VARIABLE AXIAL POWER PROFILE HEAT-LOSS ANALYSIS OF A CO_2 GAS INSULATED RE-ENTRANT SCWR FUEL-CHANNEL

J. Samuel, G.D. Harvel, and I. Pioro

Faculty of Energy Systems and Nuclear Science
University of Ontario Institute of Technology
2000 Simcoe St. North, Oshawa, Ontario, L1H 7K4 Canada
jeffrey.samuel@uoit.ca; glenn.harvel@uoit.ca; igor.pioro@uoit.ca

Summary

One of the fuel-channel design concepts for a Pressure Tube (PT) SuperCritical Water-cooled Reactor (SCWR) currently under development is called the Re-entrant Fuel Channel (REC). The current reference re-entrant fuel-channel design consists of three tubes, the inner tube (flow tube), pressure tube and an outer calandria tube. The fuel bundles are placed in the inner tube. An annulus is formed between the flow and pressure tubes, through which the coolant flows. The coolant flows through the annulus receiving heat from the inner tube from one end of the channel to the other. At the far end, the flow will reverse direction and enter the inner tube, and hence the fuel bundle-string. Carbon dioxide gas is used as an insulator in the gap in-between the pressure tube and the outer calandria tube. The objective of this work is to model the heat loss to the moderator for the REC design using a variable axial power profile.

1. Introduction

There are a number of new concepts for nuclear reactors being developed worldwide as part of the Generation IV collaboration project. One such concept is a SuperCritical Water-cooled Reactor (SCWR), which will have a thermal efficiency of about 50% [1]. SCWRs will use SuperCritical Water (SCW) as a coolant and operate at higher temperatures and pressures compared to those of current water-cooled reactors. While current PWRs operate at a coolant pressure within 10 – 16 MPa, SCWRs will operate at about 25 MPa. The coolant would thus pass through a pseudocritical region somewhere along the channel [2].

The two types of SuperCritical Water-cooled Reactor (SCWR) concepts are a large Pressure-Vessel (PV) and a Pressure-Tube (PT) Reactor. The current PT-SCWR fuel-channel reference design - the High Efficiency Channel (HEC), consists of a bundle, ceramic layer and pressure tube [3]. The outer surface of the pressure tube is in contact with the moderator, while a perforated liner protects the ceramic layer from bundles, through which flows the primary coolant. While such a design may work, there are concerns with the construction, assembly and maintenance of the HEC. Hence, alternative design concepts are under development to explore the optimum efficiency of a SCWR channel-type reactor.

A key element to consider in designing the fuel channel is the minimization of heat loss to the moderator. In this work, heat losses to a heavy-water moderator are evaluated for the Re-Entrant Channel (REC) using a variable axial power profile.

2. Design

An alternative design being considered is the Re-Entrant fuel-channel (REC) which consists of three tubes: the inner tube (flow tube), the pressure tube, and an outer tube. The fuel bundles are placed in the inner tube. The flow and pressure tubes form an annulus through which flows the primary coolant. At the far end, the flow will reverse direction and enter the inner tube, and hence the fuel string. The coolant exits the channel from the inner tube. Carbon dioxide gas flows in-between the pressure tube and the outer tube and acts as an insulator, hence reducing the heat loss to the moderator from the channel. An advantage of using carbon dioxide gas in the ceramic insulating region in the REC is that it helps in detecting a leak in the pressure tube by analyzing the moisture content in the gas. A disadvantage is that it may lead to an increased complexity in the end fitting design [3]. The REC is shown in Figure 1. For this design, a reference channel length of 5.772 m was chosen.

