DESIGN AND THERMAL/STRUCTURAL ANALYSIS OF A SUPERCRITICAL WATER THERMOHYDRAULICS LOOP

M. Balouch, R. G. Alena, A. Mason, J. Goldak, M.I. Yaras
Carleton University, Ottawa, Canada

Abstract

The Carleton University thermal-hydraulic water loop is a high-temperature high-pressure test loop developed for the study of forced-convection heat transfer in ducted water flow at supercritical conditions. The loop is designed to operate at pressures as high as 28 MPa and temperatures up to 600 °C. The supercritical water loop is housed at Carleton University's high-temperature test facility. This paper describes this high-temperature test facility, the design features of the supercritical water loop, and the results of thermal and structural analyses performed as part of the design process.

1. Introduction

Worldwide research is ongoing to develop advanced nuclear power plants with higher thermal efficiency and better fuel cycle capabilities to improve their competitiveness and long-term sustainability. International Research and Development collaborative organizations, such as the Generation IV International Forum (GIF), have been established in relation to these research activities with Canada participating in several of them. The CANDU-Supercritical Water Reactor (CANDU-SCWR) is one of the reactor concepts considered by GIF for international cooperative development [1].

The CANDU-SCWR uses light water under supercritical conditions as coolant and heavy water as the moderator [1]. The coolant enters the fuel channel at a pressure of 25 MPa and a temperature of 350°C, and exits the fuel channel at a temperature of about 625°C.

For safe and accurate design of the CANDU-SCWR, a thorough knowledge of supercritical water (SCW) heat transfer properties as anticipated in the reactor's fuel-rod bundles is required. To date, limited progress has been made in improving our knowledge of this heat transfer process, with associated ongoing difficulties in reliable prediction of the complete heat transfer coefficient spectrum of SCW [2]. To help address this issue, a high-temperature heat-transfer test facility is being developed at Carleton University. The heat transfer facility will house a SCW loop and a supercritical R-134a loop for heat transfer experiments involving a variety of test-section geometries, ranging from a straight circular pipe to configurations that closely simulate the thermal-hydraulic path encountered by the coolant in nuclear-reactor fuel-rod bundles.

This paper describes the capabilities of the Carleton high-temperature test facility and the design of the SCW loop. To ensure safe functionality of the SCW loop, a series of thermal and structural numerical simulations of the fully-assembled loop configuration have been performed. The results of the simulations for selective operating conditions of the SCW loop are presented.

2. High-temperature heat-transfer test facility

The high-temperature heat-transfer test facility at Carleton University as illustrated in Figure 1 is 7 m wide (at its narrow end), 30 m long, and 2.9 m high. Although the facility and hence the test sections are limited to 2.9 m in the vertical direction, the substantial length of the facility will allow for future experiments involving very long horizontally-oriented test sections. The facility is currently being configured to accommodate two test loops designed to allow for testing of the heat-transfer characteristics of water and Refrigerant-134a over a range of flow and thermal conditions that are compatible with those anticipated in the CANDU-SCWR.

