CONSTRUCTION OF A FLOW LOOP FOR SUPERCRITICAL HEAT TRANSFER EXPERIMENTS

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Abstract

This paper presents a progress report on the design and construction of an experimental facility suitable for supercritical heat transfer (SCHT) studies with carbon-dioxide flow in circular tubes with diameters of 8 mm and 22 mm and in a three-rod bundle subassembly. Details of the loop, including the pumping, heating and cooling systems as well as the instrumentation and control devices are described. Measurements of surface temperature will be obtained along the tubes and the rods in the bundle over a range of flow conditions corresponding to normal, enhanced and deteriorated heat transfer. Future work includes measurements of turbulence and fluctuating temperature characteristics in supercritical CO_2 flow through the 22 mm tube using hot-wires and cold-wires, respectively. These measurements will complement and expand the available database for the range of conditions relevant to the Canadian SCWR.

1. Introduction

The present research is in support of the Canadian National Program on Generation IV Energy Technologies for the development of a Super Critical Water-cooled Reactor (SCWR), which, compared to existing nuclear reactors, is expected to have increased safety, lower-cost electricity production, more compact size and reduced volume of nuclear wastes. The operation of such reactors requires heat transfer to the cooling fluid at pressures higher than the critical pressure.

At supercritical pressures, the thermophysical and thermodynamic fluid properties vary drastically in the near-pseudo-critical temperature range, giving rise to heat transfer phenomena which are not present at subcritical pressures. Previous experimental studies have identified three modes of supercritical heat transfer (SCHT) in vertical tubes with upward flow (Pioro and Duffey, 2007): i) a normal mode, comparable to that in subcritical fluids, ii) an enhanced mode, which occurs at relatively low heat fluxes when the PC temperature is approached and results in local wall temperatures that are lower than those corresponding to normal HT, and iii) a deteriorated mode, occurring at relatively low mass fluxes and high heat fluxes, provided that the PC temperature is higher than the fluid bulk temperature but lower than the wall temperature; HT deterioration is attributed to the reduction of local wall shear stress due to buoyancy and flow acceleration. Interestingly, the deteriorated HT mode was not observed in SC flow in rod bundles under conditions for which HT in tubes had deteriorated, possibly due to enhanced mixing.

The main objective of this paper is to describe the design and the construction of a new supercritical heat transfer test facility, including the pumping, heating and cooling systems as well as the instrumentation and control devices. This test facility will be commissioned using a vertical 8 mm tube as a test section. Two additional test sections will be used: a three-rod bundle and a 22 mm tube. Supercritical CO_2 will be forced to flow upwards in each of the three test sections where its state will change from liquid-like to gas-like following continuous heat addition from heated walls. The set-up can be relatively easily modified for the study of downwards flows in any of the test sections, as well as the study of horizontal flows and flows of arbitrary orientation, but such work is left for future extensions of this project. Wall temperature measurements in the 8 mm and 22 mm tubes, from which the local heat transfer coefficients will be determined, will complement and expand the available database for the range of conditions relevant to the CANDU SCWR and serve as a reference for comparisons with measurements from the rod-bundle test. The 22 mm tube test section will also be used for measurements of the mean velocity, mean temperature and velocity and temperature fluctuation statistics across the tube. The proposed measurements of turbulence characteristics will be valuable within the R&D required for the development of Generation IV SCWR in Canada.

2. Test conditions

CO_2 was chosen as a surrogate fluid instead of water because of its lower critical pressure and temperature, as can be seen in Table 1. Therefore, the CO_2 tests, compared to water tests, will operate at safer conditions, cost much less, and require much lower heating power.

Table 1 Critical conditions for water and CO_2

Parameter	**Unit**	**H_2O**	**CO_2**
Critical pressure	MPa	22.1	7.4
Critical temperature	°C	374.1	31.0
Critical density	kg m^{-3}	315	468

Tests will be conducted for the nominal ranges of conditions that have been summarised in Table 2. The full ranges may not be covered for all test sections.

Table 2 Test conditions

Parameter	**Unit**	**Range for CO_2 tests**	**Equivalent range in water**
Inlet pressure	MPa	6.60, 7.00, 7.36, 7.80, 8.36, 8.80	19.8, 21.0, 22.1, 23.4, 25.1, 26.4
Inlet temperature	°C	5 – 30	320 – 370
Outlet temperature	°C	20 – 60	350 – 435
Mass flux	kg m^{-2} s^{-1}	500, 1000, 1500, 2000, 2500[1]	594, 1188, 1782, 2376, 2970
Heat flux	kW m^{-2}	20 – 500[2]	150 – 3800

[1] representative values are shown; actual values would depend on pressure and inlet temperature
[2] actual maximum heat flux value would depend on limitations of the power supply

