resistance of the annulus gas is the determining factor in the overall heat loss from the coolant to the moderator. The thermal resistance of the annulus gas was calculated using Eq. (2). The flow rate of the annulus gas though the fuel channel is very low, which makes it possible to assume that the heat transfer in the annular gap is by natural convection. Therefore, the Nusselt number was calculated using a correlation shown as Eq. (15) [9]. The Rayleigh number and the characteristic length were calculated using Eqs. (16) and (17). Figure 4 shows the thermal resistance of the annulus gas, which varied from 0.33 to 0.28 K/W along the heated length of the fuel channel.

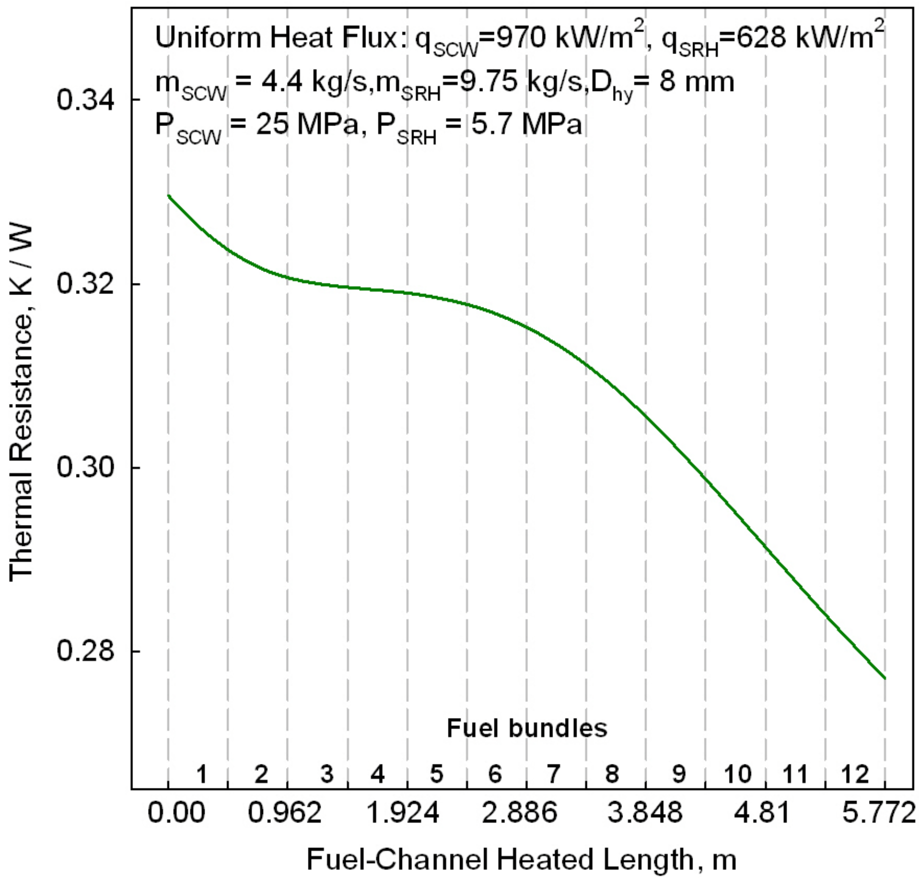

Figure 4: Thermal Resistance of Annulus Gas.

$$\mathbf{Nu} = 0.386\left(\frac{\mathbf{Pr}}{0.861+\mathbf{Pr}}\right)^{0.25}\mathbf{Ra}_c^{0.25} \tag{15}$$

$$\mathbf{Ra}_c = \frac{g\beta(T_i - T_o)L_c^3}{\nu\alpha} \tag{16}$$

$$L_c = \frac{2[\ln(r_o/r_i)]^{4/3}}{(r_i^{-3/5} + r_o^{-3/5})^{5/3}} \quad (17)$$

2.2.4 Calandria-tube thermal resistance

The material of the CT was assumed to be Zr-2, which is the same material as the CT of the CANDU-6 fuel channel. The thermal resistance of the CT was calculated using Eq. (10). The thermal conductivity of the Zr-2 was calculated based on Eq. (18), where T indicates temperature in Kelvin [15]. The thermal resistance of the CT was approximately 0.00024 K/W along the heated length of the fuel channel.