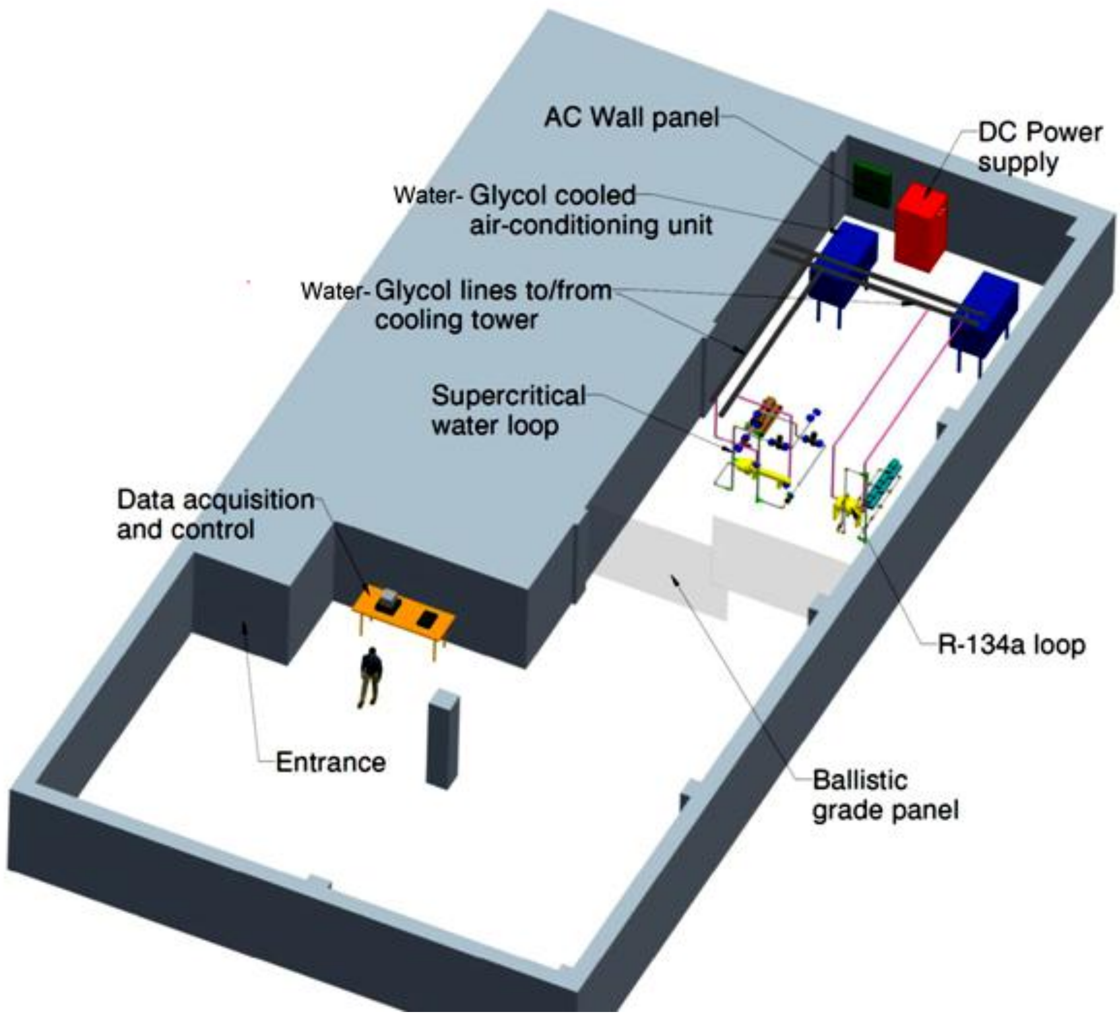


Figure 1 Layout of the high-temperature heat-transfer test facility

500 kW of 3-phase AC electrical power at 600 V is delivered to the test facility, a portion of which is then transformed to DC power (0-150 V, 0-2000 A) for use in resistive heating of the working fluids in the test loops. It has been found that the critical heat flux values obtained in a test section with DC Joule heating can differ from those obtained in a test section with AC Joule heating and the difference is more pronounced in thin-walled test sections [2]. Due to a similar phenomenon called pseudo-boiling under supercritical conditions, the Joule heating will be

restricted to DC power in the present test setups. A Magnavolt type DTLG 600-150/2000 transformer provides the AC-to-DC power conversion with an efficiency of 94% and a maximum ripple factor of 7%, and allows for control of the output power through adjustable voltage and current with ±1% stability and ±1% regulation capability. The AC power not utilized by the transformer unit is sufficient to power the pump motors and two air-conditioning units that will be used at cooling capacities up to 25 kW. This cooling capacity is estimated to be sufficient to offset the stray heat transfer from the loops, the transformer and other auxiliary equipment in the facility. The 500 kW electric power entering the facility is removed from the facility in the form of heat and released to the atmosphere through a forced-draft counter-flow wet/dry cooling tower. The heat exchangers of the two test loops and the two air-conditioning units transfer their heat to a 50-50 water/glycol mixture that is circulated at a constant rate of 107 m^3/hr (470 GPM) between the facility and the cooling tower. The water/glycol mixture returns to the facility at an adjustable preset temperature. For the design of the loops, this preset temperature was taken to be 29 °C (85 °F). The cooling tower adapts to the thermal load through adjustment of the air-fan speed and introduction of a water spray when needed.

As depicted in Figure 1, the test loops are located some distance away from the above-described infrastructure to take advantage of the highest floor-to-ceiling distance available in the laboratory. The laboratory space occupied by the two test loops and the supporting infrastructure is separated from the remainder of the laboratory by ballistic-grade composite panels for added protection of personnel during operation of the facility. The control of the cooling tower system, the electric power supply, and the test loops is realized remotely from a location in the laboratory that is not in direct line-of-sight of the test loops. Signals acquired from various sensors on the test loops are also transmitted to this location via a wiring harness.

The test loop with the R134-a working fluid is intended for heat-transfer measurements that cover thermodynamic states both above and below the critical point. The measurements in the supercritical range are to be used in conjunction with data from the water loop to support fluid-to-fluid model development efforts for heat transfer characteristics of fluids in supercritical thermodynamic states. The low critical pressure and temperature of R-134a relative to those of water make the design and instrumentation of the R-134a loop less challenging than that of the water loop. The remainder of this paper therefore focuses on the development of the water loop.

3. Supercritical water loop

Figure 2 shows the layout and major components of the Carleton SCW loop; the piping and instrumentation diagram is given in Figure 3. The loop is designed for a wide range of operating conditions with pressures up to 28 MPa and fluid temperatures up to 600°C at the test-section outlet. The loop is contained within a space that is 2 m wide, 3 m long and 2.5 m high when the test-section is in the vertical position. The test-section can be readily reconfigured to the horizontal position, in which case the loop assumes the dimensions of 2 m width and 5.5 m length.

