Pressure-Drop Analysis of a Re-Entrant Fuel Channel In a Pressure-Channel Supercritical Water-Cooled Reactor

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Summary

The objective of this paper is to perform a pressure drop analysis across a fuel channel of a SuperCritical Water-cooled Reactor. A re-entrant channel design with a 78-element fuel bundle design was selected to perform the pressure drop calculations. A one-dimensional steady state pressure drop analysis has been performed to investigate the pressure drop resulting from friction, gravity, acceleration and local losses at supercritical conditions. MATLAB was used to create a steady state thermal-hydraulic code which calculates the pressure drop across a 5 meter length heated vertical channel. The total pressure drop across the channel was calculated to 60 kPa.

1. Introduction

Generation IV reactor concepts are highly economical, inherently safer and more fuel efficient compared to their current Generation III and III+ counterparts. The Generation-IV International Forum (GIF) has narrowed conceptual designs of generation IV reactors to six concepts, which differ in terms of their design, moderator, neutron spectrum, pressures and coolant [1]. SuperCritical Water-cooled Reactors (SCWRs) are one of these six concepts, and is one of the most promising Generation IV reactor concepts due to their simplicity, high thermal efficiencies and have been evolved from the current water-cooled nuclear technologies.

Canada is currently in progress developing a generation IV reactor concept, which will meet the technological goals of the Generation-IV International Forum. The Canadian SCWR concept is a Pressure-Channel (PCh) type reactor that uses supercritical light water as a coolant and a separate low pressure heavy water moderator [2]. Vertical oriented channel concepts are currently being studied by Atomic Energy of Canada Limited (AECL). The Canadian PCh SCWR operates at a pressure of 25 MPa with inlet and outlet coolant temperatures of 350 and 625°C respectively [3]. Operating at such high temperatures and pressures results in higher thermal efficiencies, translating to increased electrical production; compared to modern operating light water cooled nuclear generating stations. Coolant, on the reactor side, enters at subcritical conditions and is heated to above the critical point (the critical point for light water (coolant) is P_{cr} = 22.064 MPa &T_{cr} = 373.95°C [4]). The thermophysical properties of the SCWR coolant undergoes a dramatic change as it passes through the critical point, resulting in the coolant which does not have distinct liquid or gas phases to act as a single phased fluid.

2. SCWR Reactor Design

The SCWR has an operating inlet pressure of 25 MPa and inlet and outlet temperatures of 350°C and 650°C, respectively. The total thermal power is 2540 MW_{th} with a thermal efficiency of 45 to 48%. The coolant is light water with an average mass flow rate of 3.92 kg/s per fuel-channel. The SCWR, analyzed, is composed of 336 vertically placed fuel channels and 10 fuel bundles per channel. The heated length of each fuel channel is 5 meters. The fuel bundle assembly is made of Inconel-600 and is comprised of 78 fuel elements in three layers of rings. The fuel is Uranium Oxide (UO_2) with a variation of enrichments at each layer of rings.

2.1 Pressure Channel & Bundle Design

A re-entrant Pressure Channel design is used with the cold leg of the coolant entering from the flow tube located in the center of the Pressure Channel. The re-entrant design (Figure 1) is used as the reference fuel channel design to perform the pressure drop analysis. It is composed of a series of components, including: a flow tube, liner tube, pressure tube and insulator. Cold coolant enters the channel through the flow tube and is driven downwards. At the end of the flow tube, the heated coolant flows upwards within the pressure tube. Heat is generated by the fuel elements located between the flow tube and pressure tube which is then transferred to the coolant by convection. The purpose of the insulator is to reduce heat loss from the pressure tube to the moderator. The design of the PCh considers SS 304 as the preferred material for the flow tube, liner tube and pressure tube. Yttria-Stabilized Zirconia (YSZ) at 70% porosity was the preferred material selected for the insulator.

