THERMAL DESIGN ASPECTS OF HIGH-EFFICIENCY CHANNEL FOR SCWRS

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ABSTRACT

This paper focuses on thermal-design aspects of a new pressure channel (i.e., High Efficiency Channel) for SuperCritical Water-cooled Reactors. Objectives of this paper are to estimate heat loss from the coolant to the moderator and to investigate the effects of the insulator thickness and moderator pressure on the overall heat loss. In order to meet the objectives of this study, a steady-state one-dimensional heat-transfer analysis was conducted. This analysis showed that heat-loss values vary approximately 30%, depending on the equation used to determine the effective thermal conductivity of the ceramic insulator. However, the upper and lower bounds were determined, which showed that the heat loss per fuel channel was approximately between 70 and 110 kW. The results showed that the optimum thickness of the insulator is between 5 to 7 mm. The effects of the moderator's operating pressure on the heat loss indicated that the heat loss can be reduced by increasing the operating temperature of the moderator, which can be achieved by increasing the operating pressure of the moderator.

NOMENCLATURE

A_{fl}	flow area, m^2
c_p	specific heat at constant pressure, J/kg·K
□p	averaged specific heat in cross section,□□=□□−□□□□−□□ , J/kg·K
D	diameter, m
D_{hy}	hydraulic-equivalent diameter, m
G	mass flux, $kg/m^2 \cdot s$; m/A_{fl}
g	gravitational acceleration, m/s^2
h	heat transfer coefficient, $W/m^2 \cdot K$
H	enthalpy, J/kg
k	thermal conductivity, W/m·K
L	length, m
m	mass-flow rate, kg/s
p	percent porosity

p_m	perimeter, m
P	pressure, Pa
Q	heat-transfer rate, W
q	heat flux, W/m^2
r	radius, m
R	thermal resistance, K/W
T	temperature, K
x	length or thickness, m

Greek symbols

α	thermal diffusivity ($k/\rho \cdot c_p$), m^2/s
β	volumetric thermal-expansion coefficient, K^{-1}
ν	kinematic viscosity, m^2/s
μ	dynamic viscosity, Pa·s
ρ	density, kg/m^3

Non-dimensional numbers

$\mathbf{Nu}_D$	Nusselt number, $\mathbf{Nu}_D = hD/k$
$\mathbf{Pr}$	Prandtl Number, $\mathbf{Pr} = c_p\mu/k$
$\overline{\mathbf{Pr}}$	averagedPrandtl Number, $\overline{\mathbf{Pr}} = c_p \mu / k$
$\mathbf{Ra}_D$	Rayleigh number, $\mathbf{Ra}_D = \dfrac{g\beta(T_i - T_o)D^3}{\upsilon\alpha}$
$\mathbf{Re}_D$	Reynolds number, $\mathbf{Re}_D = GD/\mu$

Subscripts

c	coolant
conv	convection
eff	effective
fl	flow
i	inner
m	moderator
o	outer
pc	pseudocritical
w	wall
wt	weight

1. Introduction

Currently, several countries are developing SCWR concepts. These concepts can be categorized in terms of the neutron spectrum, moderator, and/or pressure boundary. In terms of the pressure boundary, SCWRs are classified into two groups: Pressure Vessel (PV) and Pressure Channel (PCh) or Pressure Tube (PT) SCWRs. Canada and Russia are the main developers of the latter design concept, which is the focus of this paper.

Several fuel-channel designs are available for current PT reactors with liquid and solid moderators (CANDU and RBMK reactors). However, new fuel-channel designs are required for SCWRs, because of the anticipated high operating temperatures and pressures. Consequently, the Atomic Energy of Canada Limited (AECL) and NIKIET (Russia) have proposed various new fuel-channel designs. The heat losses from these fuel channels might be large due to high operating temperatures of the coolant. Therefore, it is necessary to determine these heat losses with the objective to optimize the fuel-channel design.

Previously, the heat loss from the HEC, which has been designed by AECL, was calculated [3]. This fuel channel consists of a liner tube, ceramic insulator, and pressure tube. The thermal conductivity of the ceramic insulator, which is porous and made of Yittria Stabilized Zirconia (YSZ), was calculated based on the volumetric fractions of the insulator and coolant, which was assumed to fill the porous volume of the insulator. This paper focuses on the calculation of the heat losses from the same fuel channel while using various equations and/or correlations in order to calculate the effective thermal conductivity of the porous insulator more accurately.

2. Parameters of Generic PT SCWR

A generic 1200-MW$_{el}$ PT SCWR consists of 300 fuel channels. These fuel channels can be classified into two categories: SuperCritical Water (SCW) channels and Steam Re-Heat (SRH) channels. As shown in Fig. 1, there are 220 SCW channels and 80 SRH channels. In SCW channels, the inlet and the outlet temperatures of the coolant are 350°C and 625°C at a pressure of 25 MPa, respectively. On the other hand, the coolant, which is superheated steam, operates at a pressure of 5.7 MPa in SRH channels, where the inlet temperature of the coolant is 400°C and reaches an outlet temperature of 625°C. Table 1 lists parameters of SCW and SRH channels for a generic 1200-MW$_{el}$ PT SCWR [4].

Table 1: Operating Parameters of Generic 1200-MW$_{el}$PT SCWR [4].