The loop piping is of nominal size 1.5 in schedule XXS (Double Extra-Strong) made of stainless steel 316H with an outer diameter of 48.26 mm (1.9 in) and an inner diameter of 27.94 mm (1.1 in). Pipe and component connections are made with either Grayloc™ connectors or Class-2500 ASME flanges.

The test-section leg of the loop is designed such that different test sections of up to 2.3 m length can be easily interfaced with the loop using the provided inlet/outlet connections. Heat is imparted to the water in the test section through Joule heating of selected portions of the test-section walls that are in contact with the water.

The major components of the test loop are described in the following subsections.

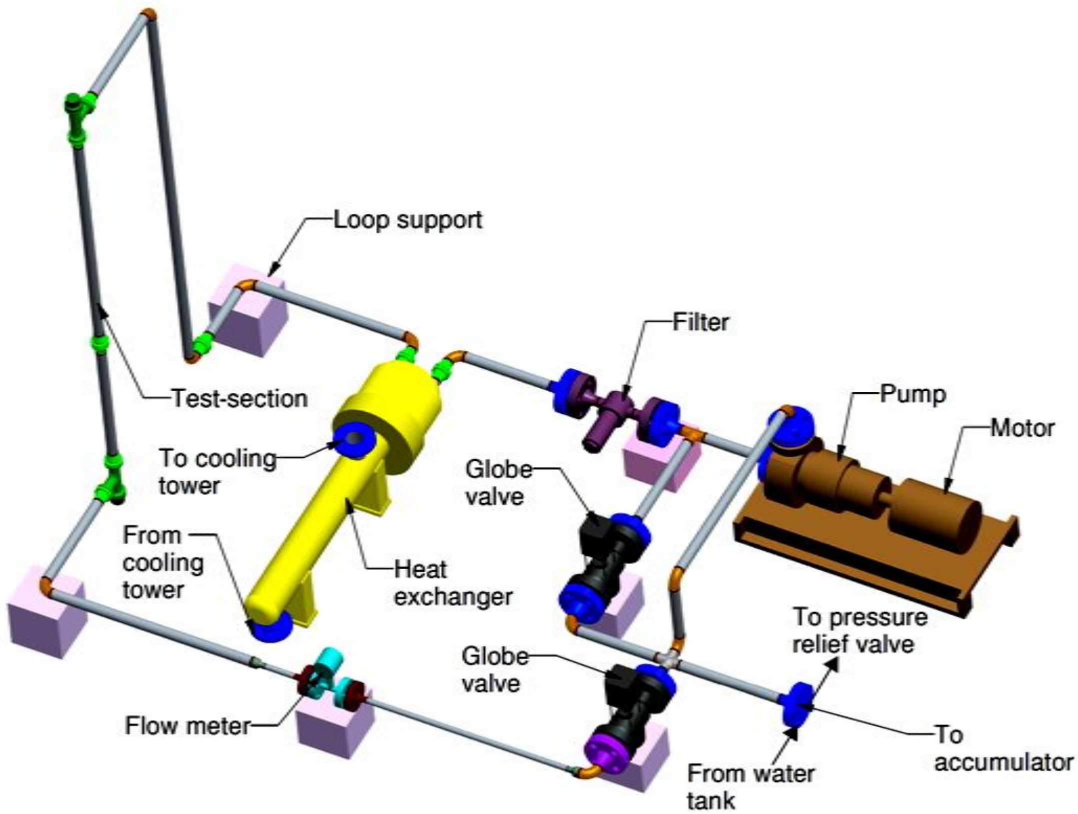


Figure 2 Layout and major components of the SCW loop

3.1 Main pump

A magnetic-drive centrifugal pump is used on the SCW loop to drive the water through the loop over the intended mass flow rate range of 0.4 to 1.6 kg/s, overcoming the frictional pressure drop in the loop that is estimated to be 0.1 MPa (1 bar) at the maximum flow rate. For a bulk fluid temperature of 600 °C at the test-section outlet, maximum mass fluxes up to 2500 kg/m^{2}s are achievable when a tubular test section geometry of 8 mm inner diameter is utilized. The pump, manufactured by Klaus Union (model SLM HVHO 040-025-160-09T02), is rated to operate at a maximum pressure of 28 MPa at 260°C. The materials for the pressure retaining parts are stainless steel 316Ti and stainless steel 316. The pump has a 160 mm (6.3 in)-diameter impeller powered by a 1.12 kW (1.5 hp) squirrel-cage induction motor. A variable frequency drive (VFD) is used to control the speed of the pump. The suction and discharge connections are achieved by NPS 1.5 class 2500 raised face (RF) ASME flanges.