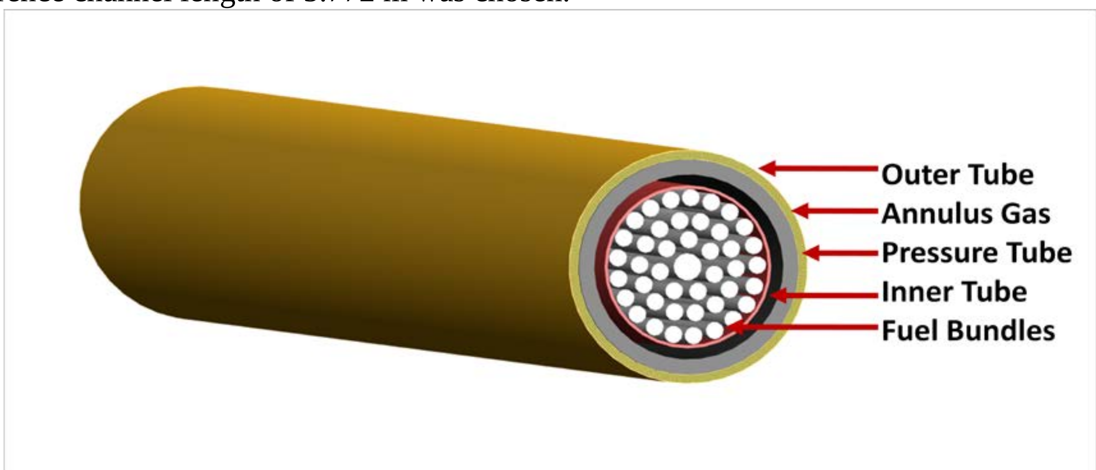


Figure 1: Re-Entrant fuel Channel

Figure 2 shows the side view of the REC. The REC is only refueled from one end [4]. For the purpose of this work, Stainless Steel – Grade 304 (SS-304) has been chosen as the reference material of construction of the flow, pressure and calandria tubes. The reference flow-tube inner diameter is 103.5 mm. The flow-tube inner diameter is a design parameter that could be changed once more knowledge of the reactor physics and recommended fuel types are known. As the flow tube does not bear any significant pressure difference, it can be made as thin as possible to improve neutron economy [3]. The reference thickness of the inner tube is 2 mm. ASME standards require that the design stress of the pressure boundary component be less than 1/3 of the UTS of the material. Thus, for an operating pressure of 25 MPa, the minimum required thickness of the pressure tube is 10.71 mm. The reference pressure-tube thickness for this analysis is 11 mm.

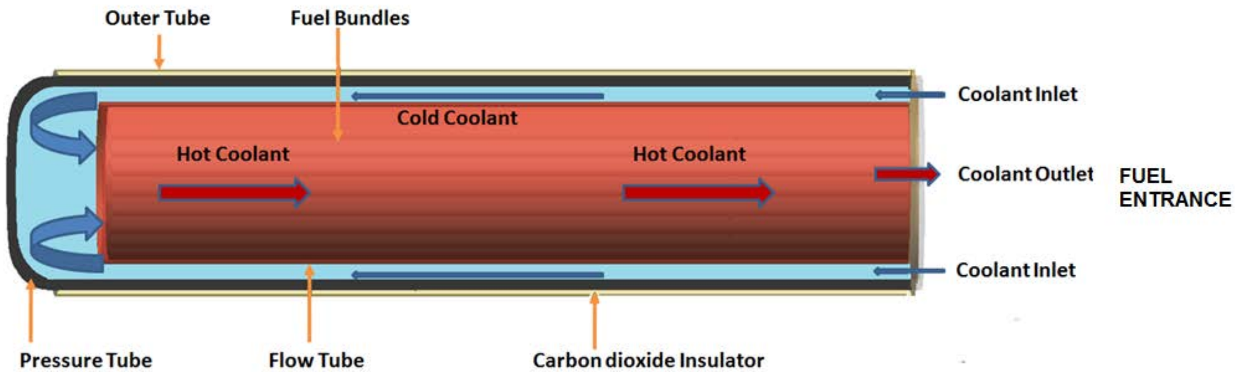


Figure 2: Side view of the Re-Entrant fuel Channel

For the purpose of this work, 7 mm is chosen as the thickness for the annulus gas gap. The rear end of the REC will be insulated at the end shield of the calandria. The outer tube can be made as thin as possible to improve neutron economy. The reference calandria tube thickness is 0.5 mm.