3. Description of the experimental facility

3.1 Laboratory space

The SCHT facility at the University of Ottawa is housed in two adjacent rooms (see Fig. 1), formerly used as Diesel engine test cells and converted to meet the present requirements. Both rooms are currently used exclusively for this project and they are separated from other working areas by secure walls. The main laboratory consists of a two-storey space, with approximate dimensions of 4.40 m (total height) × 2.90 m (width) × 5.43 m (length); the lower level has a height of 1.80 m and the upper level has a landing area with a length of 1.12 m and ledges on both its sides, each with a width of 0.35

m. Access to the lower level is through a steel staircase, whereas the landing area on the upper level and a traversable platform permit convenient handling of components located in the upper half of the space. Two specially designed gantry cranes, sliding on tracks on either side of the room at mid-level, permit the safe transport and placement of heavy components, up to 2000 kg in weight. A steel plate, approximately 3.35 m in length and 1.22 m in width, with parallel mounting grooves has been positioned on the floor. A scaffold, made from steel channels and anchored on the steel plate and the walls, will be used to mount the test sections, the heat exchangers and other loop components. A new main power line, dedicated to this facility, was installed in the room. It is certified for 600 V AC, 3-phase, 200 A electric power and a circuit breaker capacity of 208 kW. Additional power outlets and service boxes for the pump motors and other accessories were installed, giving an assortment of voltages, as required (600 V, 220 V, and 110 V).

The second room of the facility is a walk-in freezer (Copeland, Model #WZWU1500TSE, installed by a local Engineering firm), having an approximate floor area of 4.50 m × 2.50 m. The freezer compressors were restored, upgraded, and furnished with an environmentally friendly refrigerant (HP-80) and new temperature controls. It has a continuous compressor capacity of 23/19/15 kW for room temperatures of -30/-40/-50 °C. This freezer will be used to reduce the fluid temperature at the inlet of the test sections to values lower than those achievable by other available means.