Parameters	Unit	Generic PT SCWR	
Electric/Thermal Power	MW	1140 - 1220 / 2540	
Thermal Efficiency	%	45 - 48	
Coolant/Moderator	–	H_2O / D_2O	
Pressure of SCW and SHS at Outlet	MPa	25.0	5.7
T_{in} / T_{out} of SCW and SHS	°C	350/625	400/625
Mass Flow Rate per SCW/SRH Channel	kg/s	4.4	9.8
Thermal Power per SCW/SRH Channel	MW	8.5	5.5

# of SCW/SRH Channels	-	220	80

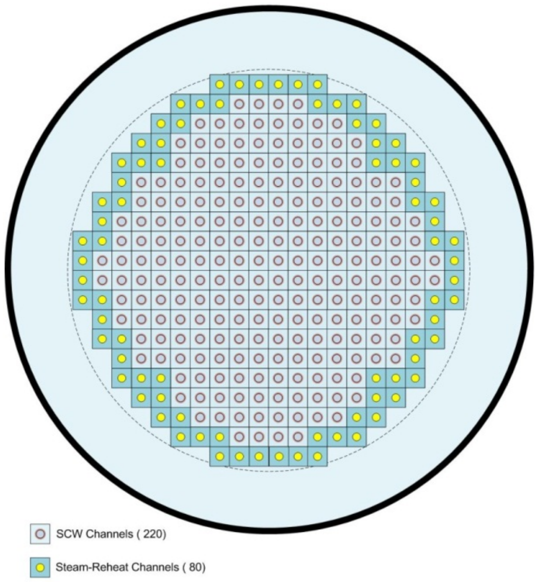

Figure 1: Core Configuration of Generic 1200-MW$_{el}$ PT SCWR.

2.1. SCWR fuel-channel designs

AECL has designed several fuel channels for its SCWR concept, but only two fuel-channel designs have been discussed in this paper. The first fuel channel is a Re-Entrant fuel-Channel (REC) design, which consists of a flow tube and a pressure tube. The pressure tube is exposed to the moderator from outside. The flow tube is separated from the pressure tube via a gap, where the coolant passes through. When the coolant reaches the closed end of the fuel channel, it flows through the flow tube and removes the heat from a fuel-bundle string, which is located inside the flow tube. Figure 2 shows a 3-D view of the REC. In general, the REC can be designed with the gas-gap insulator or a ceramic insulator.

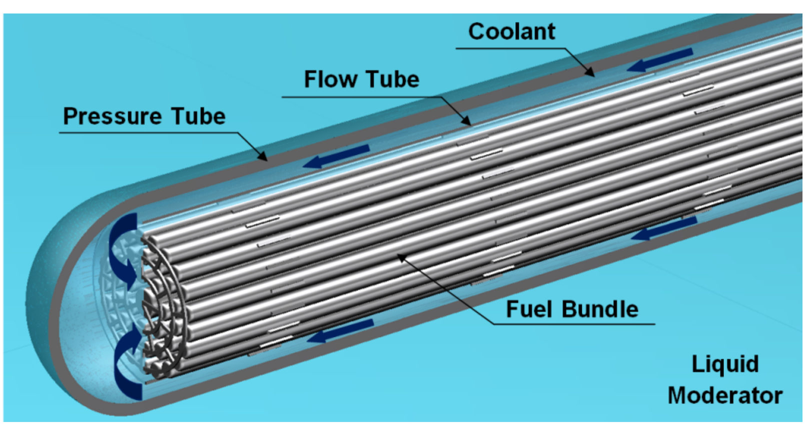

Figure 2: 3-D View of Re-Entrant fuel Channel (REC) (based on [5]).

The second fuel channel is a direct-flow fuel-channel design, known as High-Efficiency fuel Channel (HEC). This fuel channel consists of a liner tube, ceramic insulator, and a pressure tube. The outer surface of the pressure tube is in direct contact with the moderator, which is at an average temperature of 80°C. The inner surface of the pressure tube is covered with a ceramic insulator, which reduces the operating temperature of the pressure tube to temperatures, which allow for the use of Zr-2.5% Nb that has a low absorption cross-section for thermal neutrons. The inner surface of the ceramic insulator is covered with a liner tube. The liner tube is perforated and has a thickness of approximately 2 mm. In addition, the liner tube protects the insulator from being damaged during fueling and/or refueling and from erosion by the coolant flow [5]. Figure 3 shows a 3-D view of this fuel channel.

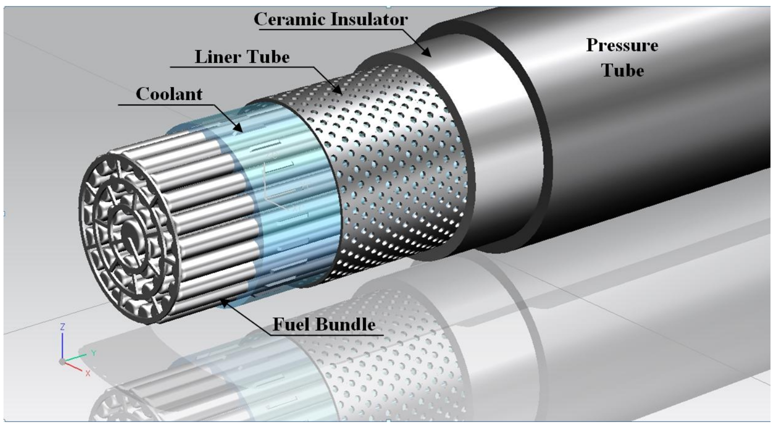

Figure 3: 3-D View of High-Efficient fuel Channel (HEC) (based on [5]).