3. Heat-Transfer Model

The reference-reactor model used for the heat-transfer analysis is a 1200-MW_e SCWR with 300 fuel channels. The inlet temperature of the coolant is 350°C. The pressure drop along the channel is not accounted for due to low mass fluxes compared to current water-cooled reactors. The pressure was assumed to be 25 MPa for determination of fluid properties in this analysis. The mass-flow rate of the coolant is chosen as 4.37 kg/s for typical operating conditions. For consistency with earlier work, Variant-18 bundles are used for the heat-transfer analysis [4]. The moderator was assumed to have a bulk-fluid temperature of 80°C and a pressure of 200 kPa. Moderator properties were calculated at 100°C for the heat-loss analysis to be more representative of fluid conditions at the wall.

A cross-sectional 1-D averaged numerical model was developed using MATLAB in which the fuel channel was divided into 121 nodes; 60 for the cold side, 60 for the hot side and one for the re-entrant mixing node, which is the region where the coolant from the annulus changes direction and flows in the inner tube. As the inlet temperature and pressure are known, the enthalpy is easily obtained using NIST REFPROP software. The heat transfer model used for this analysis is described in [5].

4. Analysis and Discussion

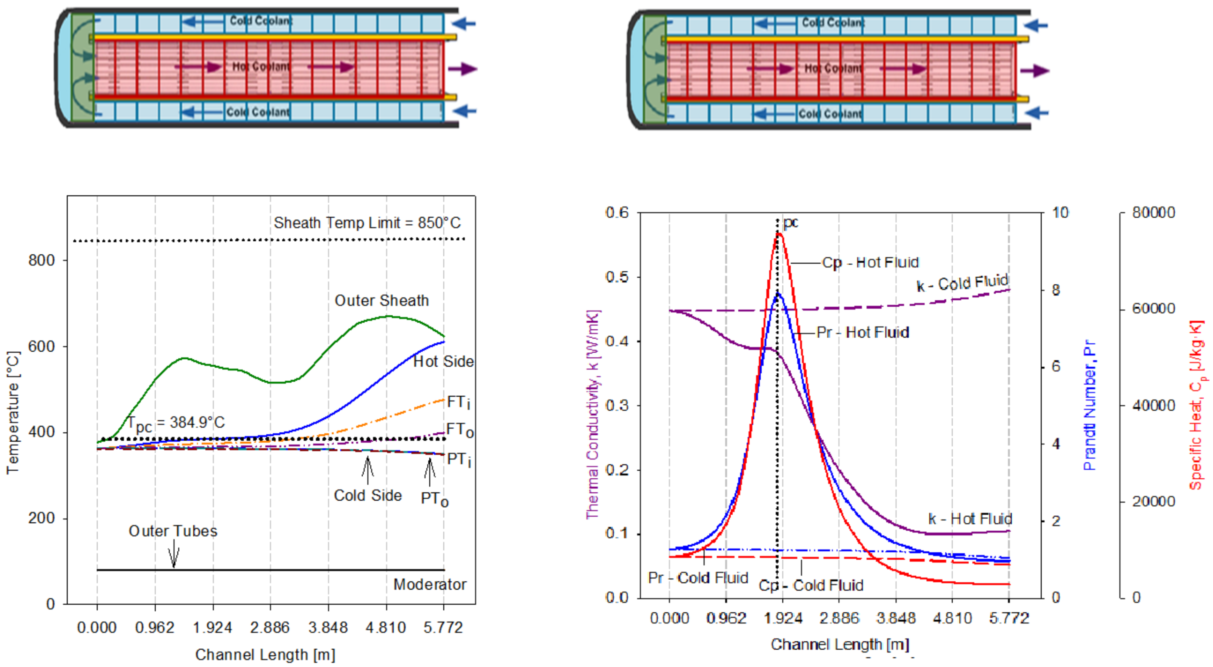
Heat-transfer analysis was performed in MATLAB with fluid properties transferred from NIST REFPROP. A two-peak disturbed flux shape usually caused by a reactivity device that is an out of normal configuration was used for this analysis as described in [5]. This shape was chosen as it implies the possibilities of having the pseudocritical point in two locations or extended over a region and hence could represent a scenario of significant safety concern. The coolant enters the cold side of the re-entrant fuel channel at x = 5.772 m, and enters the hot side at x = 0 m.

