PROGRESS ON THE INSULATED FUEL CHANNEL EXPERIMENTS FOR SUPERCRITICAL WATER-COOLED REACTORS

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Abstract

The High Efficiency Channel (HEC) design is being considered as an option for the CANDU Supercritical Water Reactor (SCWR). The current design uses a segmented yttria-stabilized zirconia (YSZ) to insulate the pressure tube from coolant reaching upwards of 650°C at 25 MPa. This paper presents the experimental facility currently being built to measure thermal conductivity of various insulators under prototypic conditions.

1. Introduction

Canada is a member of the Generation-IV International Forum (GIF), which is dedicated to the development of promising nuclear power reactors and fuel cycle technologies by 2030 [1]. The reactor designs will take advantage of the progress made in economics and safety. GIF has selected six reactor concepts to be the focus of international collaborative research and development. One of these selected concepts is the use of supercritical pressure water (SCW) as a reactor coolant, allowing for higher exit temperatures while remaining a single-phase fluid. In general, a supercritical water reactor (SCWR) will offer improved thermal efficiencies, reductions in pumping power, flow rates, and pressure drop, and elimination of steam generators [2].

The CANDU-SCWR concept, previously a CANDU-X concept, falls under this reactor category. A comparison of the CANDU 6 reactor with the current CANDU-SCWR specifications and operating conditions is given in Table 1 and Figure 1. The CANDU-SCWR will achieve thermodynamic efficiencies of ~48% by operating at coolant temperature and pressures up to 625°C at 25 MPa. These operating conditions are above the thermodynamic critical point of water. While the fluid remains single-phase, it does undergo large changes in its thermophysical properties as it passes through its pseudocritical temperature. Figure 2 shows the variation in specific heat (c_p), density (ρ), conductivity (k), and viscosity (μ) for water at 25 MPa. The pseudocritical temperature is defined as the temperature which, for a given supercritical pressure, water exhibits a maximum in its specific heat. At 25 MPa, the pseudocritical temperature for water is 385°C.

Table 1 Parameters specified for CANDU-SCWR in comparison to CANDU-6.

	CANDU-SCWR	**CANDU 6**
Efficiency (%)	48	35
Inlet temperature (°C)	350	266
Outlet temperature (°C)	625	310
Pressure (MPa)	25	10
Core flow (kg/s)	1320	7,700
Number of channels	300	380
Thermal power (MW)	2540	2,064
Gross electric power (MW)	1220	725

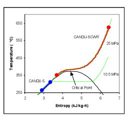

Figure 1 Operating conditions of a CANDU-6 and CANDU-SCWR.

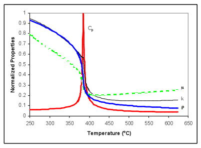

Figure 2 Thermophysical properties of light water at 25 MPa. Each property is normalized with its maximum value between 200°C and 625°C.

CANDU® reactors are particularly suitable for using supercritical water as the coolant. For example:

- The neutronics are mostly affected by the relatively constant density moderator water located outside the pressure tube rather than by the highly variable density of the primary coolant,
- The pressure boundary (pressure tube) can be adapted to accommodate the higher pressures, and
- The fuel bundle design, with its numerous end-plates and spacers, promotes turbulence, making it less susceptible to buoyancy related degradation in heat transfer as compared to other reactor designs.

With a conventional CANDU fuel channel, an increase in coolant pressure and temperature requires an increase in pressure tube thickness, resulting in a loss of neutron economy. The High Efficiency Channel (HEC) insulated fuel channel concept was selected as a way to preserve neutron economy [3]. This design uses a segmented monolithic ceramic to thermally insulate the pressure-tube from high temperature coolant. The pressure tube is designed to operate at ~80°C, reducing the required pressure tube thickness and enabling it to be in direct contact with the moderator. This eliminates the need for a calandria tube. A thin perforated liner will be used as a way to protect the insulation

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from the loading and unloading of fuel bundles; however, the insulation will be required to withstand the weight of the bundles.

