Heat Loss Analysis for a Re-Entrant SCWR Fuel-Channel Concept

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Summary

The operating temperatures and pressures of SuperCriticial Water-cooled Reactors (SCWRs) prevent the use of current CANDU fuel-channel designs and hence new concepts need to be developed. The Re-Entrant fuel-Channel (REC) is one such concept for a Pressure Tube (PT) type SCWR. In this design, the coolant flows from one end of the channel via a flow tube and then reverses its direction and flows through a pressure tube. The fuel bundles and insulator are located in the pressure tube. In this work, a heat loss analysis is conducted for the new REC concept using a uniform axial power profile along with a sensitivity analysis for the porosity of the insulator.

1. Introduction

Generation IV (Gen IV) nuclear reactor designs are under development to increase sustainability, economics and safety when compared to current Generation III and III+ reactors that are operational globally. SuperCritical Water-cooled Reactors (SCWRs) are one such Gen IV concept. SCWRs utilize light water as a coolant and operate at temperatures and pressures (350 – 650°C and 25 MPa) above the critical point of water (373.95°C and 22.064 MPa) [1]. There are two types of SCWRs: the Pressure Vessel (PV) type and the Pressure Tube (PT) type. The current reference Canadian SCWR design is a PT type reactor with 336 vertically-oriented pressure tubes [2]. As the SCWR operates at higher pressures and temperatures compared to current CANDU reactors, the existing fuel-channel needs to be re-designed due to material constraints. One new fuel-channel concept is called the Re-Entrant fuel-Channel (REC). A key element to consider in designing a fuel-channel is the heat loss to the moderator. In this work, the design of the REC is presented along with a heat loss analysis for the new design.

2. Design

The reference Canadian design is composed of 336 vertical channels that are 5.5 m in length, while the heated length of the channel is 5 m [2]. Each channel consists of an inner tube, an outer tube, a perforated liner, a porous insulator and a pressure tube. The primary coolant, which is light water, enters the channel through the inner tube at the top at 350°C and a mass flow rate of 3.92 kg/s. After travelling the length of the inner tube, the coolant reverses its direction and flows through the outer tube. The average channel power is 7.6 MW_{th} and the total power of the reactor is 2540 MW_{th}[2]. The moderator is heavy water and is located outside the pressure tube.

The fuel bundle used in this analysis is a 78-element bundle that utilizes UO_2. A perforated liner is used to protect the insulator from the fuel bundles. The channel design is shown in Figure 1 and the specifications of the design are shown in Tables 1 and 2.