3. Calculation of Heat Loss from Coolant to Moderator

A steady-state one-dimensional heat-transfer analysis has been conducted in order to determine the heat loss from HEC. A code has been developed in MATLAB. The code divides the length of the fuel channel into segments of one-millimeter lengths and calculates the heat loss based on Equation (1). As indicated by Eq. (1) [6], calculation of the heat loss from the coolant to the moderator requires the computation of the thermal resistance network of the fuel channel and the temperature difference between the coolant and the moderator.

The thermal-resistance network of HEC consists of five components, which are the thermal resistances of the coolant, liner tube, ceramic insulator, PT, and the moderator. These thermal resistances have been calculated in the following sections. It should be noted that the thermal resistance of the liner tube is negligible, so it has not been taken into account. Additionally, the NIST REFPROP software has been used to calculate the thermophysical properties of the light-water coolant and the heavy-water moderator as they were required [7].

▯=▯▯−▯▯▯▯▯▯▯▯ (1)

3.1. Coolant-temperature profile and convective thermal resistance of coolant

The thermal resistance of the light-water coolant can be calculated using Eq. (2), which requires the calculation of the Heat Transfer Coefficient (HTC). HTC was calculated by using Eqs. (3) and (4). Mokry et al. [8] have proposed a correlation shown as Eq. (4) for calculation of the

Nusselt number at supercritical conditions. The experimental data, based on which this correlation was developed, was obtained within conditions similar to those of proposed SCWR concepts. The experimental dataset was obtained for supercritical water flowing upward in a 4-m-long vertical bare tube. The data was collected at a pressure of approximately 24 MPa for several combinations of wall and bulk-fluid temperatures. The temperatures were below, at, or above the pseudocritical temperature. The mass flux ranged from 200 to 1500 kg/m^{2}s; coolant inlet temperature varied from 320 to 350°C, and heat flux was up to 1250 kW/m^2 [8].

□□□□□=1ℎ□ (2)

ℎ=□□□·□ □ (3)

□□□=0.0061 □□□0.904□□□0.684 (□□□□)□0.564 (4)

Zahlan et al. [9] have compared sixteen empirical correlations, which have been developed based on experiments in SCW. They have examined the most widely used correlations including the Mokry et al. correlation. The result of their comparison showed that the Mokry et al. correlation results in the lowest Root-Mean-Square (RMS) error within the supercritical region compared to that of other correlations. As a result, the Mokry et al. correlation has been used in this paper since it is currently the most accurate correlation.

3.2. Calculation of coolant-temperature profile

As mentioned previously, it is necessary to calculate the temperature difference between the coolant and the moderator. Since the temperature of the moderator is kept constant at 80°C, therefore, only the temperature profile of the coolant should be determined. Thus, the calculation of the temperature profile of the coolant is required, because the coolant temperature does not change linearly. This nonlinear temperature profile of the coolant is due to a significant increase in the specific heat of water as its temperature passes through the pseudocritical point. Pseudocritical points exist at pressures above the critical pressure of a fluid and at a temperature corresponding to the maximum value of the specific heat at this particular pressure [1].

The temperature profile of the coolant has been calculated based on heat balance using Eq. (5). Additionally, Newton's law of cooling, shown as Eq. (6), has been used in order to calculate the outer-surface temperature of the sheath. The heat flux in Eq. (5) has been calculated based on an average channel power of 8.5 MW$_{th}$ and 43-element Variant-20 fuel bundle. Each fuel bundle consists of 42 fuel elements with an outer diameter of 11.5 mm, and a central element, which is filled with burnable neutron absorber. The outer diameter of the central element is 20 mm [10]. Figure 4 shows a temperature profile of the coolant and cladding along the heated length of the fuel channel.

□□□=□□,□+□ □□□ □□□ (5)

□=ℎ(□□−□□) (6)

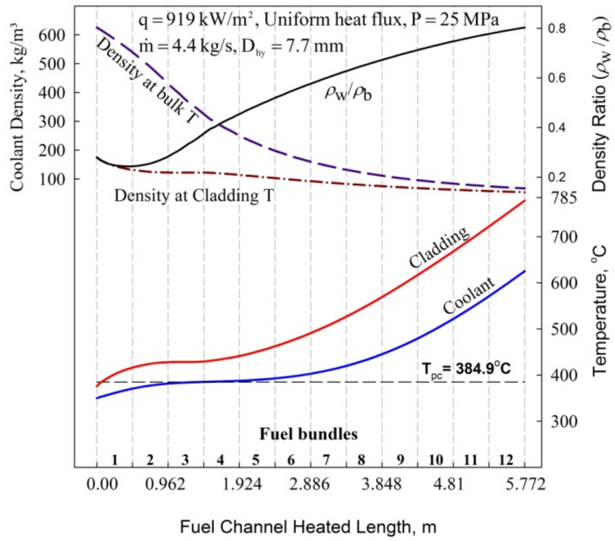

Figure 4: Bulk-Fluid and Cladding-Temperature Profiles, and Coolant-Density Profiles along Heated Channel.