Figure 3a shows temperature profiles of the coolant, the inner and outer surfaces of the flow and pressure tubes and the temperature profile of the outer sheath along the heated length of the channel. The temperature of the coolant on the cold side increases approximately linearly as expected as the heat source is the outer wall of the flow tube. The coolant temperature on the hot side increases slowly at first and then dramatically after approximately 3 m of fuelled length. The main reason for this is the transition through the pseudocritical point. The outer-sheath temperature increases at first, decreases, increases again and finally decreases. This behavior is a result of the two-peak power profile. The outer-sheath temperature is below the sheath melting temperature limit of 850°C.

The location of the pseudocritical point in the channel can be identified by the peak in the specific heat profile for the coolant as seen in Figure 3b. Thermophysical properties, such as thermal conductivity, and specific heat drastically change within the pseudocritical region. The Prandtl number, which is based on thermophysical properties, also changes drastically within the pseudocritical region. These changes result in the variation in slopes of the coolant and outer sheath temperature profiles at these locations in Figure 3a. Figure 3b also indicates that there is only one pseudocritical point for this particular power profile.

The temperature gradients across the radial section of the reference REC at x = 0 m, x = 1.83 m and x = 5.772 m are shown in Figure 4, where x = 1.83 m is the location of the pseudocritical point. The dotted line indicates the expected temperature profile in the coolant. The temperature drop between the calandria tube and the moderator indicates that boiling of the moderator does not occur.

The total heat loss from the code side of the REC to the moderator, when channel power is 8.5 MW_{th} is 22.8 kW and the corresponding heat loss of 300 fuel-channels is approximately 6.8 MW.



(a) (b)

Figure 3: (a) Temperature profile along channel length; (b) Specific heat, thermal conductivity and Prandtl number profiles along fuel-channel

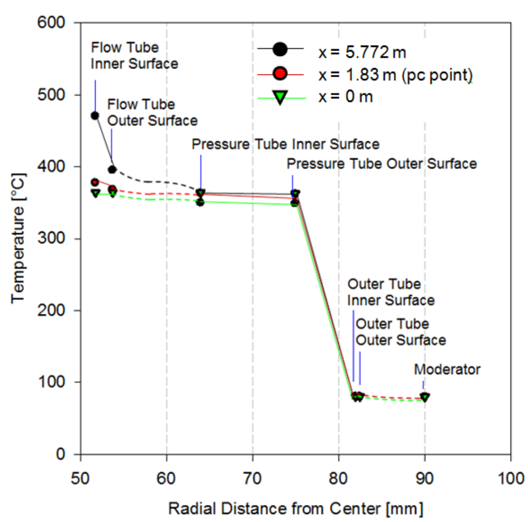


Figure 4: Temperature gradients along radial distance from center for re-entrant channel.

5. Concluding Remarks

A preliminary heat-transfer analysis was performed for a CO_2 insulated Re-Entrant Channel for PT-Type SCWRs.

The temperature profiles of the coolant, outer sheath, and inner and outer surfaces of the flow tube and the pressure tube were estimated and the total heat loss to the moderator was calculated. The temperature profiles of the coolant in the hot side and of the outer sheath change considerably within the pseudocritical region. The pseudocritical point for the reference re-entrant channel is within the hot side of the fuel channel, approximately near bundle #4.

The double-peaked power profile used for the analysis indicated that there is only one pseudocritical point in the channel. However, this may still be a cause for concern during accident scenarios. The total heat loss to the moderator for the CO_2 insulated REC is 22.8 kW for a channel power of 8.5 MW_{th}, which is approximately 0.3 % of the channel's total power.

6. Acknowledgements

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7. References

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