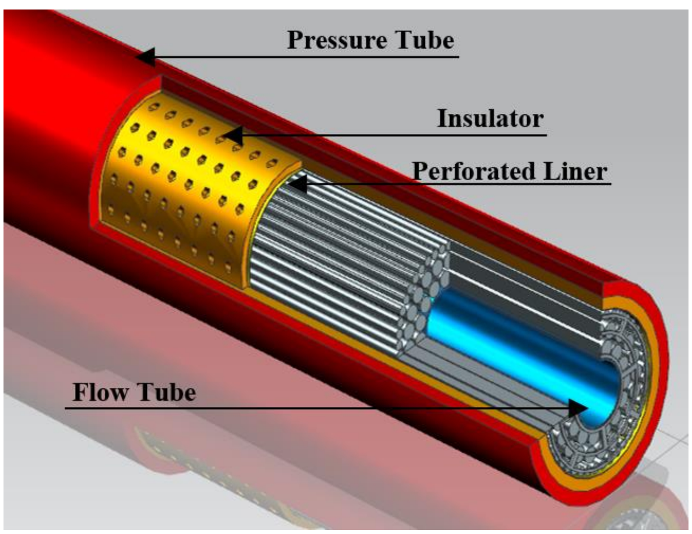

Figure 1: Re-entrant Channel Design

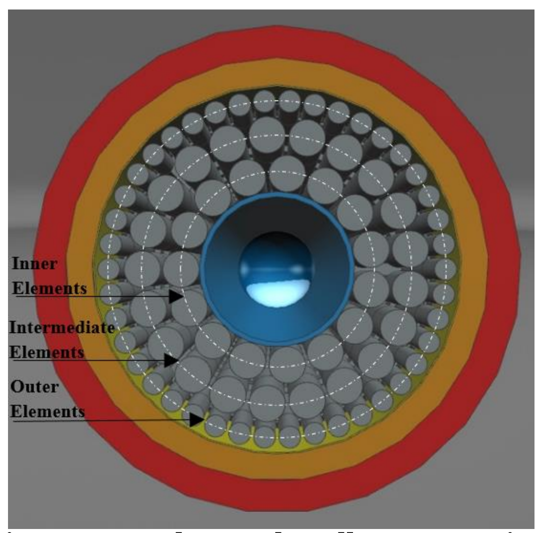

Figure 2: 78-element bundle cross section.

There are several bundle designs which can be used for a PCh SCWRs. For the purpose of this paper, the 78-element fuel bundle design will be used to perform the pressure drop calculations. The 78-element fuel bundle is comprised of 3 rings: 15 elements in Ring 1, 21 elements in Ring 2 and 42 elements in Ring 3. The elements in Rings 1 and 2 have a diameter of 1.36cm whereas, the elements in Ring 3 have a diameter of .82cm. Figure 2 provides a visual cross section representation of the 78-element fuel bundle.

3. Pressure Drop Analysis

As the coolant passes through the critical point the thermophysical properties of the coolant change significantly [5]. At supercritical conditions the coolant is similar to a subcritical single-phase fluid; therefore, the pressure drop calculations performed will be similar to a single phase pressure drop analysis. The total pressure drop across the re-entrant PCh can be determined by cumulatively summing four individual components. The four components, shown in Eq. (1), consist of frictional losses, acceleration losses, gravitational losses and local losses [6].

$$\Delta P = \sum \Delta P_{fr} + \sum \Delta P_{ac} + \sum \Delta P_{g} + \sum \Delta P_{l} \quad \textbf{(1)}$$

3.1 Frictional, Acceleration, Gravitation and Local Losses

The frictional losses were calculated based on the Darcey-Weisbach equation (Eq. (2)). Based on the assumption of a smooth pipe, the Filonenko correlation (Eq. (3)), was used to predict the friction factor applicable for Reynolds numbers in the range of $3 \times 10^4 \leq \text{Re} \leq 5 \times 10^6$ [7]. The Reynolds number was calculated using Eq. (4) and is within the applicable range to use the Filonenko correlation to predict the according friction factors.

$$\Delta P_{fr} = f\frac{L_i}{D_H}\frac{\rho V^2}{2} = f\frac{L_i}{D_H}\frac{G^2}{2\rho} \quad \textbf{(2)} \qquad f = \frac{1}{\left(1.82\log_{10}\mathbf{Re} - 1.64\right)^2} \quad \textbf{(3)}$$

$$\mathbf{Re} = \frac{GD_H}{\mu} \quad \textbf{(4)} \qquad \Delta P_{ac} = \rho_{i+1}\,V_{i+1}{}^2 - \rho_i\,V_i{}^2 = G^2\left(\frac{1}{\rho_{i+1}} - \frac{1}{\rho_i}\right) \quad \textbf{(5)}$$