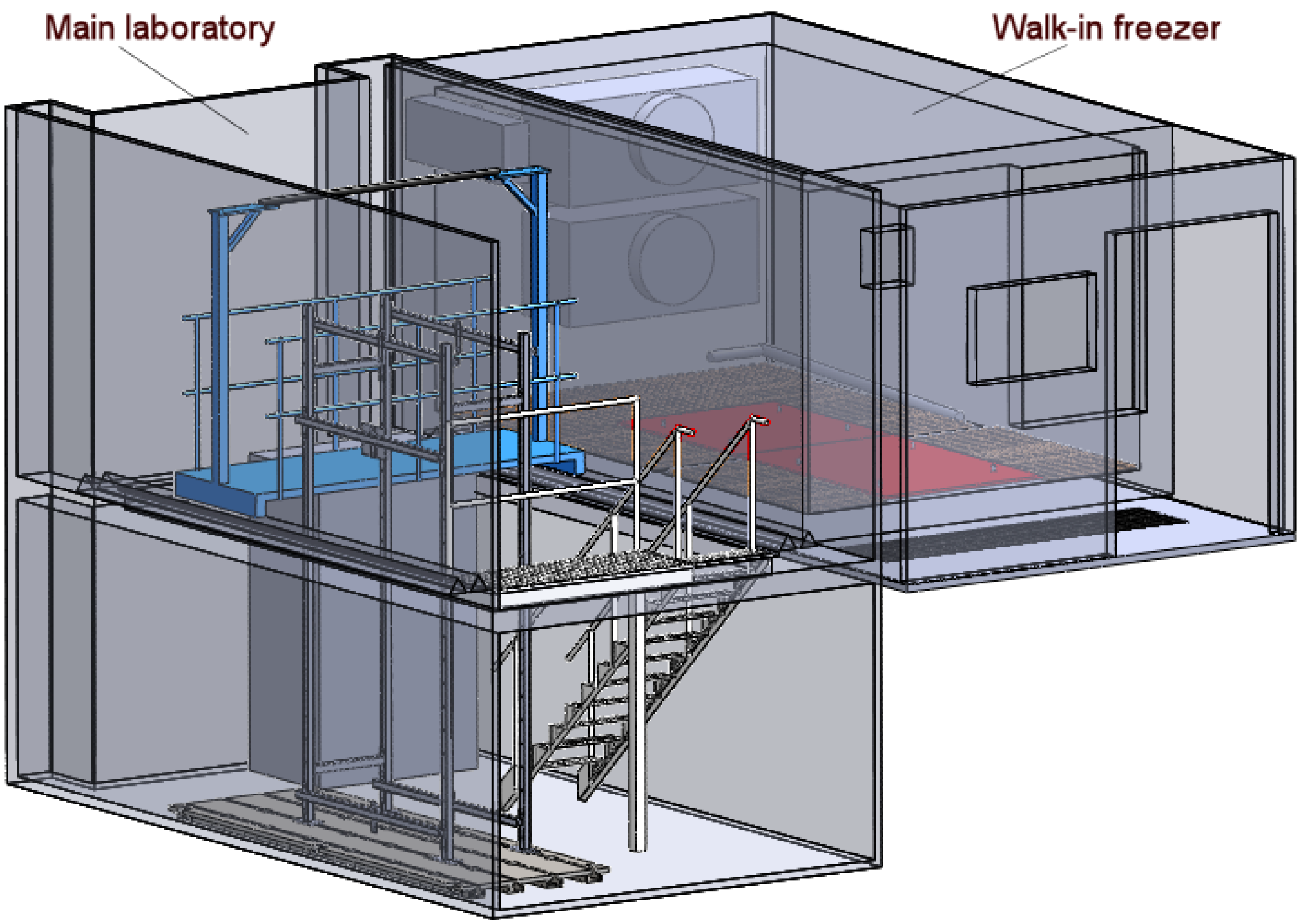

Figure 1 Laboratory space.

3.2 Main components of the loop

A schematic diagram of the loop is shown in Fig. 2. The loop was designed for a maximum hydrostatic pressure of 15 MPa and a nominal operating pressure of 10 MPa. Following evacuation using a vacuum pump and purging with nitrogen, the loop will be filled with CO_2 from cylinders with an internal pressure of 13 MPa through a regulating valve set at the desired pressure. In the early stages of the work, the CO_2 flow in the loop will be maintained by two gear pumps (Cole-Palmer, Model GLH23.JVS.E.M2N1CH15) connected in parallel; in later stages, additional pumps will be connected in parallel to provide higher flow rates. Each pump has a maximum flow rate of 21.6 l/min and a maximum differential pressure of 860 kPa. Each pump will be operated by a three-phase AC electric motor, and the rotational speed of all motors will be adjusted by a single inverter. A bladder accumulator, having the high-density CO_2 on the liquid side and gaseous Nitrogen on the gas side, will be installed downstream of the pumps to maintain the loop pressure at the desired value during its operation. A pressure relief device and a rupture disc (Fike Canada, Inc., Poly SD style, scored, forward-acting, non-fragmenting rupture disc) will be used to prevent over-pressurization of the loop. The loop piping will consist of 316/316L stainless steel seamless tubing, with a 25.4 mm OD and a wall thickness of 2.11 mm. All components will be connected with Swagelok fittings.