3.3. Thermal resistance of ceramic insulator

The thermal resistance of the ceramic insulator has been calculated using Eq. (7). Equation (7) indicates that the most important property of the insulator is its thermal conductivity, which changes as a function of temperature, porosity, and pore size. A higher porosity results in a lower thermal conductivity, which in turn results in less heat losses. As a result, the ceramic insulator of the proposed fuel-channel design is 70% porous and made of Yttria Stabilized Zirconia (YSZ) [5]. YSZ has a low neutron absorption cross-section, low thermal conductivity and high corrosion resistance against exposure to water at supercritical conditions [5]. These properties make YSZ a good candidate as an insulator. The thermal resistance of the insulator, which is a function of its thermal conductivity, is the primary factor in governing the heat loss from the fuel channel. Therefore, it is necessary to calculate the effective thermal conductivity of the porous YSZ insulator as a function of temperature and the percentage of the porosity based on appropriate theories and available equations or correlations.

□□□□□=ln(□□□□)2□□□ (7)

Schlichting et al. [11] have developed a theory, which describes the thermal conductivity of dense YSZ as a function of temperature. According to their theory, the intrinsic thermal conductivity of YSZ decreases as a result of scattering of phonons due to point defects. On the other hand, the effective thermal conductivity increases at high temperature due to irradiation effects. The theoretical and experimental results of the Schlichting et al. study have shown in Fig. 5, which indicates that for dense YSZ and within the operating-temperature range of SCWRs, the thermal conductivity does not have a strong dependency on temperature.

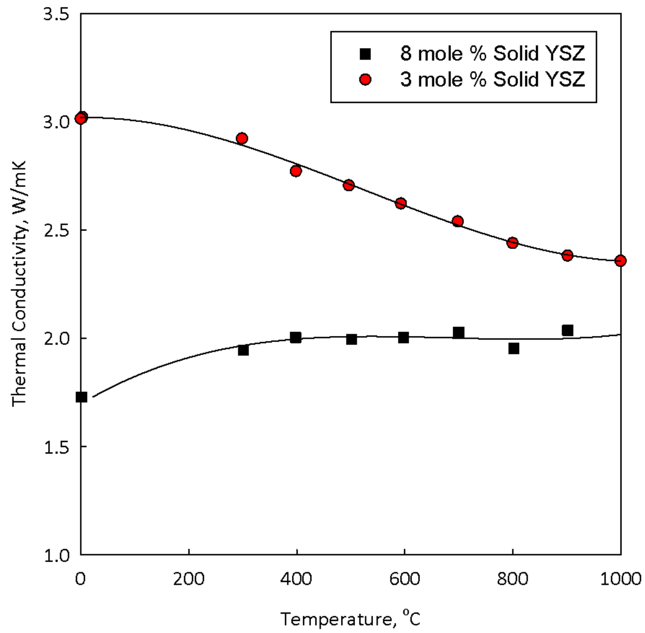

Figure 5: Thermal Conductivity of Solid YSZ as Function of Temperature.

In case of the SCWR fuel channel with a porous insulator, pores are filled with the light-water coolant. The thermal conductivity of light water varies significantly as a function of temperature, especially, at temperatures close to the pseudocritical region. Therefore, the effective thermal conductivity of the insulator must be determined based on theories that are applicable to porous media.

There are various theories and equations, which can be used in order to calculate the effective thermal conductivity of a porous medium. In this study, the effective thermal conductivity of the porous YSZ insulator has been calculated based of several theories and corresponding equations including the Maxwell theory, Maxwell-Eucken, Jiand and Sousa, Landauer, Meredith and Tobias equations.

Maxwell [12] provides an equation, which determines the effective electric conductivity of a medium that consists of small spheres of another medium. Since the conduction of electricity through a medium is analogous to the conduction of heat through a medium, the Maxwell equation, shown as Eq. (8), can be used in order to calculate the effective thermal conductivity of a medium inside which small spheres of another medium are distributed [12]. Similarly, the Maxwell equation can be used in order to determine the thermal conductivity of a porous medium, where small spheres of the second medium represent pores. In Equation (8), k_1, k_2, and p are the thermal conductivity of the primary medium, the thermal conductivity of the secondary medium or pores, and the volume fraction of pores to the total volume of the medium, respectively.

$$\frac{k_{eff}}{k_1}=\frac{2k_1+k_2+2p(k_2-k_1)}{2k_1+k_2-p(k_2-k_1)} \quad (8)$$

Hu et al. [13] provide information on the Maxwell-Eucken model and the Effective Medium Theory (EMT) as part of their study that they conducted on the thermal conductivity of porous YSZ. They used the Maxwell-Eucken equation, shown as Eq. (9), which has been developed based on EMT, Eq. (10), in order to theoretically calculate the thermal conductivity of porous YSZ, where pores were filled with air. Similarly, these equations have been used to determine the effective thermal conductivity of the YSZ insulator based on operating conduction of the studied SCWR.

▯▯▯▯▯2=2▯2+▯1−2▯2−▯1(1−▯) 2▯2+▯1+(▯2−▯1)(1−▯) (9)

1−▯ ▯1−▯▯▯▯▯1+2▯▯▯▯+▯ ▯2−▯▯▯▯▯2+2▯▯▯▯=0 (10)

Jiang and Sousa [14] have developed a 2-D modeling system, which allows for a prediction of the effective thermal conductivity of heterogeneous materials containing of two or three different components. They developed an equation, shown as Eq. (11), based on the EMT and used it in their model in order to simulate the effective thermal conductivity of a heterogeneous porous medium. Moreover, Khan et al. [15] provides an equation, Eq. (12), developed by Meredith and Tobias [16]. In addition to the previous equations, Chow and Khartabil [5] have provided Eq. (13) for calculation of the thermal conductivity of porous YSZ. The latter equation is based on the volumetric fraction of the primary medium and the porous medium.

