DESIGN OF AN R-134a LOOP FOR SUBCRITICAL AND SUPERCRITICAL FORCED-CONVECTION HEAT TRANSFER STUDIES

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Abstract

The R-134a test loop is a forced-flow experimental facility for the study of heat transfer properties of R-134a under subcritical and supercritical thermodynamic conditions. The loop is designed to operate with pressures as high as 6 MPa and temperatures up to 140 °C. The intended mass flux is in the range of 500-6000 kg/m^2s for the experiments with subcritical thermodynamic states and 500-4000 kg/m^2s for supercritical conditions. The loop has been designed to accommodate a variety of test-section geometries, ranging from a straight circular tube to a 7-rod bundle, achieving heat fluxes up to 2.5 MW/m^2 depending on the test section geometry. The design of the loop allows for easy reconfiguration of the test-section orientation relative to the gravitational direction and adjustment to the length of the test section.

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. Collaborative international research and development organizations, such as the Generation IV International Forum (GIF), have been established to coordinate 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. 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 [1].

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. However, performing experiments with SCW at the conditions encountered in the CANDU-SCWR involves high pressures and temperatures. In order to simplify experiments under supercritical conditions, fluids with lower critical pressures and temperatures, such as CO_2 and R-134a, are used as substitutes for SCW [2][3]. To expand on the currently available data and further investigate the heat transfer and thermalhydraulic properties of R-134a under subcritical and supercritical conditions, a thermalhydraulic test loop with a range of test-section geometries and flow directions relative to the gravitational field has been developed at Carleton University. The experimental data obtained will be used in part to identify correlations for fluid-to-fluid modelling between the convective heat-transfer properties of supercritical R-134a and supercritical water.

The use of supercritical R-134a as a modelling substitute for SCW is driven by its lower critical pressure and temperature. The critical point of R-134a occurs at 101.1 °C and 4.06 MPa, whereas the critical point of water occurs at 373.9 °C and 22.06 MPa [4]. The lower critical pressure and temperature of R-134a provides a simpler design for the test loop with shorter development and commissioning times, a safer testing environment and reduced cost of the experimental facility.

Table 1 lists the operating conditions intended for the R-134a loop based on the conditions in the test section. The loop will be operating over temperature and pressure ranges of 40 – 140 °C and 1.7 – 6 MPa, respectively.

Table 1 Operating parameters of the supercritical R-134a loop

<table>
<tr><td rowspan="4">Subcritical</td><td>Pressure</td><td colspan="2">1.7 – 4 MPa</td></tr>
<tr><td rowspan="2">Temperature</td><td>Inlet</td><td>Outlet</td></tr>
<tr><td>40 – 80 °C</td><td>60 – 100 °C</td></tr>
<tr><td>Mass flux</td><td colspan="2">500 – 6000 kg/m²s</td></tr>
<tr><td rowspan="4">Supercritical</td><td>Pressure</td><td colspan="2">4.4 – 6MPa</td></tr>
<tr><td rowspan="2">Temperature</td><td>Inlet</td><td>Outlet</td></tr>
<tr><td>60 – 100 °C</td><td>102 – 140 °C</td></tr>
<tr><td>Mass flux</td><td colspan="2">500 – 4000 kg/m²s</td></tr>
</table>

A paper presented at the 5th International Symposium on SCWR [5] described the design of the Carleton SCW loop and the capabilities of the high-temperature heat-transfer facility located on Carleton University's campus. The design of the R-134a loop follows a similar philosophy as the SCW loop. Therefore, the contents of this paper are biased towards the description of the test-section designs, and the data acquisition and control system, while accompanied by relatively brief descriptions of high-temperature heat-transfer facility and the R-134a loop.

2. Carleton high-temperature forced-convection heat-transfer test facility

The Carleton University supercritical fluid test facility is a high-temperature high-pressure facility for performing forced-convection heat transfer experiments over a broad range of the thermodynamic states for the working fluids, including the supercritical region. Initially, the test facility will house two test loops, namely a supercritical water loop and a subcritical/supercritical R-134a loop.

Figure 1 depicts the locations of the test loops and supporting infrastructure in the 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 fluid in either of the test loops. A Magnavolt Model DTLG 600-150/2000 transformer

provides the power conversion with an efficiency of 94%, and allows for control of the output power through adjustable voltage and current with ±1% regulation capability. A remotely adjustable DC electronic load connected in parallel to the test section facilitates further precise control (±0.025%) of the DC power passed through the test section. The 500 kW electric power entering the facility is removed from the facility in the form of heat via the loops' heat exchangers and two 25 kW (7.1 ton) air-conditioning units, which transfer the heat to a water/glycol mixture that is circulated between the laboratory facility and a forced-draft counter-flow wet/dry cooling tower.