The geometry and materials for the HEC have not yet been finalized [3]. The pressure tube will remain similar to the CANDU-6 diameter, but the exact dimensions depend on the material used. The proposed insulator material is yttria-stabilized zirconia (YSZ), due to its low susceptibility to corrosion in SCW and its relatively low neutron cross-section. The perforated liner material also requires a high corrosion resistance to the fuel coolant. Several suitable materials have been selected [3]. Table 2 highlights important parameters for the HEC fuel channel materials.

Table 2 Parameters of the experimental apparatus simulating the HEC fuel channel.

Item	**Material**	**ID/wall thickness (mm)**	**Proposed Operating Temperature (°C)**	**Conductivity at Operating Conditions (W/m-K)**
Moderator	D_2O	-	80	-
Pressure Tube	Zr-2.5Nb	~103.4/~6.5	~100	~20
Insulation	YSZ	~76.2/~13.6	80-650	~0.1-0.3
Liner	Chrom-moly Ferritic steel	~74.2/~1	300-650	~20
Coolant	H_2O	-	80-650	0.68-0.11

With coolant temperatures reaching up to 625°C, the requirement to keep the pressure tube at 100°C necessitates a significant temperature gradient existing across the YSZ insulation. Because water will occupy the porous openings in the insulation, it will also experience the same temperature gradient. This means the water will undergo significant changes in its thermophysical properties from the inner to the outer wall of the insulation, leading to a complicated "effective" thermal conductivity. Thus, experiments are required to determine the "effective" thermal conductivity of proposed insulators exposed to prototypic conditions.

This paper provides details of the current design of the HEC test apparatus, its instrumentation, and a preliminary experimental plan.

2. Experimental design

The large-scale test apparatus is intended to be as prototypical as possible, however, no specific dimensions or materials have been chosen at this time. The dimensions of this test apparatus are based on the current knowledge of the HEC design and that of the current reactor designs (*i.e.*, CANDU 6). A schematic diagram of the conceptual design is given in Figure 3. A cross-sectional view of the test section is given in Figure 4. The experimental apparatus, as discussed in the following sections, consists of a test section, calorimeter, pressure control system, and flow loop (optional).