▯▯▯▯=1▯−2▯2▯2−1▯2+▯2▯1−1▯1+▯2▯2−1▯2+▯2▯1−1▯12+(2▯−4) ▯1▯2 (11)

▯▯▯▯=▯1▯−2▯+0.409▯ ▯7/3−2.133▯ ▯10/3▯+▯+0.409▯ ▯7/3 −0.906▯ ▯10/3 (12)

▯=2+▯ 1−▯ , ▯= 6+3▯ 4+3▯ , ▯= 3−3▯ 4+3▯ , ▯= ▯2▯1

▯▯▯▯=1−▯ ▯1+▯ ▯2, ▯= ▯2▯▯▯▯▯▯ (13)

Figure 6 shows the effective thermal conductivity of 70% YSZ calculated based on aforementioned equations. As shown in Fig. 6, the thermal conductivity of porous YSZ calculated based on volumetric fraction of the solid and porous media has the highest value compared to those calculated based on other equations. As a result, the volumetric fraction method provides effective thermal conductivity, which can be considered as an upper bound for the thermal conductivities of porous media. Similarly, calculated heat-loss values would be the highest when the thermal conductivity of a porous insulator has been calculated based on the volumetric-fraction method. On the other hand, Maxwell-Eucken Equation and the correlation provided in [14] result in the lowest effective thermal-conductivity values. Therefore, the effective thermal conductivities calculated from the latter equations can be considered as a lower bound of the effective thermal conductivity of porous media. Other equations provide effective thermal conductivities between the upper and lower bounds.

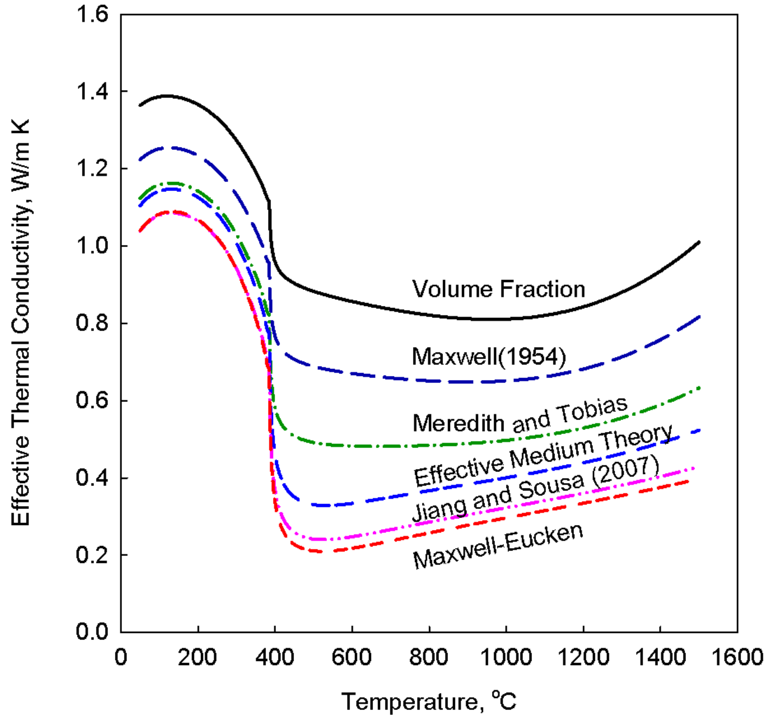

Figure 6: Effective Thermal Conductivity of 70% Porous YSZ as Function of Temperature.

3.4. Pressure tube

Two potential materials for PT are Excel (Zr-3.5%$_{wt}$Sn-0.8%$_{wt}$Mo-0.8%$_{wt}$Nb-1130 ppm O) and Zr 2.5 %$_{wt}$Nb [12]. The former has a high creep resistance, consequently lower creep-growth rates than Zr 2.5%$_{wt}$Nb while exposed to radiation. However, more research and development are required to select the final material, but for the purpose of calculation of the heat loss from the coolant to the moderator Zirconium 2.5%$_{wt}$Nb was selected as the material of choice. The thermal resistance of PT was calculated using Eq. (7). In Eq. (7), *k* is the thermal conductivity of PT, which was calculated using Eq. (14) [17]. According to the temperature of PT, it was estimated that the uncertainty involved in the calculation of the thermal conductivity of the PT is approximately ± 4%.

$$k_{PT}=12.767-5.4348\cdot10^{-4}T+8.9818\cdot10^{-6}T^2 \qquad (14)$$

3.5. Moderator

The heavy-water flow in a Calandria vessel is very complex due to momentum forces generated by the inlet jets and buoyancy forces [18]. For the purpose of calculating the heat-transfer rate between the fuel channel and the heavy-water moderator, the flow of the moderator inside the Calandria vessel was assumed to be natural circulation. Further, Eqs. (2) and (3) were used to calculate the thermal resistance and the convective HTC of the moderator, respectively. Churchill and Chu recommended a correlation shown as Eq. (15), which was used to calculate the Nusselt number [5]. In Eq. (15), **Ra** D is the Rayleigh number, which was calculated using Eq. (16).

□□={0.60+0.386 □□D1/6[1+(0.559/□□)9/16]8/27}2 (15)

□□□=□□(□□−□□)□3□□ (16)

4. Results and Discussion

A result of this analysis shows that there is a large variation among the calculated effective thermal-conductivity values of the porous YSZ based on various examined equations. As shown in Fig. 7, the volumetric-fraction method results in the highest heat loss or effective thermal conductivity. On the other hand, Maxwell-Eucken and Jiang and Sousa equations are in good agreement with each other while resulting in the lowest heat losses. Other equations including the Maxwell equation predict heat losses between the upper and lower bounds. Table 2 lists the total heat loss per fuel channel calculated based on the aforementioned equations. It should be noted that heat loss values corresponds to a 70%-porous ceramic insulator.