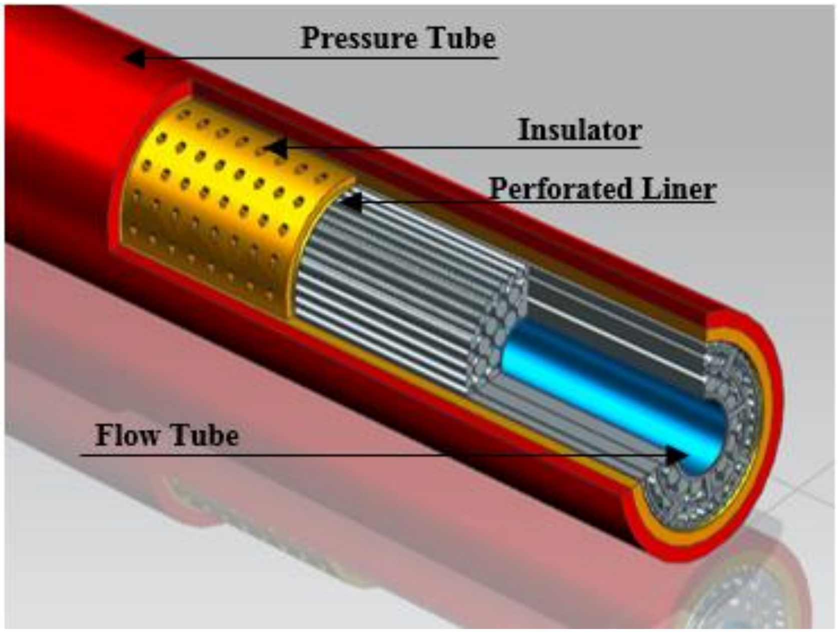

Figure 1: New Re-Entrant Channel Design Concept

The reference material for the inner flow tube, perforated liner and the pressure tube was chosen to be Stainless Steel 304 (SS304) as it has the ability to handle high stresses [3]. Along with high stresses, the material should also be able to withstand the high radiation fields and the creep as well [4]. Further research and tests need to be conducted to find materials that are can withstand all aforementioned issues.

Yttria Stabilized Zirconia (YSZ) at 70% porosity was chosen as the material for the insulator as it has a low neutronic cross section [5]. The reference thickness of the insulator is 10 mm. This thickness can be modified to increase the effectiveness of the design. As part of the heat loss analysis, a sensitivity analysis was also conducted for the porosity of the insulator.

Table 1: Dimensions of the Re-Entrant Channel

Parameter	Value
Flow tube – Inner diameter, mm	54.0
Flow tube – Outer diameter, mm	57.6
Perforated liner thickness, mm	0.50
Insulator thickness, mm	10.0
Pressure tube – Inner diameter, mm	157.0
Pressure tube – Outer diameter, mm	180.0

Table 2: Parameters of the Fuel Bundle

Parameter	Value
Total # of fuel elements	78
# of elements on ring 1, 2, 3	15, 21, 42
Diameter of one fuel pin in ring 1, mm	13.6
Diameter of one fuel pin in ring 2, mm	13.6
Diameter of one fuel pin in ring 3, mm	8.2

3. Methodology and Discussion

A 1-D averaged numerical model was developed using MATLAB to calculate the heat loss from the new REC design. The thermophysical properties of the coolant, light water, were obtained from NIST Refprop software. The inlet temperature of the water is 350°C and the pressure is assumed to be constant at 25 MPa. The moderator temperature was assumed to have a bulk-fluid temperature of 75°C. The fuel-channel was divided into 121 nodes and a uniform axial power profile was used so that the results can be verified experimentally in the future. The heat transfer model used for this analysis is described in [6].

Figure 2 shows the temperature profiles of the coolant, the inner and outer surfaces of the flow tube and insulator, the outer surface temperature of the pressure tube, and the temperature profile of the outer sheath along the heated length of the channel. As expected, the temperature profile of the cold fluid increases linearly as the fluid flows through the inner tube. After the coolant turns around at the end of the channel, the hot fluid temperature increases slowly at first and then dramatically after the fluid crosses the pseudocritical region and then exists the channel at 650°C. The pseudocritical point is determined to be 1.07 m into the hot side of the channel (not shown in figure). The outer sheath temperature also increases slowly at first, plateaus around the pseudocritical region and then sharply increases. The outer-sheath temperature is below the sheath melting temperature limit of 850°C.