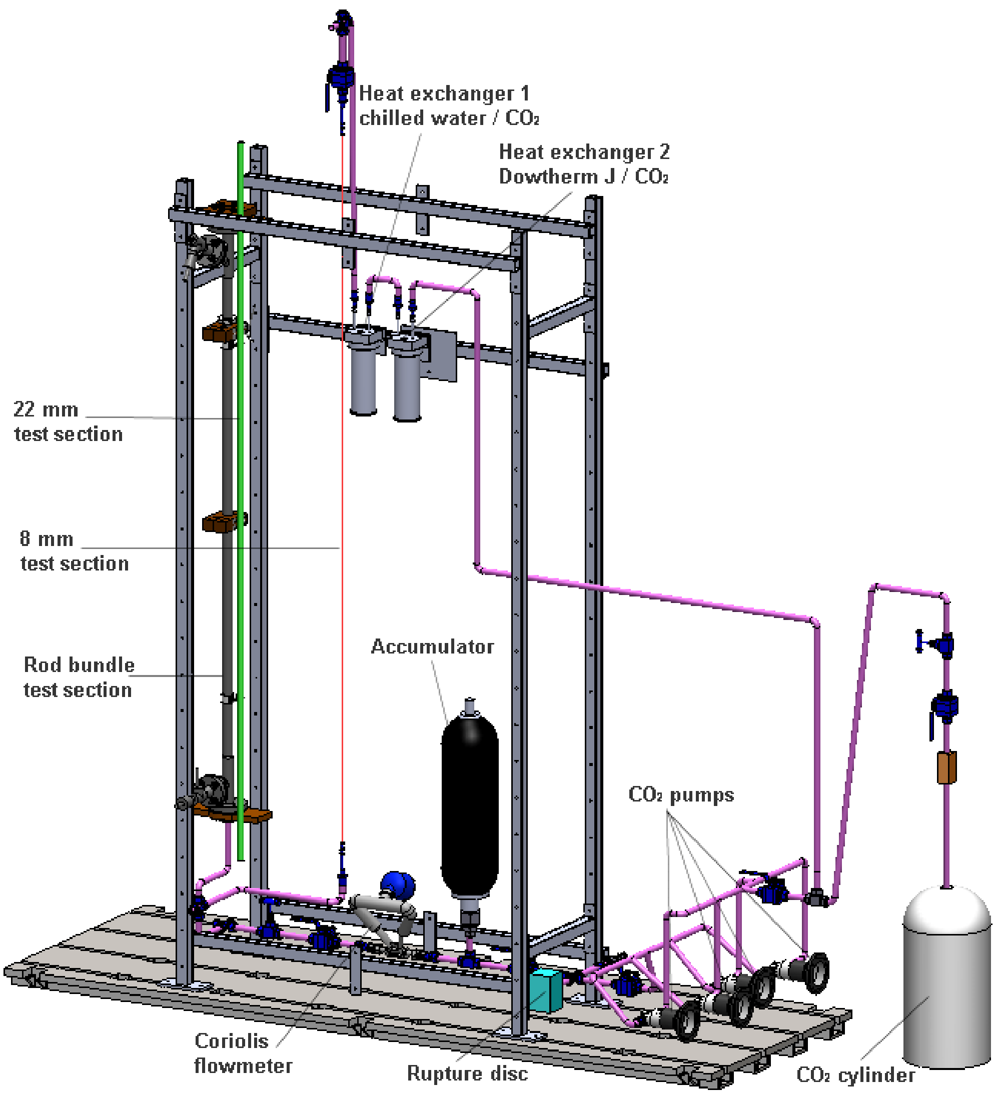

Figure 2 Schematic representation of the supercritical CO_2 loop.

3.3 Heating system

All test sections will be heated electrically by passing direct current through the wall of each of the two tubes or the three rods of the rod bundle. In consideration of the very low electric resistance of the test sections, a low-voltage/high-current DC power supply, shown in Fig. 3, will be used to provide the required heating power. This device was available at the University of Ottawa and recently restored and recertified. It is rated at a maximum voltage of 60 V DC and a maximum current of 2833 A. It is currently equipped with four cable pairs supplying a maximum total current of 1600 A, but it can easily supply its maximum current by the addition of more cables. Depending on the needed heating power each test section will be connected to the power supply by one or more cable pairs.