Table 2: Total Heat Loss per Fuel Channel Based on Examined Equations.

Equation	**Porosity, %**	**3 mole % YSZ**	**8 mole % YSZ**
		Heat Loss per Fuel Channel, kW	
Maxwell-Eucken	70	70.3	64.0
Jiang and Sousa (2007)		71.9	64.6
Effective Medium Theory		79.2	68.8
Meredith and Tobias		85.2	71.6
Maxwell (1954)		96.0	77.3
Volumetric Fraction		108.1	84.2
Solid YSZ	0.0	218.0	155.5

In order to calculate the optimum thickness of the insulator, the insulator of 4-mm thickness was selected as a reference. Then saving in the heat loss was calculated per one millimeter addition into the thickness of the insulator. As shown in Fig. 8, the optimum thickness of the insulator varies depending on the equation that is used to calculate the effective thermal conductivity of the insulator. However, considering all examined equations, the optimum thickness of the insulator is between 5 to 7 millimeters for the 70% porous 3-mole-% YSZ insulator.

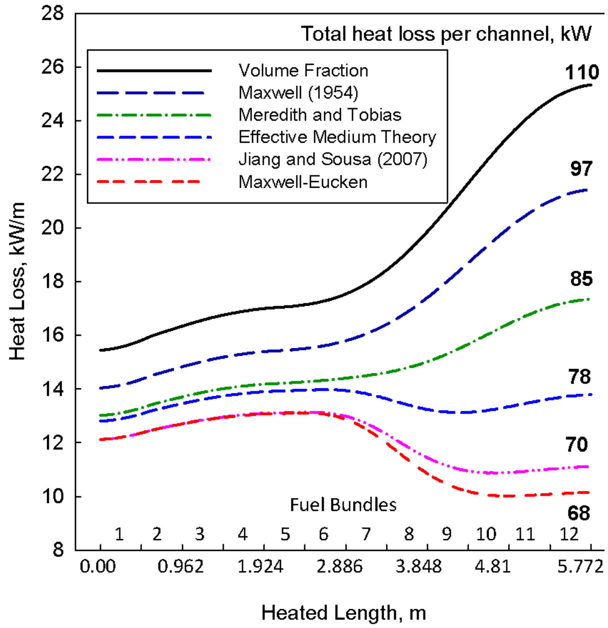

Figure 7: Heat-Loss Profile along Heated Length of HEC with 7-mm of 3-mole-% YSZ with 70% Porosity.

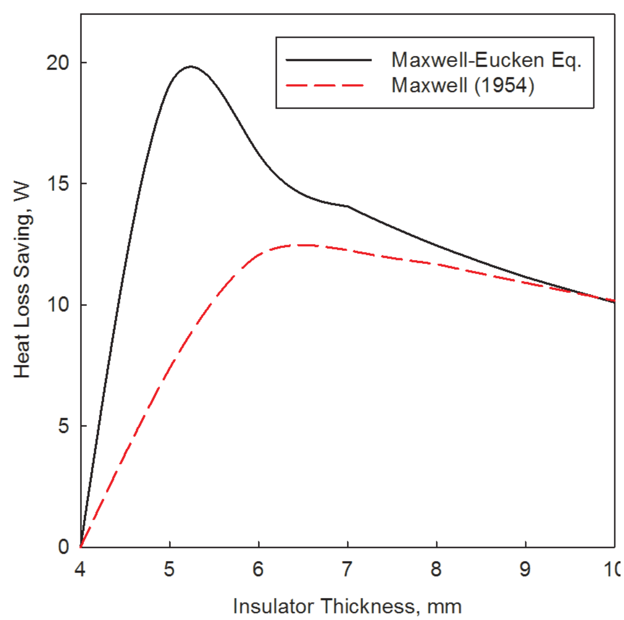

Figure 8: Optimum Thickness of Ceramic Insulator.

The heat loss per fuel channel of a solid insulator (e.g., without porosity) with a 7-mm thickness is 133 kW, which is approximately 30% higher than that of the 70%-porous ceramic insulator. This comparison shows effectiveness of the porosity in reducing the heat loss to the moderator. In other words, higher the porosity - lower the heat loss. However, other factors such as a mechanical integrity and thermal-shock resistance of the ceramic insulator should be taken into account before finalizing the porosity of the insulator. Moreover, it should be noted that further research is required to investigate the potential effects of hydrogen or deuterium build-up in the porous areas of the insulator.

Further studies have been conducted to determine effects of the ceramic-insulator thickness and operating pressure of the moderator on the heat loss. The results depict that the heat loss decreases as the thickness of the insulator increases. Figure 9 shows the heat-loss profile as a function of the insulator thickness. The total heat loss is approximately 110 kW with a 7-mm thick insulator. However, this total heat loss decreases to 88 kW, 75 kW and 65 kW when the thickness of the insulator increases to 9 mm, 11 mm, and 13 mm, respectively. Therefore, the thickness of the insulator has a significant impact on the heat loss from the fuel channel. However, it should be mentioned that an increase in the thickness of the insulator changes the distance between the two adjacent fuel channels (i.e., lattice pitch). This change in the value of the lattice pitch has an effect on the core neutronics as well as configuration of the fuel channels. Therefore, the aforementioned factors should be taken into consideration when the thickness of the insulator is increased.