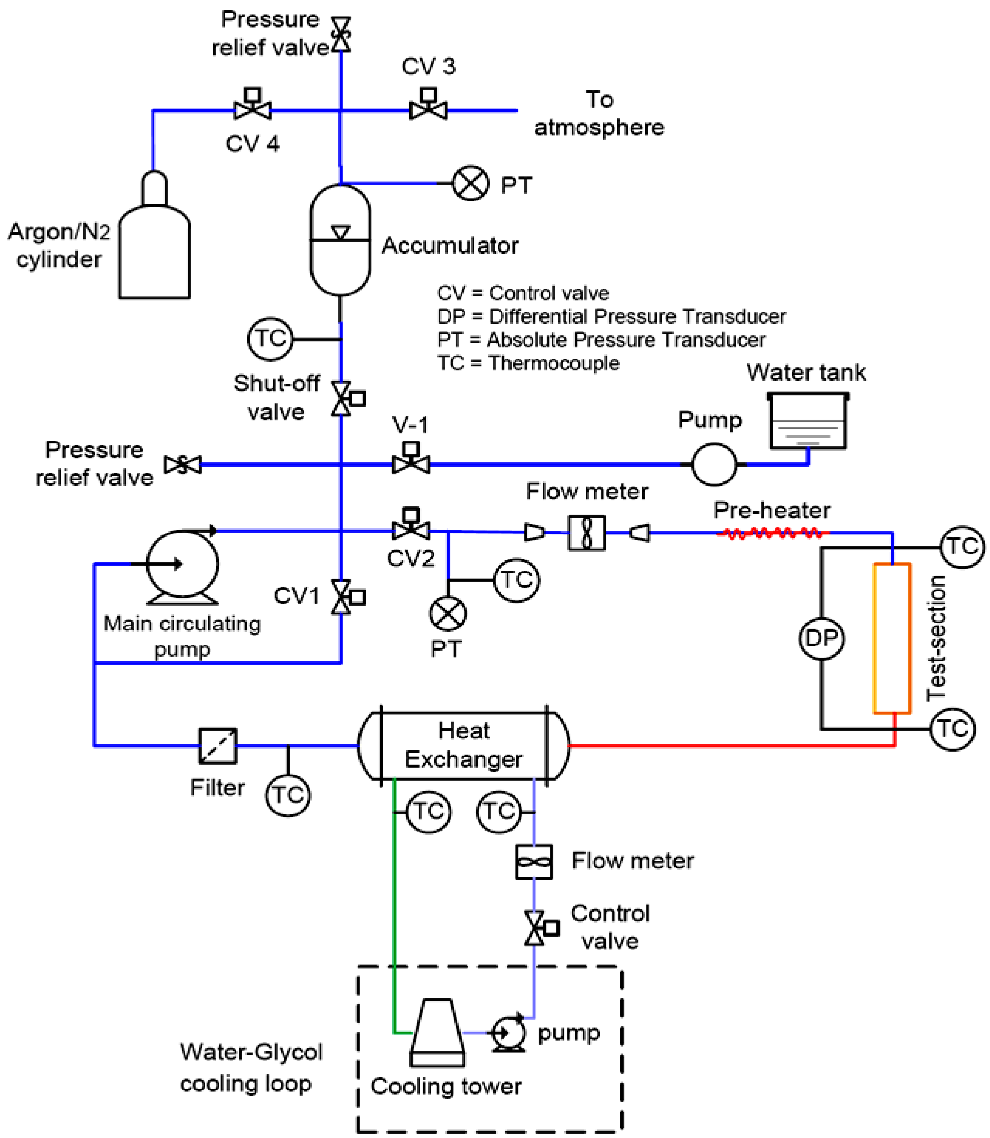


Figure 3 Piping and instrumentation diagram of the SCW loop

3.2 Flow control and measurement

The flow of water in the SCW loop can be regulated in two ways: by adjusting the rotational speed of the pump and/or through adjustment of the split of the pump discharge flow between the test-section feed and the loop-bypass lines. Two globe valves made of stainless steel grade CF8M, NPS 1.5 RF Class 2500 are used to control this flow distribution. One control valve is situated on the feed line leading to the test-section, while the other is positioned on the loop-bypass line. The bypass line is to have a nonzero flow rate for all intended operating conditions of the loop to accommodate the pump flow rate which is somewhat greater than the maximum test-section flow rate at supercritical water states at the test-section discharge.

The flow rate of water to the test section is measured with high accuracy (±0.05% of reading) using a 3/4 in - diameter turbine-type flow meter manufactured by FTI Flow Technology. The flow meter has a range of 0.11 to 5.68 m^3/hr (0.5 to 25 GPM) with a magnetic pick-up sensor rated to 400 °C. The interfacing of the flow meter with the rest of the SCW loop is realized through NPS 3/4 Class 2500 RF flanges. The pipe leading to the flow meter is reduced to the correct diameter at a sufficiently far distance upstream (68 diameters) to ensure a velocity profile at the flow meter inlet that is consistent with the calibration conditions of the meter.