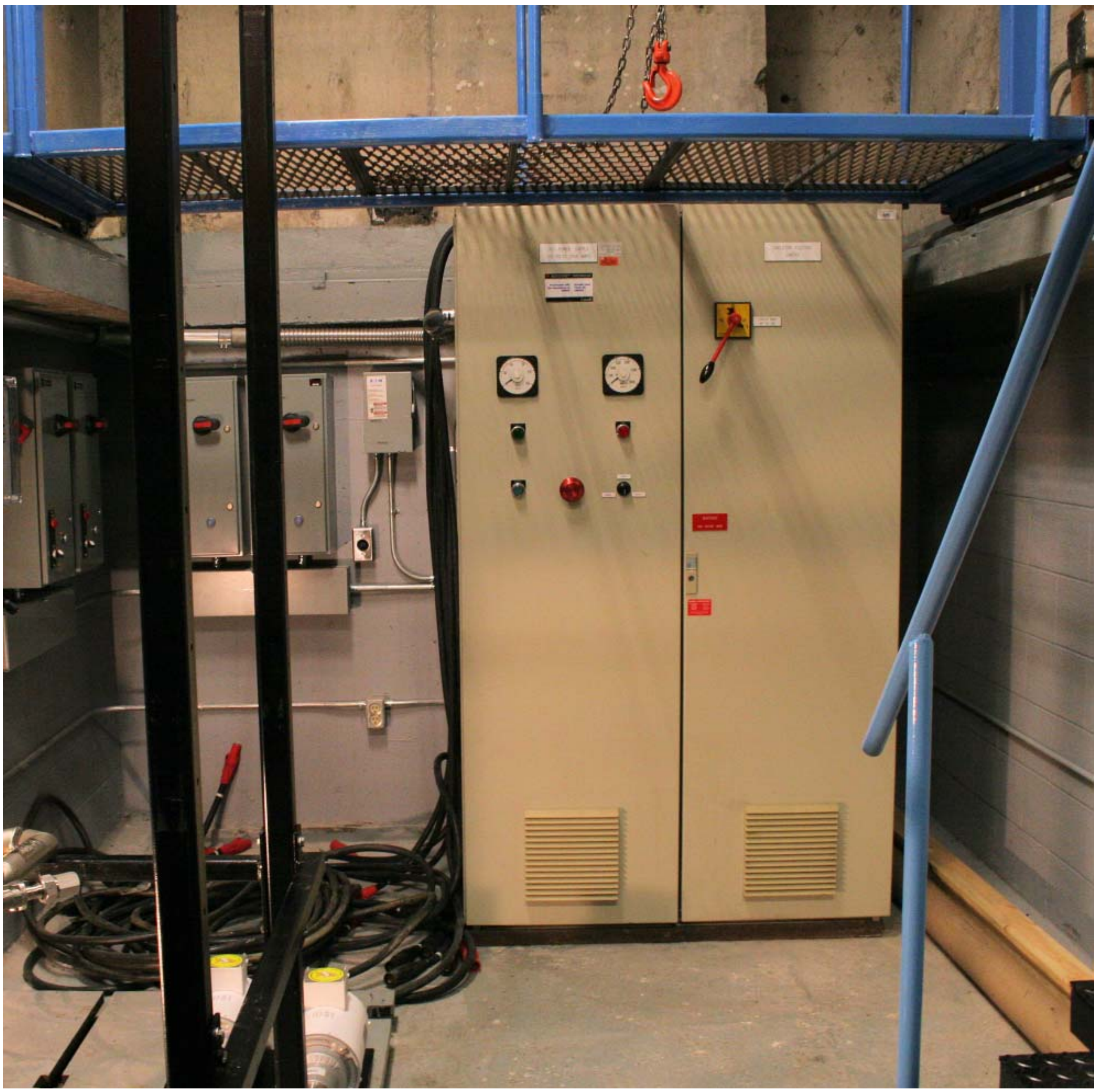

Figure 3 Photograph of the DC power supply.

3.4 Cooling systems

A main challenge of the facility design was to put in place a high-capacity, low temperature cooling system for removing the heat generated in the test sections, as required for the short-term or continuous operation of the loop. Following careful consideration of the possible alternatives, we have adopted a two-stage cooling system. The first stage uses the University's chilled water supply. To enable this, we have installed a new instrumented and filtered chilled water line dedicated to our lab. The chilled-water system specifications are summarised in Table 3. Although, at first glance, the chilled-water system has sufficient capacity to remove all Joule heating power from the loop, it operates at a temperature that is not low enough for our needs. So this system will be used mainly to cool the supercritical CO_2 to the lowest possible temperature below the pseudocritical temperature. The second stage cooling system will bring the CO_2 to the desired inlet temperature by using a coolant operating at a much lower temperature. The fluid chosen for use in this second stage is Dowtherm J synthetic organic heat transfer fluid (Dow Chemical Co.), which has a relatively low viscosity at low temperatures (1.8 mPa s at -20 °C, which is much lower than that of glycol or other commonly used low-temperature liquids). A large quantity (currently 400 liters, to be increased in the future, if necessary) of this liquid is contained in a tank, made of polyurethane material, 0.81 m in diameter and 1.75 m high, with a capacity 662 liters. The tank is fastened to the floor of the walk-in freezer, from which the coolant will be pumped to the loop location using a low-temperature pump (Dynapump Corp., Model JSB-2HP-1S, rated at 75 l/min). The same liquid is recirculated by a separate pump (similar to the previous one, but rated at 37.8 l/min) to two radiators (Heat Innovations, Inc., 2-Row, 36×36) inside the freezer to restore its temperature to a level as low as possible. Both pumps are located outside the walk-in freezer.

At present, two heat exchangers have been installed in the loop. Both are single helical tube sample coolers (Sentry Equipment Corp., Model FXF-6223U). The first one, connected at the outlet of the test section, will use the chilled water and the second one, connected to the outlet of the first heat exchanger, will use the Dowtherm J fluid. These heat exchangers are expected to be sufficient for the 8 mm tube and the rod bundle, but two larger heat exchangers, tentatively of the spiral tube type, will be acquired for use with the 22 mm tube.

Table 3 Cooling system specifications

Parameter	**Unit**	**Value**
Chilled water system:		
Inlet temperature	°C	10 (winter), 5 (summer)
Flow rate	l/min	166
Cooling capacity	kW	215 (winter), 274 (summer)
Dowtherm J system:		
Inlet temperature	°C	-35 (higher for continuous operation)
Flow rate	l/min	180
Cooling capacity	kW	92