$$k = 12.767 - 5.4348 \cdot 10^{-4} T + 8.9818 \cdot 10^{-6} T^2 \quad (18)$$

2.2.5 Moderator thermal resistance

In order to calculate the thermal resistance of the moderator, a number of assumptions were made. First, the flow of the moderator inside a calandria vessel is natural convection. Second, the temperature of the moderator is kept constant, at approximately 80℃. Third, the pressure of the moderator is 0.2 MPa in order to avoid boiling inside the calandria vessel. These assumptions would simplify the complexity of the problem, and make it possible to solve the problem using available correlations/equations.

The Nusselt number was calculated using Eq. (19) in which the Rayleigh number was calculated using Eq. (16) [9]. This should be noted that the characteristic length in Eq. (16) was replaced with the outer diameter of the CT. The thermal resistance of the moderator was approximately 0.002 K/W along the heated length of the fuel channel.

$$\mathbf{Nu} = \{0.60 + \frac{0.386\mathbf{Ra}_D^{1/6}}{[1+(0.559/\mathbf{Pr})^{9/16}]^{8/27}}\}^2 \quad (19)$$

2.3 Radiative heat loss

Radiative heat loss from the PT to CT was calculated using Eq. (20), which required the emissivity of both surfaces [16]. The emissivity of the Inconel-718 and Zr-2, which are 0.875 and 0.8 in accordance to SCW operating temperatures [17, 18], respectively.

$$Q = \frac{A_1 \sigma (T_1^4 - T_2^4)}{\frac{1}{\epsilon_1} + \frac{1-\epsilon_2}{\epsilon_2}(\frac{r_1}{r_2})} \quad (20)$$

2.4 Results

The convective and radiative heat losses were calculated at SCW and SRH conditions. The total convective and radiative heat losses were 29.6 and 43.2 kW per fuel channel at SCW and SRH conditions, respectively. Figure 5 shows the convective and radiative heat-loss profiles along the heated length of the fuel channel at these conditions.

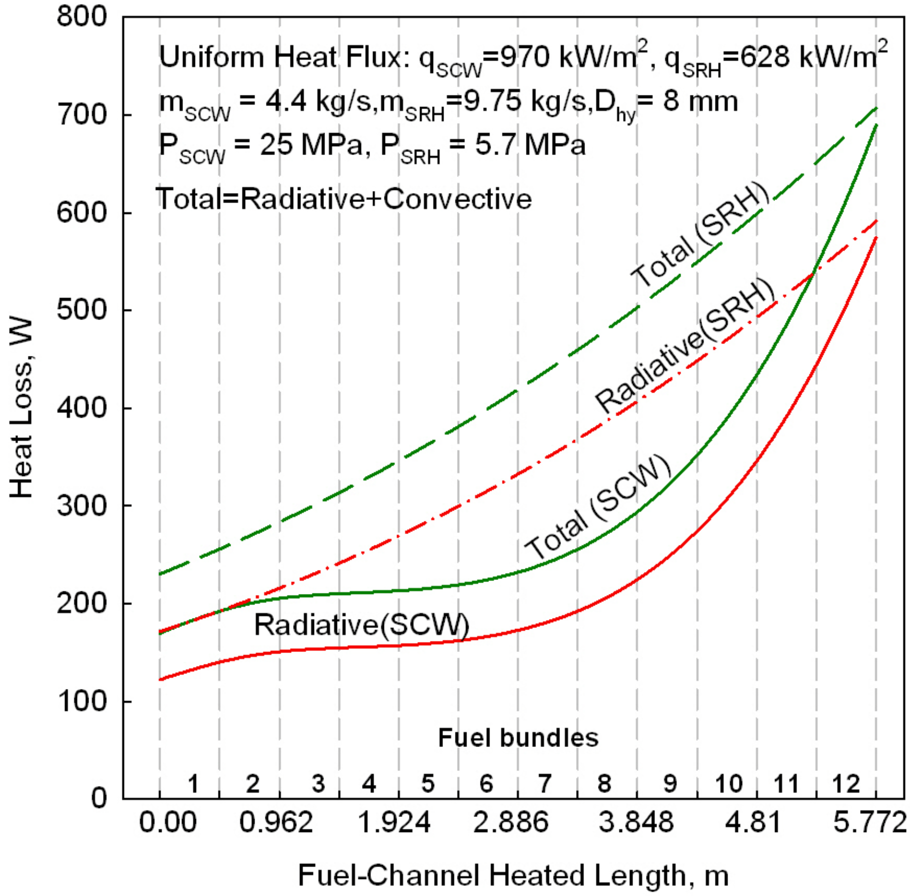

Figure 5: Convective and Radiative Heat Loss Profiles under SCW and SRH Conditions.