3.3 Temperature control and measurement

A shell-and-tube heat exchanger situated downstream of the test section lowers the temperature of the water to meet the 260 °C temperature rating of the pump. Cooling the water to this temperature from the maximum test-section discharge temperature of 600 °C at the maximum loop mass flow rate at such conditions requires the heat exchanger to be sized for 300 kW heat-exchange capability. Consistent with the maximum pressure rating of the loop (28 MPa), the shell-and-tube heat exchanger is designed to withstand a maximum pressure differential of 30 MPa. The coolant circulating through the heat exchanger is a 50/50 water-glycol mixture that is maintained at 29 °C (85 °F) at the heat exchanger inlet. The heat exchanger, manufactured by Advanced Industrial Components Inc., is made of stainless steel 304 rated for operation at 30 MPa and 630 °C, and is connected to the upstream and downstream loop piping via 1.5 in Grayloc™ connectors.

An electrical pre-heater located upstream of the test section increases the fluid bulk temperature to the desired test-section inlet temperature. The tubular test-section can provide up to 82 kW of heat input to the fluid resulting in a heat flux of 1.6 MW/m^2 based on the test section’s inner diameter.

Thermocouples installed at a number of locations along the loop (Figure 3) allow for monitoring of the SCW loop for unintended temperature excursions. Additionally, thermocouples located close to the flow meter and at locations upstream and downstream of the test section detect the bulk fluid temperature for data analysis purposes. Type-N thermocouples are used at the test section inlet and exit along with other locations on the loop, and a type-E thermocouple is used close to the flow meter. All thermocouples are sheathed with 1.5 mm (1/16 in) diameter Inconel sheath.

3.4 Pressure control and measurement

The pressure in the SCW loop is controlled via a high-pressure bladder-type accumulator. The bladder of the accumulator separates Nitrogen gas, the pressure of which can be regulated via a supply tank (41.3 MPa) and a relief valve, from the water in the loop. The accumulator is used for raising the loop pressure prior to starting the flow through the loop and introducing heat in the test section. As the water temperature rises, the accumulator allows for expansion of the 16 L of water contained in the test loop thus allowing for independent control of the temperature and pressure of the water circulating in the loop. The accumulator has a total internal volume of 20 L, which is expected to adequately damp any pressure fluctuations that may develop during operation of the loop. It is sized to have similar volume to that of the SCW loop. The accumulator is connected to the loop by a 100 cm long small-diameter (6.4 mm or 1/4 in) tube.

The absolute pressure in the accumulator is measured using a Rosemount 2088 pressure transducer with a measurement range of 1.4–27.6 MPa and a line pressure rating of 55.2 MPa. A second pressure transducer of the same type, installed close to the flow meter, monitors the SCW loop pressure. The static pressure drop across the test section is measured using a Rosemount 3051CD differential pressure transducer. This transducer is rated for a maximum line pressure of 31 MPa (4500 psi) with a pressure range of -250 to +250 kPa.

The pressure transducer itself is rated for a maximum temperature of 85 °C. A remote diaphragm seal system, which consists of a fluid (silicon) filled capillary, can increase the operating temperature of the pressure transducer to 320 °C. At the test-section outlet, the fluid temperature is expected to be as high as 600 °C. In order to use the pressure transducer at such a high temperature, impulse tubing is required. The impulse tubing connected to the SCW loop lowers the fluid temperature through natural convective heat transfer with the ambient air to below 320 °C, at which point, silicon filled remote seals are attached to the impulse tubes.

3.5 Flow conditioning

Before the water returns to the pump, it is passed through a Norman Tee-type filter to protect the centrifugal pump from debris that may be dislodged from the tubing, in particular the test-section where direct Joule heating of the tubes is carried out, and other components on the loop due to corrosion and/or erosion. The filter element consists of a 20 micron stainless steel mesh. The filter is rated to 37 MPa at 260 °C and has a maximum flow-rate capacity of 7.98 m^3/hr (35 GPM) at 18 kPa pressure drop. It is connected to the upstream and downstream piping via Class 2500 RF ASME flanges.

3.6 Data acquisition System

The data acquisition system consists of a 24 bit analog-to-digital (A/D) convertor. The system incorporates 32 multiplexed analog input channels and 8 digital input/output channels. The sampling rate of the A/C convertor can be varied between 2.5 and 3750 samples per second. The A/D convertor is connected to the computer through a USB interface and LabVIEW™ is the user interface. The A/D converter type USB-2416 is manufactured by Measurement Computing.

4. Structural analysis of the SCW loop

As stated earlier, the operation of the SCW loop will involve pressurization followed by heating processes. As part of the design optimization of the loop, simulations have been performed to ensure that the final loop design is safe to operate through the desired start-up and shut-down schedules. This section summarizes the structural simulations of the loop through the initial pressurization and subsequent heating during a start-up process. The simulation is based on Finite Element Analysis of the complete loop assembly with constraints that are consistent with the intended installation of the loop in the facility. The pressurization and heating transients considered in the presented simulation are one of a series of schedules that have been considered in the design process. The finite element analyses were performed using VrSuite, an in-house software suite that is based on a combination of 8-noded hexahedral and 10-noded tetrahedral element discretization of the computational space, and second-order implicit time integration of the governing equations. The software has been extensively used for structural analyses at

Carleton University, and has been benchmarked against a broad range of test cases for which analytical and high-fidelity experimental data are available, including geometric configurations similar to the various components of the present SCW loop. One such benchmarking example is presented in the next section preceding the simulation results for the SCW loop.