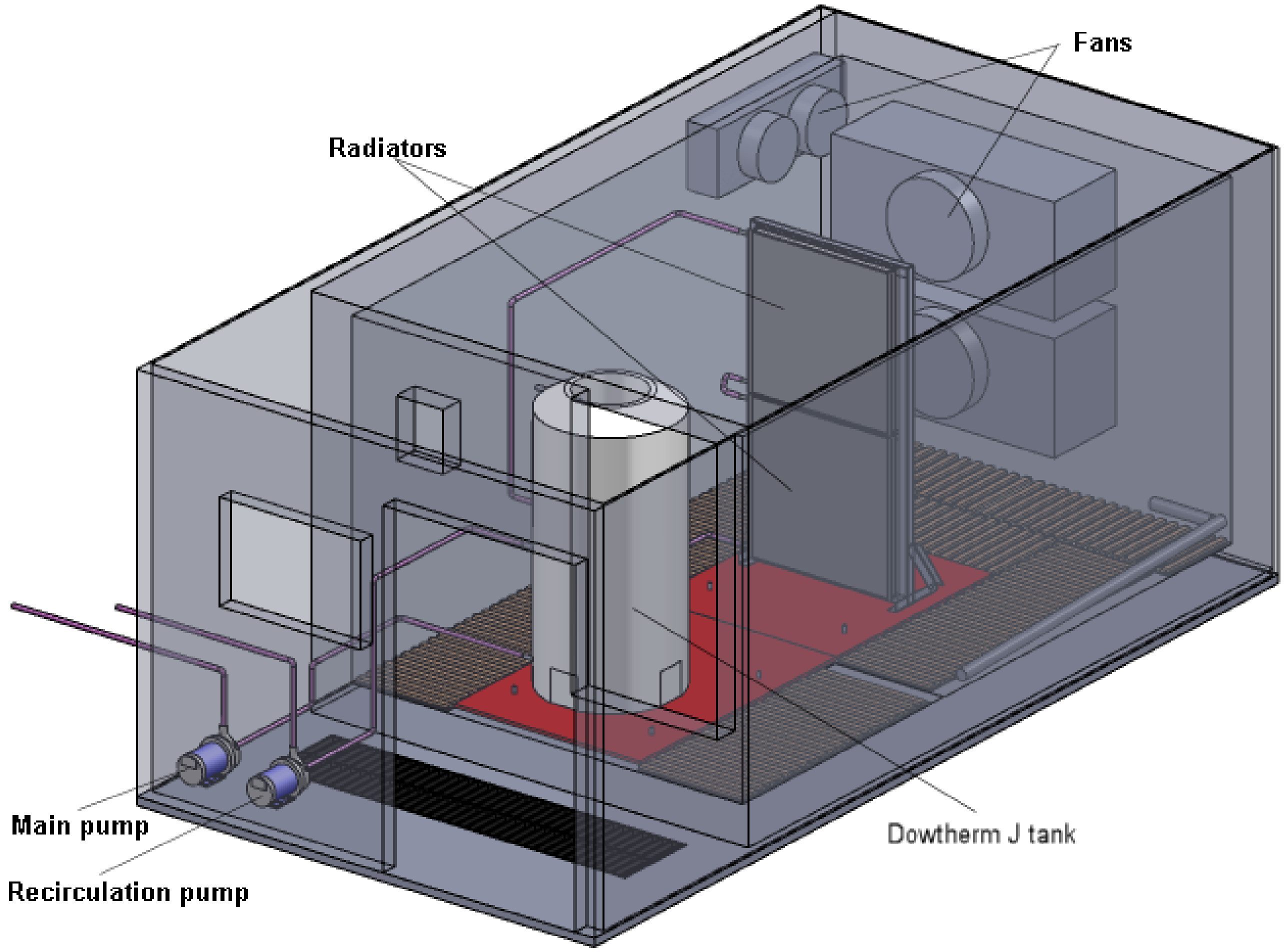

Figure 4 Schematic diagram of the Dowtherm J cooling system.

3.5 Test sections

The following three test sections will be used in this study:

- A circular tube made of Inconel 625 with an ID of 8.0 mm, a wall thickness of 1.0 mm and a length of 3.05 m. This tube will be mounted vertically for upward flow using electrically insulating connectors. The tube will be connected to the power supply using two electric terminals, which will be clamped on the tube, one near its downstream end and another at a position that could be adjusted so that different temperature fields could be generated within the tube. An upstream part of the tube, a least 1 m (i..e., 125 diameters) long, will remain unheated to allow the flow to develop without complications due to heating.
- A circular tube made of Inconel 600 with an ID of 22.0 mm, a wall thickness of 1.5 mm and a length of 3.05 m. This tube will be connected in the loop and heated in a manner similar to the 8.0 mm tube.
- A pressure tube with an inner diameter of 25.4 mm (Fig. 5), which contains a rod bundle subassembly comprising three directly heated rods and three wall inserts to simulate the subchannels of larger bundle assemblies (Fig. 6). The rod bundle has five sections connected in tandem, thus resembling a segment of a fuel bundle string in a CANDU reactor pressure tube. Each section is 500 mm long, and is separated from the neighbouring sections by endplates.

Spacers are positioned between the rods and bearing pads are positioned between the rods and the pressure tube at regular intervals to ensure that the gaps remain as uniform as possible. The first and last sections of the rod bundle are made of copper, whereas the three sections in the middle are made of Inconel, so that only these three sections are subject to significant direct heating. The rod diameter is 10.0 mm and the pitch to diameter ratio is 1.14. The hydraulic diameter of the rod bundle is 6.7 mm and the flow area is 177 mm^2. The ends of the three rods are fastened on copper plates, which will be connected to the power supply. The inner surface of the pressure tube is electrically insulated.