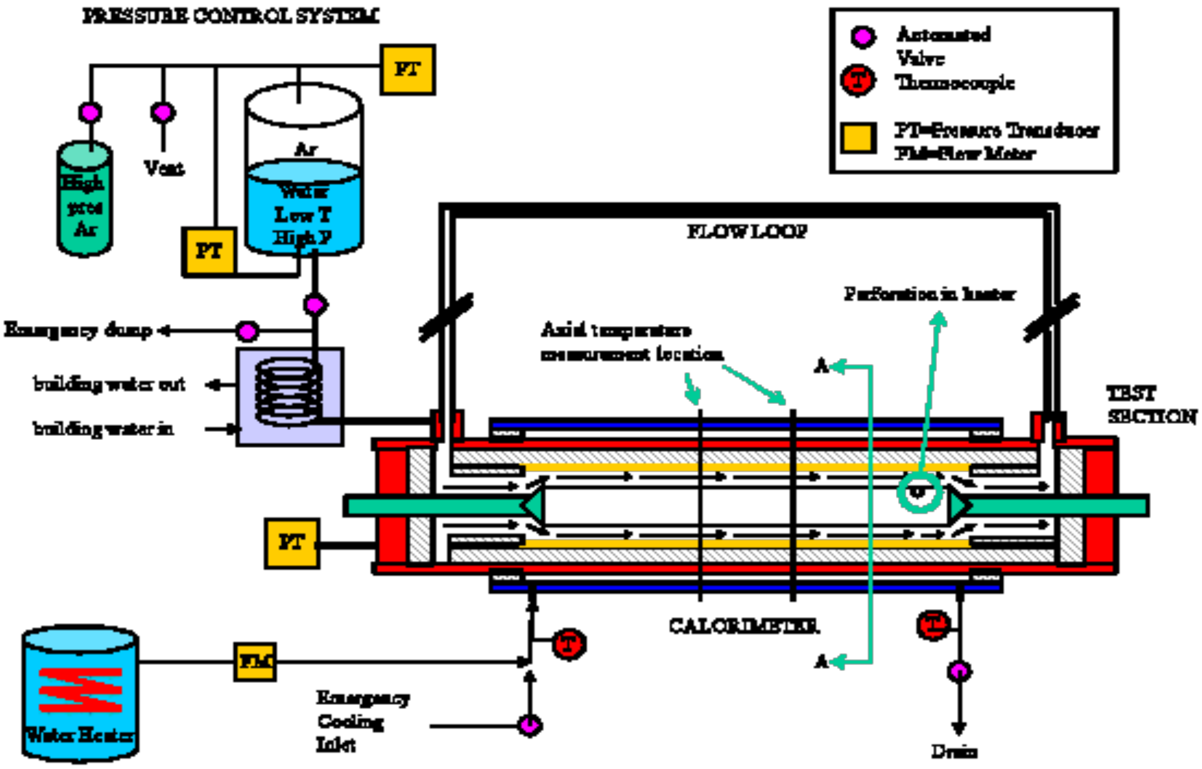

Figure 3 Schematic of the HEC test apparatus.

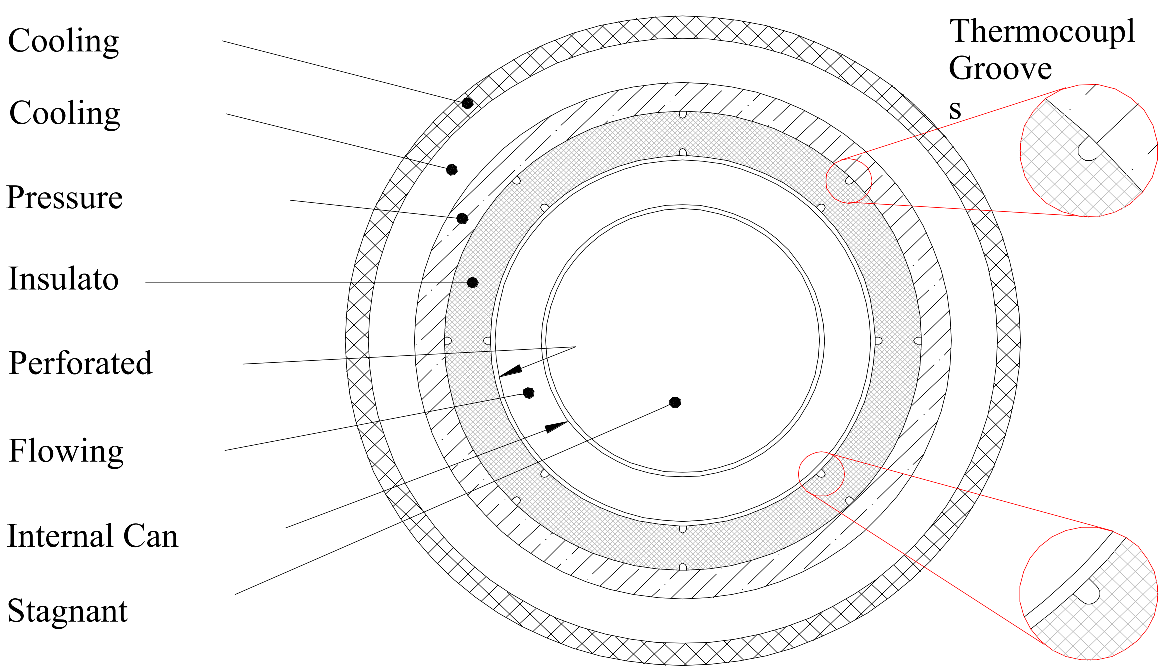

Figure 4 Cross-sectional view of the HEC test section (A-A).

2.1 Test section

2.1.1 Pressure tube

The pressure tube will have an inner diameter (ID) of 103.4 mm (+0.8/-0 mm) with a wall thickness of 6.5 mm. The overall pressure tube length will be 1600.0 mm, with the central 876.3 mm simulating the insulated channel. Assuming a safety factor of 3, this pressure tube will work safely up to 250°C at 25 MPa based on a hoop stress analysis. However, under normal operating conditions, the pressure tube will only approach ~100°C.