It is predicted that there will be a significant impact on the pressure drop resulting from acceleration losses as the coolant reaches the critical point and the density of the coolant decreases significantly. The acceleration loss component was calculated using Eq. (5) [6]. Since the PCh is oriented in the vertical direction, the pressure drop due to gravity must be accounted for. The gravitational loss component was calculated using Eq. (6) [6]. In regards to Eq. (6), when the coolant is flowing downwards, the value of sin θ, is equal to ***-1*** and when the coolant is flowing upwards, the value of sin θ, is equal to ***+1***.

$$\Delta P_g = \pm g\left(\frac{H_{i+1}\,\rho_{i+1} + H_i\,\rho_i}{H_{i+1} + H_i}\right)\Delta L_i \sin\theta \quad \textbf{(6)} \qquad \Delta P_l = \xi_l\,\frac{\rho V^2}{2} = \xi_l\,\frac{G^2}{2\rho_i} \quad \textbf{(7)}$$

Local losses occur due to the presence of flow obstructions, such as the fuel bundles and their appendages, including but not limited to, endplates and spacers [8]. It was assumed that the local losses resulting from the presence of the appendages such as the endplates and spacers were cumulatively applied at the end of the fuel bundle along the heated length of the PCh. The local loss component was calculated using Eq. (7) [6].

3.2 Methodology

The pressure drop calculations were performed using MATLAB by creating a one dimensional steady state thermal-hydraulic code. A series of functions allowed the thermal-hydraulic code to be linked to NIST REFPROP [9]. Using this software allowed the thermal-hydraulic code to grab the correct thermophysical properties; such as density, enthalpy and dynamic viscosity, of the coolant. In other words, the pressure and temperature change with every interval, along the heated length, results in the thermophysical properties of the light water coolant to change.

Assuming a linear power distribution as well as the known inlet temperature and pressure parameters of the coolant, the temperature profile can be determined by calculating the enthalpy at each segment, and performing a cumulative sum. Enthalpy is determined from NIST REFPROP with the corresponding pressure and temperature at each segment. At each segment along the heated length the enthalpy is calculated using the heat balance equation.

4. Results

The temperature profile along the heated length is illustrated in Figure 3.This profile was further used to calculate the pressure profile. The pressure drop resulting from friction, acceleration, gravitation and local losses within the heated length of the channel was calculated to 60 kPa. It should be noted that all tubes within the PCh assembly were assumed to be smooth; the pressure drop from perforations were not taken into consideration and a local resistance coefficient of 25% was taken to perform the pressure drop analysis. Figure 4 illustrates the Pressure Profile of the PCh along its heated length.

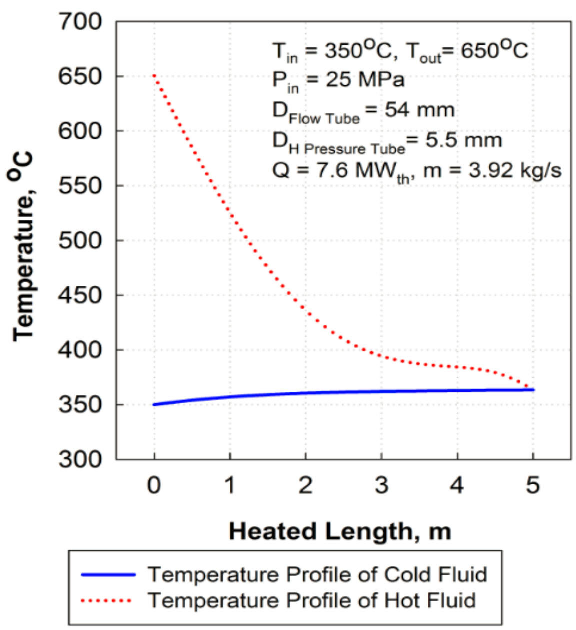

Figure 3: Temperature Profile along PCh.