4.1 FEA validation

The classical problem of a thick-walled pipe subjected to internal pressure and constrained to have zero elongation constituted one of the benchmarks for VrSuite. The geometry of this test case is given in Figure 4. The inner and outer radii were set to 13.97 mm and 24.13 mm, respectively, and the pipe material was selected as AISI 316 steel. The pipe was pressurized to 24 MPa. These geometric, material and loading choices correspond closely to those of the SCW loop pipe segments. The simulation was performed with the pipe segment set to 500 mm length and discretized using an 8-node brick mesh, 800 elements in total and 2 elements through the thickness. The predicted hoop and radial stresses are compared to the analytical results in Figure 5.

The second benchmark consists of the same geometry as the first benchmark, with the internal pressure loading removed and the inner and outer surfaces of the pipe thermally constrained to temperature values of 400 K and 300 K, respectively. The axial ends of the pipe are set to adiabatic condition. The temperature distribution of this test case is given in Figure 6. The predicted hoop, radial, axial and effective stresses are compared to the analytical results in Figure 7.

The spatial discretization of the components of the SCW loop was performed with a resolution that is comparable to that of the benchmark cases.

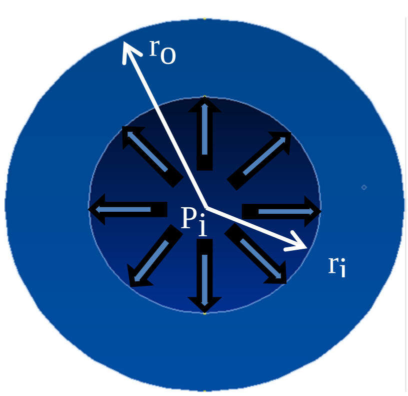


Figure 4 Thick-walled pipe under internal pressure

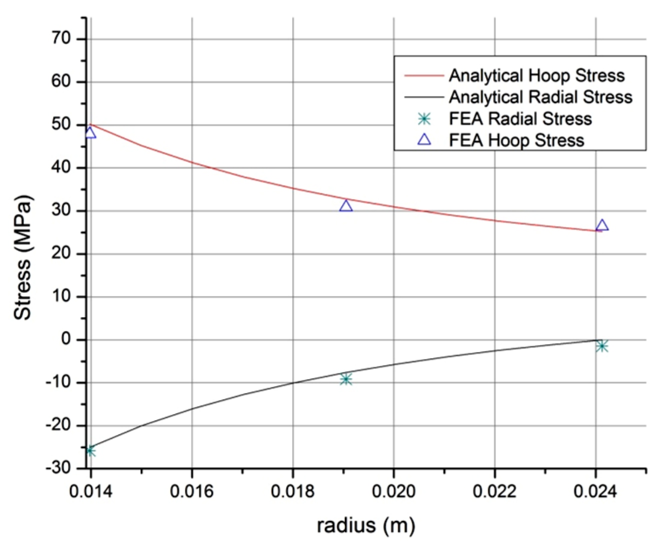
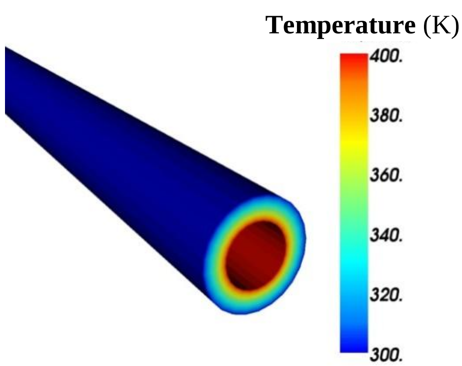


Figure 5 Comparison of numerical and analytical results for the hoop and radial stresses