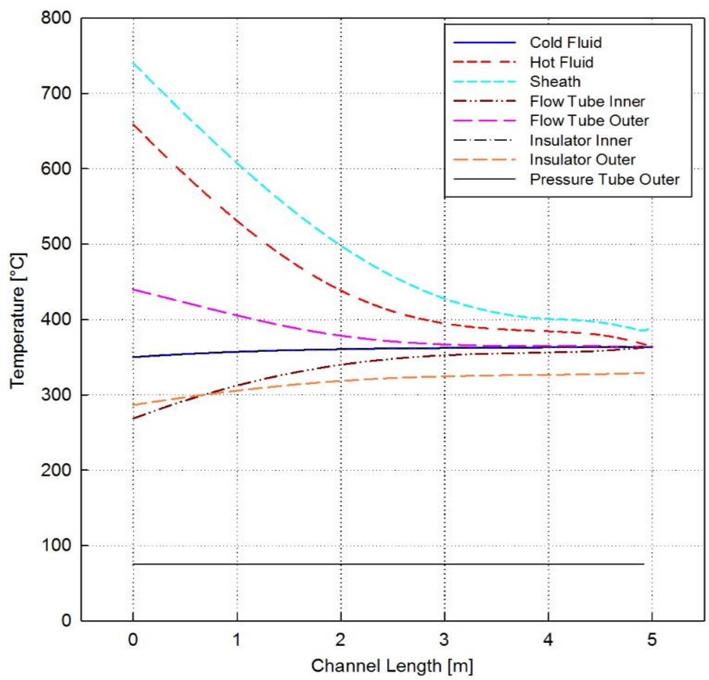

Figure 1: Temperature Profiles for the Coolant, Outer Sheath, Flow Tube, Insulator and Pressure Tube

Heat transfer is reliant on temperature between two surfaces. Heat is gained by the coolant in the inner flow tube through conduction from the tube and through convection from cold and hot fluid. As the fluid reaches the pseudocritical region, its thermophysical properties change drastically. Thermal conductivity, one of the key properties in heat transfer, drops marginally in the outer tube. This decrease in thermal conductivity is due to high temperature difference between the inner and the outer tube.

Heat loss through the pressure tube to the moderator is a function of the type and thickness of the insulator. Figure 2 shows the heat loss to the moderator along the heated length for the reference 70% insulator porosity. A sensitivity analysis was conducted for the porosity of the YSZ insulator. The heat loss was observed at 0%, 50%, 70% and 90% porosity of the insulator and the results are shown in Table 3. As expected, the heat loss to the moderator is higher as the porosity is increased. However, the difference between the different porosities is marginal. This implies that the insulator thickness is ineffective and needs to be increased. However, increasing the insulator thickness would result in a larger diameter of the fuel-channel. Other solutions would be to use a different insulator on the whole or to place the insulator outside the pressure tube.

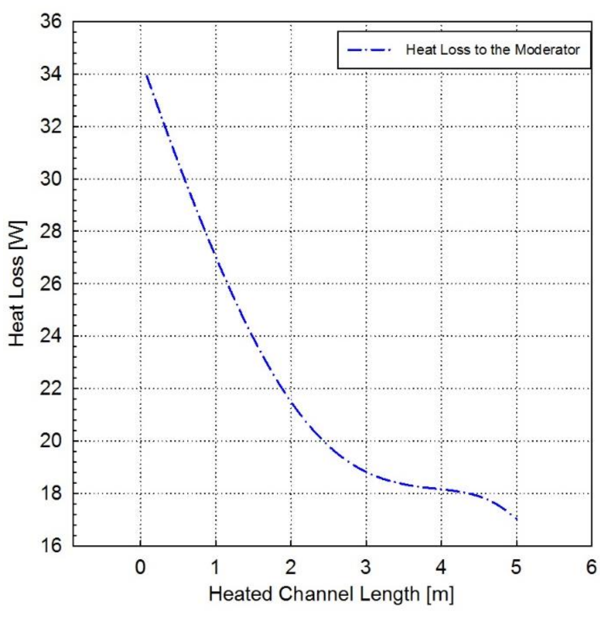

Figure 2: Heat Loss to the Moderator Along the Heated Channel Length for the Reference 70% Porosity Insulator

Table 3: Heat Loss Comparison for Insulator Porosity

Insulator Porosity (%)	Heat Loss [W]
0	1314
50	1319
70	1321
90	1323

4. Concluding Remarks

A preliminary heat transfer analysis was performed for a Re-Entrant fuel-Channel for the Canadian SCWR concept. The temperature profiles of the coolant, outer sheath, inner and outer surfaces of the flow and pressure tube and the insulator were estimated and the heat loss to the moderator was calculated. The thickness and the type of insulator are the key factors that determine the amount of heat loss to the moderator. The current reference insulator thickness is ineffective and needs to be increased; however, this would lead to a bigger fuel-channel design. Further research is required to determine viable insulator materials and thicknessess While a reference model has been developed for the REC, future work should be performed to optimze the current design.

5. Acknowledgements

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References

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