3. Heat loss from ceramic-insulated fuel channel

The heat losses from the coolant to the moderator for a ceramic-insulated fuel channel (for details, see [3]) at SCW and SRH conditions are shown in Table 1. Section 3.1 provides a brief description of the fuel channel, and Section 3.2 covers the analysis of the convective heat loss at studied conditions.

3.1 Fuel channel description

The ceramic-insulated fuel channel consists of a liner tube, ceramic insulator, and PT, as shown in Fig. 6. The main purpose of the liner tube, which is a perforated tube, is to protect the ceramic insulator during re-fuelling and operation with fuel bundles inside. The ceramic insulator, which is 70% porous and made of Yttria-Stabilized Zirconia (YSZ), should provide good thermal insulation [3].

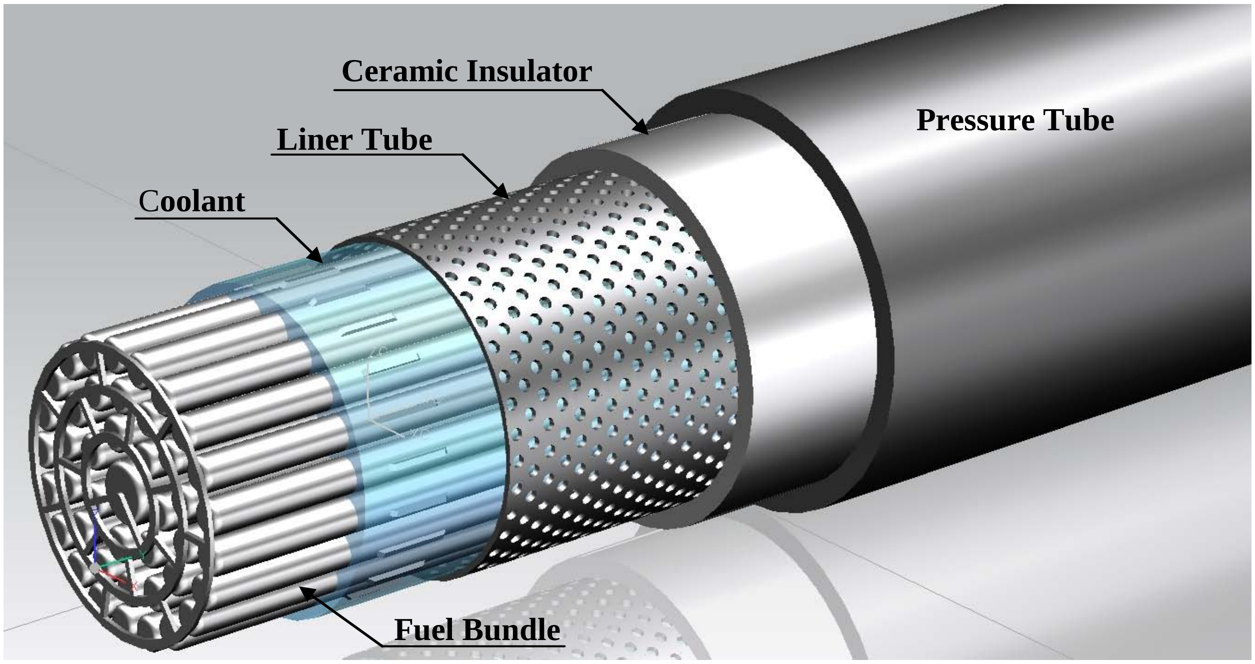

Figure 6: 3-D View of Ceramic-Insulated Fuel Channel for SCWRs [3].