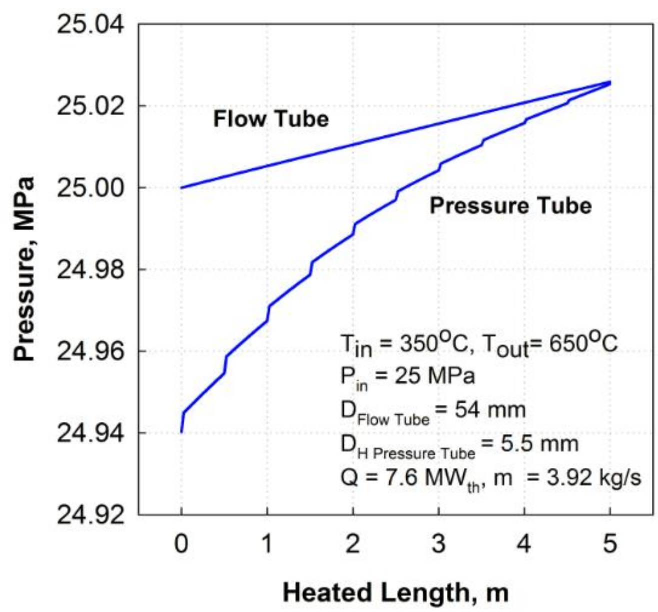

Figure 4: Pressure Profile along PCh.

As there are no fuel bundles in the flow tube there is no pressure drop from local losses. Pressure drops resulting from acceleration losses are not significant as there is not a large change in coolant density. Pressure changes, resulting from gravitation within the flow, are the most significant and act in the same direction as the flow of the coolant resulting in a pressure increase. Pressure drops, due to friction and acceleration, cannot balance out the pressure increase resulting from gravitation resulting in a net pressure increase over the length of the flow tube (inner tube).
As the coolant begins to flow up through the pressure tube (outer tube), the coolant begins to gain significantly more heat than compared to the coolant flowing through the flow tube. This significant increase in heat results in the coolant passing through the critical point within the pressure tube. Due to the presence of the bundles within the pressure tube, friction and local losses become the predominant pressure losses within the pressure tube. As there is a greater heat flux and surface area within the pressure tube which the coolant can contact, the frictional pressure drop is higher in the pressure tube compared to the flow tube. Due to the increase in heat flux within the pressure tube, the density of the coolant decreases resulting in a lower gravitational pressure drop within the pressure tube compared to the flow tube.

As the local resistance coefficient increases, it was observed that the pressure drop, due to local losses, increases. Table 3 provides further detail on the sensitivity analysis and the impact, which the local resistance coefficient has on the pressure drop caused by local losses. Table 4 provides a percentage breakdown of each of the pressure components within the flow tube and pressure tube. A negative sign represents a pressure drop whereas a positive sign represents a pressure increase.

Table 3: Local Loss Sensitivity Analysis.

Local Resistance Coefficient	Pressure Drop due to Local Losses (kPa)
15%	8
25%	22
35%	43

Table 4: Pressure Component Percentage Contributors.

Pressure Component	Percent Contribution %	
	Flow Tube	Pressure Tube
Friction	-8	-50
Acceleration	-2	-13
Gravitation	+90	-11
Local	0	-26
	100	100

5. Conclusion

The total pressure drop across the length of the heated PCh was calculated as the sum of four components which consist of friction, acceleration, gravitation and local. It was determined that the effect gravitation has on pressure is the single largest contributor in the inner tube as the coolant travels downwards and that friction and local are the largest contributors to pressure drop as the coolant travels upwards through the fuel bundles in the pressure tube. It was determined that the pressure profile has an impact on moving the pseudocritical point of the coolant, which has an adverse impact on the thermophysical properties of the coolant.

Based on the assumptions taken to determine the pressure profile along the PCh, there is uncertainty with the pressure drop due to the local losses. Future experiments are required to be performed to accurately determine the local resistance coefficient of the proposed fuel bundle for the re-entrant channel design since the local losses contribute to a significant pressure drop within the pressure tube.

6. References

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