2.1.2 Insulator

Based on corrosion and dimensional stability tests, a YSZ material from Zircar Zirconia (Type FBD) has been selected for large scale testing. The insulator is composed of 90 wt% ZrO_2 + HfO_2 and 10 wt% Y_2O_3. Hafnia (HfO_2) occurs naturally with zirconia (ZrO_2) at 1-2 wt%. The insulation thickness could range from 5 mm to 20 mm, although initial tests will use a thickness of ~13.0 mm. The outer diameter will be important since the gap between the insulation and the pressure tube will affect the overall thermal conductivity of the channel. The outer diameter for the initial tests will be 103.5 mm. This gap of 0.1 mm will account for any ovality encountered in the pressure tube and any thermal expansion differences. Grooves will be made along the insulation for passing thermocouple wires for pressure tube ID and liner OD temperature measurements.

2.1.3 Liner

The liner will be made of a rolled, perforated Inconel 625 sheet that tightly fits within ID of the insulator. The material thickness will be on the order of ~1 mm. The perforation style will likely be chosen from an available standard.

2.1.4 Test section heater

Heating will be done internally within the test section to raise the temperature of the primary coolant from room temperature to the test conditions and to maintain steady state temperature during testing. Steady state operation will require up to 10 kW DC depending on the insulator performance.

The internal heater will be shaped as a tube, with a small coolant gap in the annulus formed between the heater and the protective liner. The ends of the heater tube will be sealed by the contact with bus bars supplying the electrical power. The heater will have several perforations to prevent it from being a pressure barrier. The material chosen for the heater is Inconel 625 due to its corrosion resistance and its electrical resistivity.

2.1.5 End hubs

The end hubs are required to allow the buss bars of the internal heater to extend out of the test section for the electrical connections to be made. The end hubs will be made of 304 stainless-steel and will be electrically isolated from the buss bars. A Teflon material will be used as the electrical insulator between the end hub and buss bar, requiring that the buss bars be cooled, as this material cannot withstand the high temperatures of the primary coolant.

Each end hub will have fittings to allow up to 20, 1.59 mm (1/16 inch) diameter thermocouples within the test section. Pressure boundaries between the end hub and pressure tube, as well as end hub and bus bar, will be sealed with O-ring and backup rings.

2.2 Calorimeter

The calorimeter is designed to minimize the uncertainty in determining the effective thermal conductivity while maintaining nearly prototypic OD pressure tube temperatures. A 120 kW boiler will be used for supplying water at elevated temperatures in a once through configuration. In the event the insulator material fails, additional cooling will be available to allow sufficient time for depressurization of the test section.

2.3 Pressure control system

The pressure control system (PCS) both controls the pressure and the water volume from the test apparatus. The accumulator volume is sized to handle the density changes of the water going from 20°C to 650°C at 25 MPa.

The top of the accumulator will be connected to both a high-pressure head gas (~40 MPa argon) and a vent to atmosphere, both controlled by automated valves. A pressure gauge will monitor the accumulator pressure. A differential pressure transducer will track the level of water in the accumulator. The diameter of the connection between the accumulator and test apparatus is very important as it will control the response time between the two systems. A 3 mm diameter tube is expected to provide a compromise between pressure drop and coolability of the water from the test apparatus. The line is required to handle up to 25 MPa and 625°C water. From the test apparatus, the line will enter a cooling bath to bring the fluid temperature below 40°C. After passing through the cooling bath, the water is directed to an automated valve and then to the lower end of the accumulator.

2.4 Flow loop (optional)

The previous horizontally oriented HEC test apparatus exhibited significant circumferential temperature gradients due to the circulation of the highly variable density fluid within the test section. Several different methods have been identified to overcome this problem and will be implemented based on cost and simplicity. First, the heater in the new test apparatus is designed to minimize the gap between the heated surface and the perforated liner. This should reduce the circumferential temperature gradient by reducing internal circulation. If this method does not give sufficient results, the test apparatus will be oriented vertically. This should eliminate the circumferential temperature gradient but introduce an axial gradient. This may be sufficient provided the axial gradient is not too large. Should this fail, the next step is to introduce flow through a natural circulation loop. The test section will have an inlet and outlet port that connects with a loop approximately 3.0 m high. Calculations suggested that a velocity of ~1 m/s could be achieved through external heating and cooling. The inlet and outlet ports will initially be included in the test section but the loop piping will not be finalized unless it is necessary.