3.2 Convective heat loss

The heat loss from the coolant to the moderator was determined using Eq. (1), which required calculation of the thermal-resistance network of the fuel channel components. Figure 7 depicts the thermal-resistance network of the ceramic-insulated fuel channel. It should be noted that the thermal resistance of the liner tube was not considered in the heat loss calculation due to its negligible impact on the total heat loss.

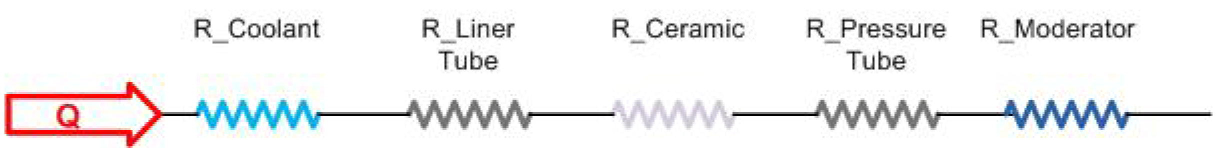

Figure 7: Thermal Resistance Network.

3.2.1 Coolant-thermal resistance

The thermal resistance of the coolant at SCW condition was calculated using Eq. (2) in which the HTC and Nusselt number were calculated using Eqs. (3) and (4). It should be noted that instead of Eq. (4), Eq. (21) was used to calculate the Nusselt number at SRH conditions [9]. Friction factor in Eq. (21) was calculated using Eq. (22).

$$\mathbf{Nu}_D = \frac{(f/8)(\mathbf{Re}_D - 1000)\mathbf{Pr}}{1 + 12.7(f/8)^{1/2}\left(\mathbf{Pr}^{2/3} - 1\right)} \tag{21}$$

$$f = (0.790 \ln \mathbf{Re}_D - 1.64)^{-2} \tag{22}$$

3.2.2 Ceramic-insulator thermal resistance

In the proposed fuel channel design, the ceramic insulator is 70% porous in order to reduce the heat loss from the coolant to the moderator. Therefore, the effective thermal conductivity of the insulator was calculated using Eq. (23), which required calculation of the temperature of the insulator both in radial and axial directions [3]. Having the effective thermal conductivity of the ceramic insulator calculated, Eq. (10) was used to calculate the thermal resistance of the ceramic insulator.

$$k_{eff} = 0.7 \cdot k_{H_2O} + 0.3 \cdot k_{ZrO_2} \tag{23}$$

3.2.3 Pressure-tube thermal resistance

The thermal resistance of the PT was calculated using Eq. (10). For the purpose of heat loss analysis, Zr-2.5% Nb was selected as the material of choice for the PT, because the operating temperature of the PT at both SCW and SRH conditions will be below that of the CANDU-6. Equation (24) was used to calculate the thermal conductivity of the PT, where T indicates temperature in Kelvin [15].

$$k = 16.85 - 2.186 \cdot 10^{-3} T + 8.899 \cdot 10^{-6} T^2 \tag{24}$$

3.2.4 Moderator thermal resistance

As mentioned in Section 2.2.5, the flow of heavy water inside the calandria vessel was assumed to be the natural convection. Additionally, the moderator temperature and pressure were assumed to be approximately 80℃ and 0.2 MPa, respectively. Equations (3) and (19) were used to calculated the HTC and Nusselt number, respectively. Further, HTC was substituted into Eq. (2) to calculate the thermal resistance of the moderator.

3.3 Results

The total heat losses were approximately 105 and 112 kW per fuel channel at SCW and SRH conditions, respectively. Figure 8 shows the heat-loss profiles along the heated length of the fuel channel at SCW and SRH conditions.