In regards to the effect of the moderator on the heat loss, a higher moderator pressure allows for an increase in the operating temperature of the moderator, which in turn results in a smaller temperature difference between the coolant and the moderator. As indicated in Eq. (1), a smaller temperature difference between the coolant and the moderator leads into lower heat losses. Additionally, higher pressures in the moderator ensure that boiling will not occur in the moderator and minimize the potential danger associated with the excess concentrations of oxygen and deuterium inside the Calandria vessel. As a result, the heat loss has been determined at the moderator pressures of 0.3 MPa, 0.5 MPa, 0.7 MPa, and 0.9 MPa. As shown in Figure 10, the heat loss can be decreased approximately on 25 % by increasing the operating pressure and temperature of the moderator to 0.9 MPa and 155°C. Heat-loss profiles in Figure 10 correspond to a 7-mm thick, 70% porous, 3-mole-% YSZ insulator. As a conservative approach, the effective thermal conductivity of the ceramic insulator has been calculated using the volumetric fraction method.

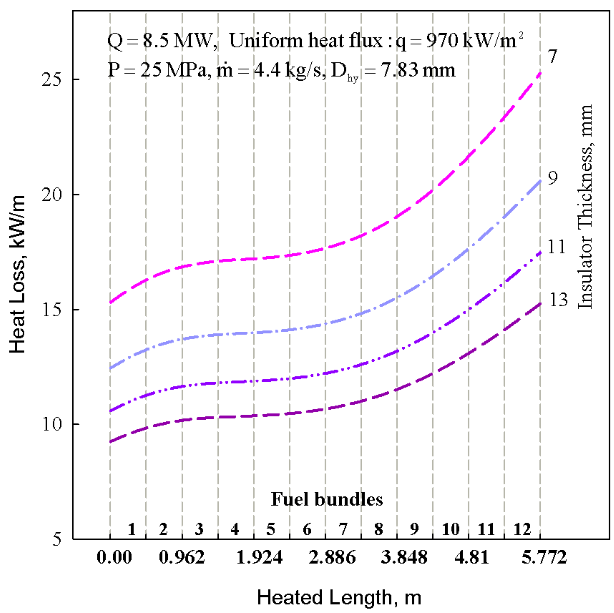

Figure 9: Heat-Loss Profiles of HEC as Function of Insulator Thickness.

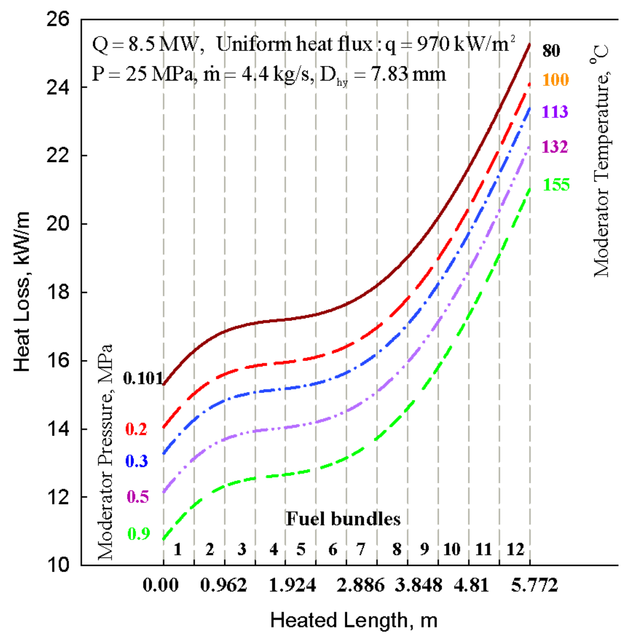

Figure 10: Heat-Loss Profile from HEC as Function of Moderator Pressure.

In regards to the HEC design, there are two important parameters: namely, the temperature gradient across the ceramic insulator and the operating temperature of the pressure tube. High temperature gradients across the insulator may results in the formation of cracks in the insulator in the case of power maneuvering. Moreover, if the operating temperature of the pressure tube exceeds the saturation temperature of the moderator, which is a function of the operating pressure of the moderator, boiling occurs in the moderator that is not favorable per previous explanations. Therefore, it is necessary to determine the temperature gradient across the ceramic insulator and the operating temperature of the pressure tube. These parameters are shown in Fig. 11.

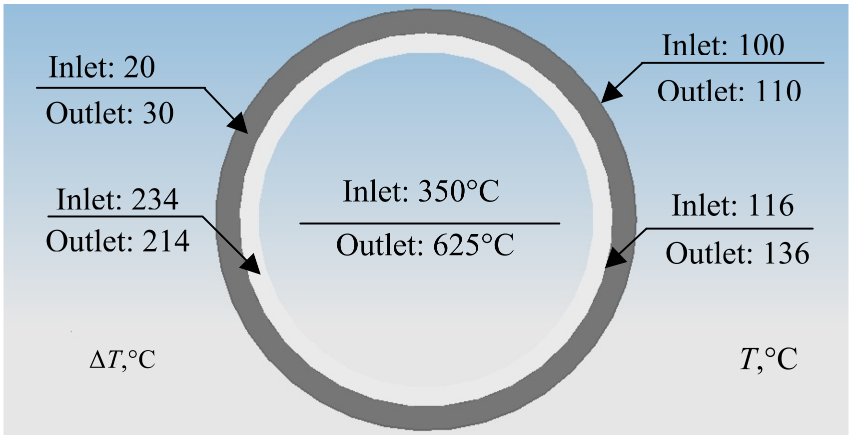

Figure 11: Temperature Differences and Absolute Temperatures of Ceramic Insulator and Pressure Tube.