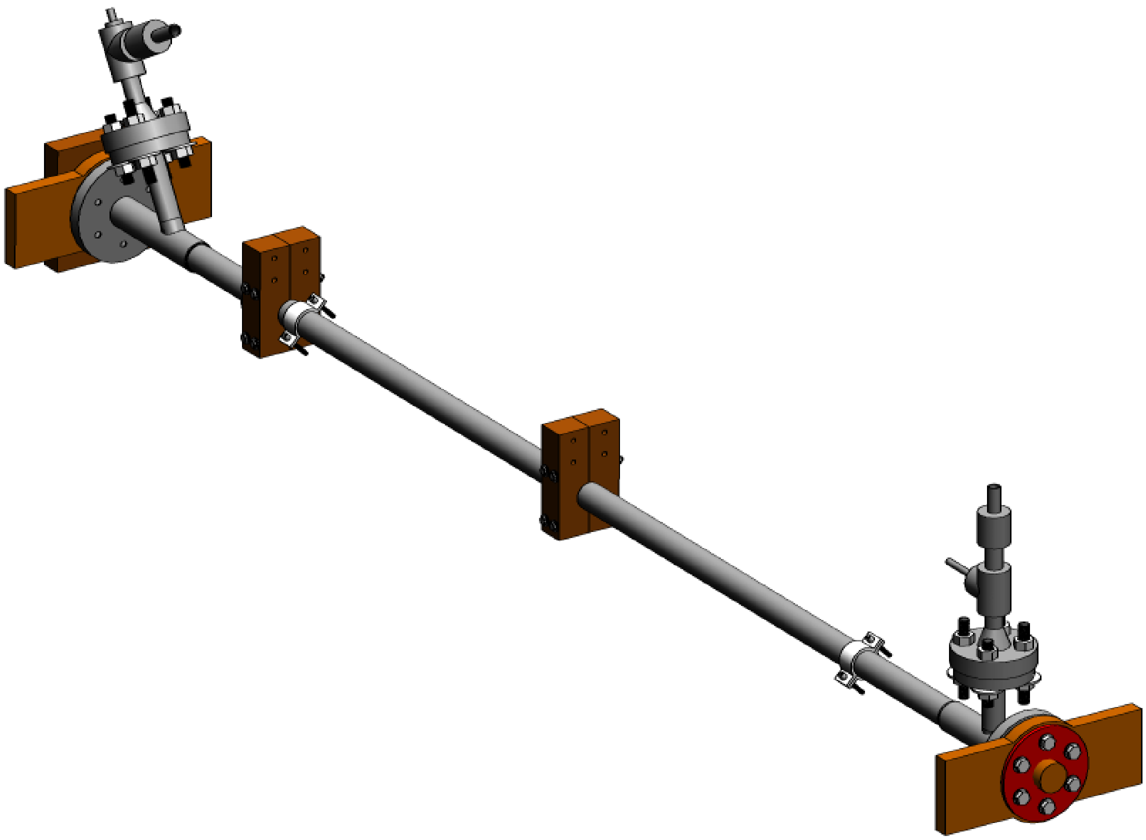

Figure 5 The pressure tube containing the rod bundle.

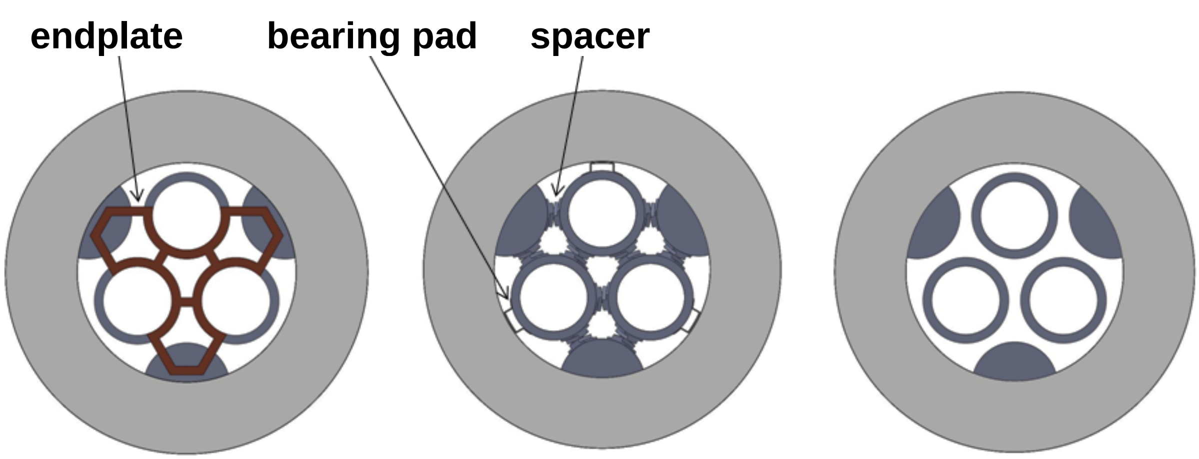

Figure 6 Rod bundle cross-sections showing the different components.