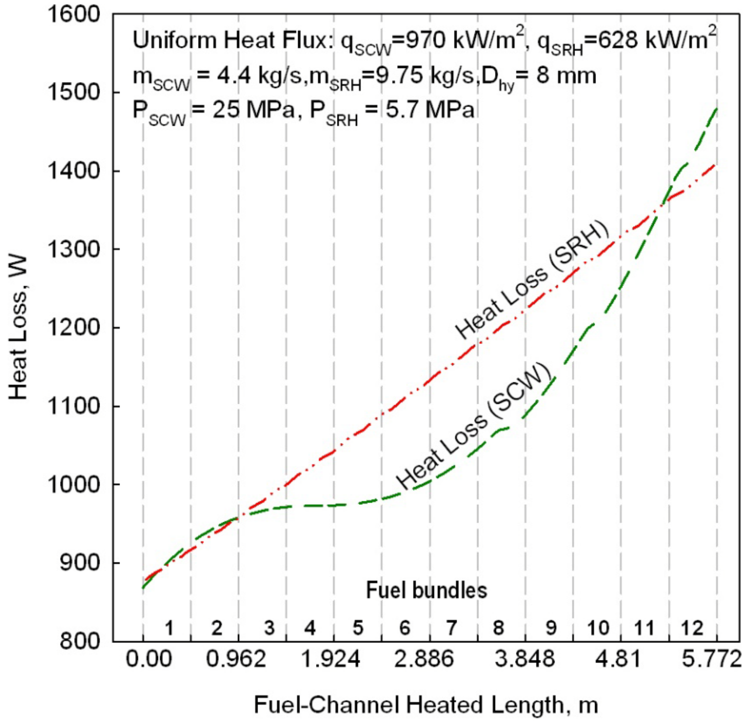

Figure 8: Heat-Loss Profiles at SCW and SRH Conditions.

4. Discussion

A comparison between the ceramic-insulated and CANDU-6-type fuel channels showed that the total heat loss from the CANDU-6-type fuel channel was approximately one-third of that of the other fuel channel. Table 2 summarizes the total heat losses per fuel channel and the corresponding heat loss of 300 fuel channels.

Table 2: Total Heat Losses per Fuel Channel and for 300 Fuel Channels.

Fuel Channel	Ceramic-Insulated	Modified CANDU-6
Heat Loss/ SCW Channels, kW	105.2	29.6
Heat Loss/ SRH Channels, kW	112.3	43.2
# of SCW Channels	220	220
# of SRH Channels	80	80
Total Heat Loss (300 Channels), MW	32.7	10.0

Each fuel channel has its own advantages and disadvantages. The ceramic-insulated fuel channel utilizes YSZ insulator, which is 70% porous and has a low neutron absorption cross-section. Additionally, the operating temperature of the PT will be low, which allows the use of materials such as Zr-2.5%Nb that has a low thermal neutron absorption cross-section as well, good corrosion resistance properties, and high creep strength. On the other hand, the disadvantage of this fuel channel is that the heat loss from the coolant to the moderator is high compared with the modified CANDU-6 fuel channel.

The advantage of the CANDU-6 fuel channel is that the heat loss is very low. The disadvantage of this fuel channel is that the thickness and material of the PT must be modified in order to make the fuel channel operational at SCW conditions. Inconel-718 is a potential candidate, which can be used as the material of choice for the PT. The minimum required thickness of PT at SCW conditions is approximately 7.6 mm, which poses a challenge due to high neutron absorption cross-section of Inconel-718 or other materials, which have resistance to high temperatures.

The low heat loss of the CANDU-6 fuel channel is due to utilization of a gas, which fills the gap between the PT and CT. The thermal conductivity of gases varies as a function of temperature and pressure. Figure 9 shows the thermal conductivity of a number of gases as a function of temperature at 300 kPa. There is a possibility of reducing the amount of heat loss from the the aforementioned value by selecting another gas with a lower thermal conductivity, but formation of activation products must be studied.