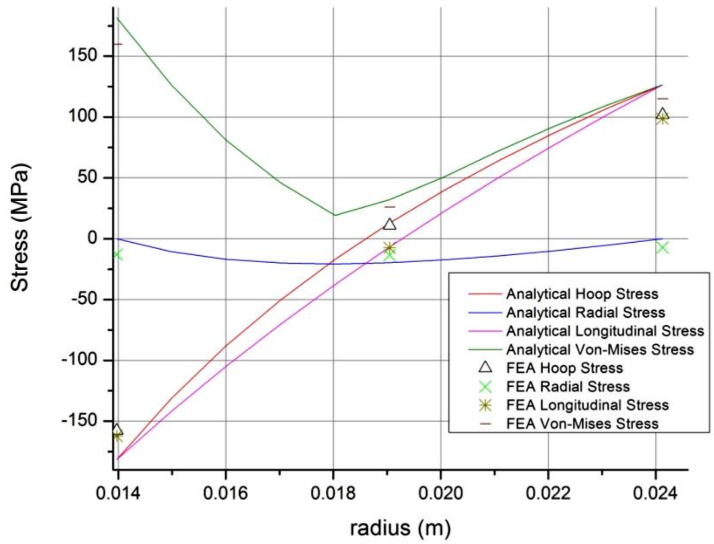


Figure 6 Temperature distribution of the thick-walled pipe

Figure 7 Thermal stresses for the thick-walled pipe

4.2 Computational setup for structural simulation of the SCW loop

The structural simulation results presented herein are based on a start-up schedule in which the loop is pressurized at 25 MPa and the temperature of the fluid is increased to 600 °C at the test-section outlet over a one hour period by applying 300 kW of heat input with a linear ramp-up rate starting at 0 kW. The loop is constrained in all three directions at the points where the heat exchanger is mounted to the floor, and in two directions where the pump is mounted to the floor. Additionally, the structural simulation was set up with displacement constraints that are compatible with the loop support platforms mounted at several points along its length, as shown in Figure 2.

The SCW loop is modeled by a combination of 8-noded hexahedral and 10-noded tetrahedral elements. The total number of elements is 130444 and the number of nodes is 99223. The analysis time is 3600 seconds and 53098 CPU seconds are required to complete the analysis for 600 seconds of time step size on a 4 CPU Intel Core Quad Q9650 3.0 GHz processor.

4.3 Simulation results

The predicted displacements and effective stresses are presented in Figures 8 and 9, respectively. It is important to note that the pressurization simulation does not capture the transient effects of pressurization; the results correspond to a steady-state structural load of 25 MPa internal pressure. The thermal loads on the loop as used in this structural simulation are produced by another numerical calculation, as presented in Section 5 of this paper.

The displacements have been magnified four times for illustration purposes. The displacements are confirmed to be within a range that will not interfere with the functionality of the test setup, and the stresses remain well within safe operating conditions. The maximum allowable stresses for the pressure and thermal loadings are given in ASME B31.1 [3]. For sustained stresses (e.g.

due to internal pressure), the maximum allowable stresses for the loop piping material range from 80.3 to 138 MPa, depending on temperature. For displacement stresses (e.g. due thermal expansion/contraction), the maximum allowable stresses for the loop piping material range from 189 to 200 MPa depending on temperature. The results of this simulation and many others that have been performed for different operational schedules confirm the structural integrity and functionality of the SCW loop for the intended series of experiments to study the heat transfer characteristics of water at supercritical conditions.

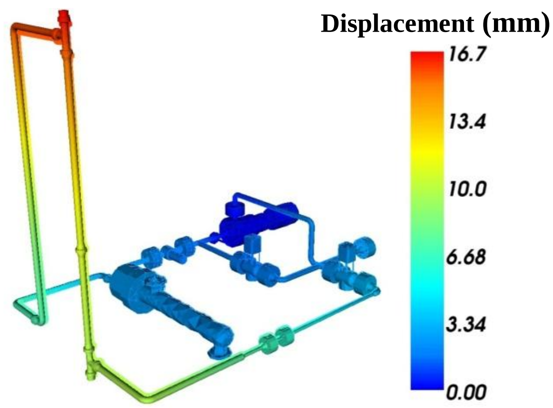


Figure 8 Predicted displacements on the SCW loop (25 MPa and heat input in the test section that is linearly varied from 0 to 300 kW over 60 minutes)

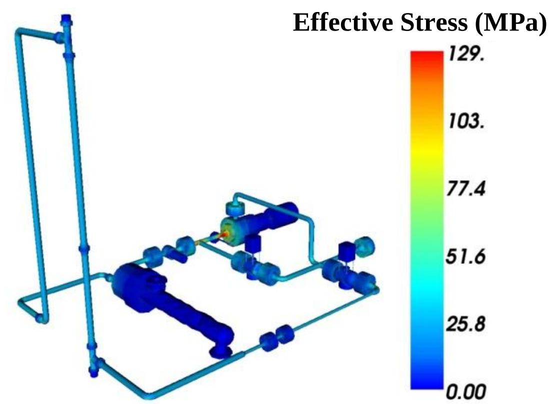


Figure 9 Predicted stresses on the SCW loop (25 MPa and heat input in the test section that is linearly varied from 0 to 300 kW over 60 minutes)

5. Thermal analysis of the SCW loop

As noted earlier, one of the start-up schedules of the SCW loop involves heating of the working fluid once the fluid pressure is raised to its intended operational level through the use of the accumulator. Upon commencement of heating of the water in the test section and cooling in the heat exchanger of the SCW loop, thermal gradients will develop along the length of the loop.

The structural stresses associated with these thermal gradients will superimpose on those due to the pressure loading. It is essential that the structural integrity of the SCW loop be verified for this state of combined thermal and pressure loading, including the transient phase.

Simulations were performed to predict the temperature distribution along the length of the loop and the variation of this distribution in time until the loop reaches a steady operational state. The results of these simulations are used as input to the structural simulation software to produce the results presented in the preceding section. The following sections outline the algorithm used for these thermal simulations and present sample results for the temporal variation of temperature at selected points on the loop.