5. Conclusions

The results of this study indicate that the heat loss per fuel channel from the High Efficiency Channel (HEC) design is between 70 kW and 110 kW. The examination of the effects of the insulator thickness and the moderator pressure indicates that the efficiency of the examined fuel-channel design can be improved. Consequently, it is recommended that the thickness of the insulator and/or the operating pressure of the moderator should be increased in order to reduce the heat loss to the moderator.

In regards to the operating pressure of the moderator, it is recommended to increase the pressure, because the operating temperature of the outer surface of the fuel channel (i.e., pressure tube) is currently above the saturation temperature of the moderator. As a result, boiling of the moderator will occur, which in turn results in the formation of high concentrations of deuterium and oxygen in the Calandria vessel. Therefore, the pressure of the moderator should be increased to ensure lower heat losses and to eliminate the boiling of the moderator inside the Calandria vessel. However, the reactivity effect due to this temperature increase should be taken into consideration.

6. Acknowledgements

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7. References

[1] I. L. Pioro, and R. B. Duffey, (2007).*Heat Transfer and Hydraulic Resistance at Supercritical Pressure in Power-Engineering Applications*. New York,ASME.

[2] P.L. Kirillov, M.I. Terent'eva and N.B. Deniskina, (2007).*Thermophysical Properties of Nuclear Engineering Materials*, third ed. revised and augmented, IzdAT Publ. House, Moscow, Russia.

[3] Peiman, W., Saltanov, Eu., Gabriel, K. and Pioro, I., 2010. Heat-Loss Calculations in a SCWR Fuel-Channel, Proceedings of the 18th International Conference On Nuclear Engineering (ICONE-18), Xi'an, China, May 17-21, Paper 30069, 9 pages.

[4] M., Naidin, I. L., Pioro, R., Duffey, U., Zirn, and S., Mokry, (2009). SCW NPPs: Layouts and Thermodynamic Cycles Options. Proc. Int. Conf. “Nuclear Energy for New Europe”, Bled, Slovenia, Sep. 14-17, Paper #704, 12 pages.

[5] C. K., Chow, and H.F., Khartabil, (2008). Conceptual Fuel Channel Designs for CANDU-SCWR. J. Nuclear Engineering and Technology 40, 1−8.

[6] F. P., Incropera, D. P., Dewitt, T. L., Bergman, andA. S., Lavine, (2006). *Fundamentals of Heat and Mass Transfer.* John Wiley & Sons.

[7] NIST Reference Fluid Thermodynamic and Transport Properties—REFPROP, (2007). NIST Standard Reference Database 23, Ver. 7.0, E.W. Lemmon, M.O. McLinden and M.L. Huber, National Institute of Standards and Technology, Boulder, CO, U.S. Department of Commerce, April.

[8] S., Mokry, Ye.,Gospodinov, I. L., Pioro, and P.L., Kirillov, (2009). Supercritical Water Heat-Transfer Correlation for Vertical Bare Tubes. Proc. ICONE-17, July 12-16, Brussels, Belgium, Paper #76010, 8 pages.

[9] H., Zahlan, D., Groeneveld, and S., Tavoularis, (2010). Look-Up Table for Trans-Critical Heat Transfer. Proc. 2nd Canada-China Joint Workshop on Supercritical Water-Cooled Reactors (CCSC-2010), Toronto, Ontario, Canada: Canadian Nuclear Society, April 25-28.

[10] L. K. H., Leung, (2008). Effect of CANDNU Bundle-Geometry Variation on Dryout Power. Proc. ICONE-16, Orlando, USA, Paper #48827, 8 pages.

[11] K. W., Schlichting, N. P., Padture, P. G., Klemens, (2001). Thermal conductivity of dense and porous yttria-stabilized zirconia. J. of Materials Science 31, 3003-3010.

[12] J. C., Maxwell, (1954). *Treatise on electricity and magnetism.* Dover Publications.

[13] L., Hu, C., Wang, and Y., Huang, (2010). Porous Yttria-Stabilized Zirconia Ceramics with Ultra-Low Thermal Conductivity. J. of Materials Science 45, 3242-3246.

[14] D., Jain, C., Pillai, B. K., Rao, and K., Sahoo, (2006). Thermal Diffusivity and Thermal Conductivity of Thoria-Lanthana Solid Solutions up to 10 mol.% LaO (1.5), J. of Nuclear Materials 353, 35-41.

[15] J. A., Khan, T. W., Knight, S. B., Pakala, W.,Jiang, and R., Fang, (2010). Enhanced Thermal Conductivity for LWR Fuel. J. Nuclear Technology 169, 61-72.

[16] R. E. Meredith and C. W. Tobias, (1962). “In Advances in Electrochemistry and Electrochemical Engineering”. Vol. 2, p. 15, C. W. TOBIAS, Ed., Interscience, New York.

[17] International Nuclear Safety Center., 2008. *Zircaloy Thermal Conductivity.* Argonne National Laboratory.

[18] M., Kim, S.-O., Yu, andH.-J., Kim, 2006. *Analyses on fluid flow and heat transfer inside Calandria vessel of CANDU-6 using CFD*. *Elsevier* , 1155-1164.