2.5 Instrumentation

2.5.1 Temperature

Thermocouples passing through the high-pressure boundary must have a sheathing diameter of 1.6 mm outer diameter (OD) for swaging and sealing purposes. The YSZ thermal conductivity will be determined from thermocouples placed in 8 circumferential locations at cross sectional locations 100 mm axially off centre in both directions. The thermocouple sensor wire will be spot welded directly to the outside of the perforated liner and the inside of the pressure tube. Grooves will be machined into the YSZ to allow thermocouple access. This configuration should offer the most consistent and accurate surface temperature measurement that is reasonably possible.

The total number of thermocouples penetrating the pressure boundary is expected to be at least 32 for thermal conductivity measurements. Additional temperature measurement access would be required to monitor the internal heater for any degradation in heat transfer.

Temperature measurements will also be made on the outside of the pressure tube at the axial and circumferential locations of the insulation temperature measurements. An adequate number of thermocouples should also be used to monitor other locations on the pressure tube outer surface to help determine local failure of the YSZ insulator during operation.

Two high-accuracy thermocouples will be used for the inlet and outlet water temperatures of the calorimeter.

2.5.2 Pressure

Two high-pressure gauge pressure transducers will be used, one to monitor the accumulator pressure and the other to monitor the test section pressure.

A differential pressure transducer will be used to monitor the height of water in the accumulator. Two low-pressure gauge pressure transducers will be used to monitor the inlet and outlet pressure of the calorimeter.

A differential pressure transducer will be used to monitor the height of the reservoir supplying the pump in the calorimeter system.

A differential pressure transducer will be used to measure the pressure drop across the orifice for determining the primary loop mass flow rate. The transducer model will be dependent on the orifice sizing and the primary coolant pump specifications.

2.5.3 Flow

A high accuracy mass flow meter will be used in the calorimeter system as its measurement will be used in the calculation of the thermal conductivity

3. Experimental plan

3.1 Full scale experiments

3.1.1 Commission test apparatus

The objective of the commissioning tests is to explore instrumentation techniques for determining the effective thermal conductivity. Several experiments may be performed to test instrumentation techniques and make necessary changes. These tests may not require the flowing system, as stagnant conditions may suffice. Alternately, these tests could be performed with gases, such as argon, helium, and carbon dioxide at various temperatures and pressures similar to what was done in the previous HEC experiments. The compressibility of these gases would also eliminate the need for the PCS and these commissioning tests could be performed using the existing high temperature fuel channel laboratory systems, at Chalk River Laboratories, prior to completion of the HEC facility modifications.

3.1.2 Test considerations

The objective of the test program is to determine the thermal conductivity of proposed insulators exposed to prototypic conditions. Once the facility design is finalized, a detailed test plan will be documented. When formulating the detailed test plan, the following must be considered:

- Completion of the full experimental program will likely require the entire facility outlined in Section 3 to be operational, although some initial tests may be completed without flow. In this case, the primary loop would not be used.
- For a given insulator material and thickness, approximately 10 steady state experiments should be conducted varying the primary coolant temperature from 300°C to 625°C, all at a pressure of 25 MPa.
- The amount of data collected will depend on uncertainties and the conditions at which the experiment is done.
- As previously stated, the proposed insulator material is YSZ. Other insulator materials will need to be determined by small scale testing.

4. Conclusion

One of the design concepts for a CANDU SCWR is to insulate the coolant within the pressure tube with a yttria-stabilized zirconia insulator so that the pressure tube can operate at the temperature of the moderator, reducing its required thickness and eliminating the need for a calandria tube. The objective of the proposed experiments presented here is to determine the effective thermal conductivity of a yttria-stabilized zirconia insulator exposed to prototypic CANDU SCWR conditions. The preliminary design for a refurbished HEC test apparatus along with test considerations for the proposed thermal conductivity tests are documented here.

5. References

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