5.1 Governing equations and discretization

The prediction of the thermal field throughout the loop for use in structural simulations is based on discretization of the solid and fluid-filled regions of the loop into finite volumes, and coupled time-integration of the advection and diffusion equations for these volumes. The fluid and solid regions are respectively discretized with finite volumes arranged in a one-dimensional sense (along the length of the loop), and the convective and diffuse energy transfer between these finite volumes is modeled through the use of material properties and empirical correlations for convective heat transfer rates, as applicable. The thermal inertia of the various components of the SCW loop was accurately allocated to the fluid and solid finite-volumes. The time integration was performed explicitly, and owing to the small time-step size used in the integration, first-order discretization of the time derivatives was deemed adequate. The validity of this choice and the adequacy of the number of solid and fluid finite volumes for the thermal simulations of the SCW loop were established through extensive temporal and spatial grid-sensitivity studies.

5.2 Results

Sample results of the thermal simulations are presented in Figure 10, for a start-up schedule in which Joule heating is ramped up linearly to 300 kW over varying periods of time. The transients in the temperature of the water observed at the test section inlet and outlet follow the expected trends.

The temperature profile at the outlet of the test section shows a change in the curvature of the profile part way through the power ramp-up period. This corresponds to the point where fluid is crossing the critical point near the outlet of the test section. This change in curvature can be attributed to the associated change in properties near the supercritical point; namely the anticipated spike in the convective heat transfer coefficient. These transients together with temperature data corresponding to fourteen other locations along the length of the SCW loop were used as input to the calculation of thermal stresses, as presented the preceding section. These thermal stress simulations are currently being performed for a range of operational schedules of the SCW loop, and this step constitutes the final increment of the design optimization of the loop. Results obtained to date confirm the suitability of the SCW loop design presented herein for the intended heat transfer experiments

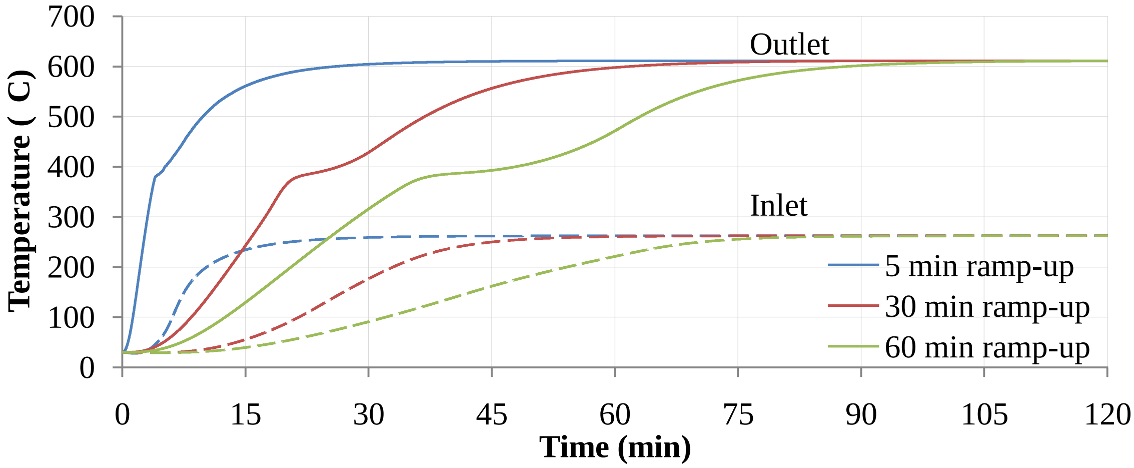


Figure 10 Predicted temperature transients at the test section inlet and outlet for a typical start-up schedule and several rates of heat ramp-up

6. Conclusions

The paper presents a high-temperature heat-transfer test facility being developed at Carleton University in support of studies of heat transfer properties of fluids at supercritical conditions.

The facility is shown to provide unique features that will enable undertaking of these studies over flow and thermal ranges and geometric configurations that are substantially broader than those that have been performed by other research groups to date. Sufficient detail on the infrastructure and design choices is presented in the paper to provide guidance for the development of similar facilities by others. Specifically, the paper elaborates on the design philosophy followed in the development of the SCW loop, and provides rationale for the choices of structural components, layout selections, instrumentation, control strategies, and data acquisition arrangements.

The paper also presents samples of results for computational efforts undertaken in support of the structural design optimization of the loop. These computational efforts included simulations of the start-up and shut-down phases of operation for a number of possible schedules, and accounted for both pressure and thermal loading that the loop is expected to encounter during these phases.

7. References

[1] Chow CK et. al. "A fuel channel design for CANDU-SCWR". Proceedings of the 14th International Conference on Nuclear Engineering; 2006 July 17-20, Miami, Florida, USA. New York: American Society of Mechanical Engineers; 2006.

[2] Pioro IL, Duffey RB. "Heat transfer and hydraulic resistance at supercritical pressures in power-engineering applications". ASME Press, New York, NY; 2007.

[3] Power Piping. ASME B31.1-2007. ASME Code for Pressure Piping, B31. ASME; 2007.