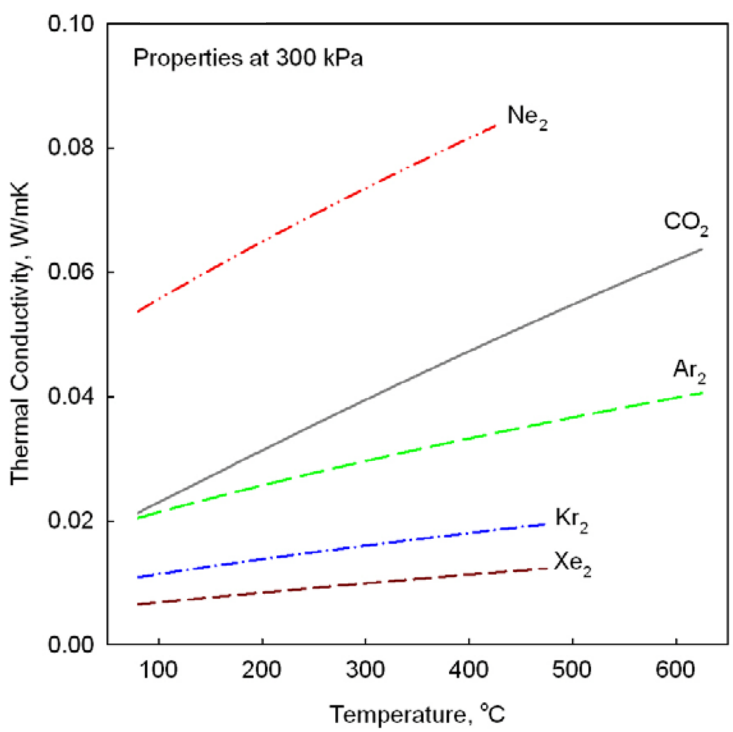

Figure 9: Thermal Conductivity of Gases at 300 kPa.

5. Conclusions

Heat losses from the coolant to the moderator from a ceramic-insulated and CANDU-6-type fuel channels were calculated. The result of the analysis showed that the total heat loss corresponding to 300 fuel channels were approximately 32.7 and 10 MW, respectively. The heat loss from a CANDU-6 fuel channel, which was modified according to the SCW conditions, was significantly lower than the ceramic-insulated fuel channel. However, further study and alteration of the fuel channel is required in terms of selection of material and modification of the dimensions of the fuel channel components in order to make it more efficient at SCW conditions.

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NOMENCLATURE

A	cross-sectional area, m^2
A_{fl}	flow area, m^2
C_{p}	specific heat at constant pressure, J/kg K
$\bar{C}_p$	averaged specific heat, $(\frac{H_w - H_b}{T_w - T_b})$, J/kg K
D	diameter, m
D_{hy}	hydraulic diameter, m
f	friction factor
G	mass flux, (m/A_{fl}), kg/m^2 s
g	gravitational acceleration, m/s^2
h	heat transfer coefficient, W/m K
h	enthalpy, J/kg
k	thermal conductivity, W/m K
k_{eff}	effective thermal conductivity, W/m K
L	length, m
L_{c}	characteristic length, m
m	mass flow rate, kg/s
p	perimeter, m
P	pressure, Pa
Q	heat transfer rate, W
q	heat flux, W/m^2
R	thermal resistance, K/W

S	permissible design stress, MPa
T	temperature, K
t	thickness, mm

Greek symbols

α	thermal diffusivity ($k/\rho \cdot c_p$), m^2/s
β	volumetric thermal-expansion coefficient, 1/K
ε	emissivity
μ	dynamic viscosity, Pa·s
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
σ	Stefan-Boltzman constant, $5.67 \cdot 10^{-8}$, W/m^{2}K^4

Non-dimensional numbers

$\mathbf{Nu}_D$	Nusselt number, $\mathbf{Nu}_D = h \cdot D/k$
$\mathbf{Pr}$	Prandtl Number, $\overline{\mathbf{Pr}} = \mu \cdot C_p/k$
$\overline{\mathbf{Pr}}$	averaged Prandtl Number, $\overline{\mathbf{Pr}} = \mu \cdot \bar{C}_p/k$
$\mathbf{Ra}_c$	Rayleigh number, $\mathbf{Ra}_c = \frac{g\beta(T_i - T_o)L_c^3}{\nu\alpha}$
$\mathbf{Re}_D$	Reynolds number, $\mathbf{Re}_{\boldsymbol{D}} = \boldsymbol{G} \cdot \frac{\boldsymbol{D_{hy}}}{\boldsymbol{\mu}}$

Subscripts

b	properties calculated at bulk fluid temperature
cond	conduction
conv	convection
i	inner
o	outer
pc	pseudocritical point
w	properties calculated at wall temperature

Abbreviations

AECL	Atomic Energy of Canada Limited
CANDU	CANada Deuterium Uranium
CT	Calandria Tube
HTC	Heat Transfer Coefficient
NIST	National Institute of Standards and Technology (USA)
PT	Pressure Tube
PV	Pressure Vessel
SCWR	SuperCritical Water-cooled Reactor
SHS	Super-Heated Steam
SRH	Steam Re-Heat

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