3.6 Instrumentation

A Coriolis-type flow meter (Micro Motion, Model CFM050M320N0A2E2ZZ) will be installed near the inlet of the test section to measure the mass flow rate. A differential pressure transmitter (Omega Engineering, Inc., Model PX771A-300WCDI) will be used to measure the pressure drop from the inlet to the outlet of the test section. The CO_2 temperatures at the inlet and the outlet of each test section will be measured by platinum, ultra-precise, long-stem RTDs (Omega Engineering, Inc., Model P-M-1/10-8-5-1/2-G-15) inserted in elbows so that their stem is parallel to the flow. The temperature along the outer walls of the two tubular test section will be measured using glue-on, electrically insulated thermocouples and RTDs. The thermocouples (Omega Engineering, Inc., Model SA1XL-T-SRTC) are of T-type, and will be calibrated individually before installation to reduce their uncertainty. The RTD are miniature flexible thin platinum type (RDF Corp., Model 29223 - three-wire type). The ranges and uncertainties of these instruments are summarized in Table 4.

Table 4 Instrument range and uncertainty

Instrument	Unit	Range	Uncertainty
Coriolis flow meter	kg s^{-1}	0 – 25	0.05%
Thermocouple	°C	-73 – 260	0.5 (to be lowered by calibration)
Wall RTD	°C	0 – 200	0.15 + 0.002|T|
In-flow RTD	°C	-73 – 400	0.03 + 0.0005|T|
Differential pressure transmitter	kPa	0 – 75	0.1%

On the 8 mm tube, thermocouples will be installed at distances of 300 mm in the upstream one third of the tube (unheated section) and at distances of 50 mm further downstream. Several RTDs will be installed at the same downstream locations as some thermocouples to allow comparisons of independent wall temperature measurements. Similar installations of thermocouples and RTDs are planned for the 22 mm tube. Each of the three rods of the rod bundle is equipped with a pair of spring-loaded, insulated, sliding thermocouples, arranged across each other on the upstream end of a shaft sliding in the interior of the rod and protruding from its downstream end. The thermocouple-shaft assembly can be both traversed axially and rotated, so that the temperature variation can be measured along and around the inner wall of the third heated section of each of the three rods. These thermocouples are of K-type and, although no specifications are available for them, they were found to be operational and all six had readings that were within 0.1°C from each other in the unheated rod-bundle.

The velocity and temperature fluctuations in the 22 mm ID test section will be measured with hot-wire and cold-wire probes, respectively. The velocity sensor will be operated in the constant temperature mode and the temperature sensor will be operated in the constant current mode. The design of these probes will be similar to the one used by Vukoslavčević et al. (2005), who have also presented significant results of probe calibration and response under a range of conditions comparable to those of interest in this work. The design of the probe insertion and traversing system poses significant challenges. Because of the direct heating of the test section wall, it is not permissible to interrupt the continuity of the wall by installing ports in the heated section. The most viable approach seems to be to insert the probes into the heated part of the test section axially through its downstream end. Another possibility to be examined is to insert the probes transversely through the downstream copper clamp that serves as electric terminal and then through the tube wall. In either case, the probes must be electrically insulated from the test section as well as sealed to a pressure of at least 10 MPa. As the probes need to be traversed across a test section diameter, the probe support and traversing system must also be designed to meet the insulation and sealing requirements. It is desirable to have simultaneous measurements of the fluctuating velocity and temperature, not only to measure their correlation and other joint statistical properties, but also to correct the instantaneous hot-wire signal for temperature variations. Another challenge will be to design a calibration procedure of the probes that avoids, as much as possible, the frequent evacuation and refilling of the loop. A separate calibration facility, similar to the one used by Vukoslavčević et al. (2005), will be constructed for the initial calibration of the probes, but we will also consider the possibility of performing *in situ* calibrations against a micro-Pitot tube and a micro-thermocouple or micro-thermistor, which will be inserted and traversed in the test section together with the hot- and cold-wire probes, thus also providing independent measurements of the local mean velocity and temperature in the CO_2. Although the probe size and the flow disturbance caused by probe insertion are too large to permit measurements very close to the wall, this set of measurements of velocity and temperature fluctuations are expected to contribute to the understanding of the complex phenomena of heat transfer enhancement and deterioration, which occur under certain conditions of interest to SCWR, and to serve as benchmarks for the validation of analytical models and numerical simulations.

Acknowledgments

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