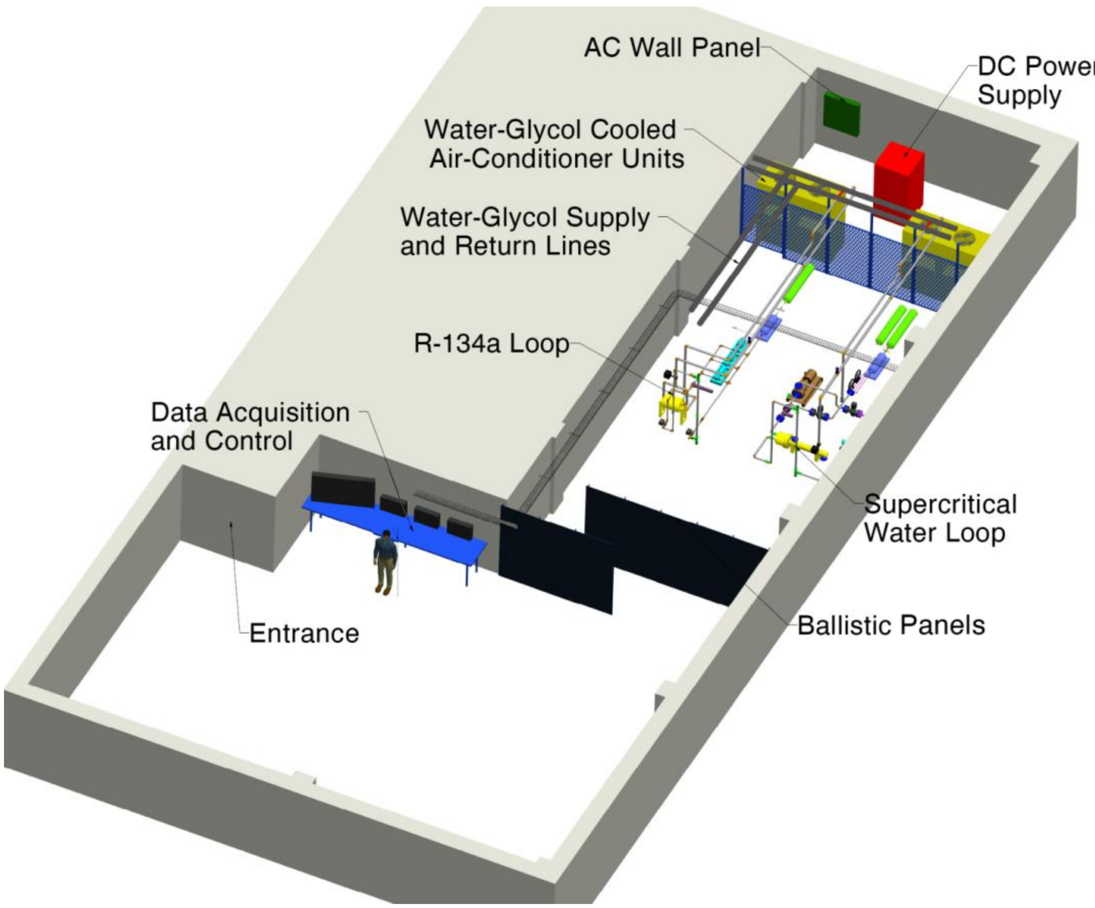

Figure 1 Layout of the high-temperature heat-transfer and fluid-flow test facility

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.

3. Design and Instrumentation of the R-134a Loop

Figure 2 shows the layout and major components of the R-134a 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 6 MPa and fluid temperatures up to 140°C at the test-section outlet. The loop is contained within a space that is 2 m wide, 4 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 6.5 m length. All the design calculations are performed based on the rules stipulated by ASME pressure piping code B31.1 [6].

The loop tubing is of 31.75 mm outer diameter (1.25 in) with a wall thickness of 2.8 mm (0.109 in) and is made of SA-213 stainless steel 316. Tube and component connections are realized with Swagelok™ NPT threaded and compression type fittings. Threaded joints are found at the locations where components, such as flow meter, filter, valves and pumps are connected to the loop tubing. The test sections are interfaced with the loop via Grayloc™ connectors.

The test-section leg of the loop is designed such that test sections of up to 2.3 m length can be easily interfaced with the loop using the provided inlet/outlet connections. In the horizontal orientation, there is no limit on the length of the test section with the only required adjustment to the loop being the length of the return leg facing the test section. Heat is imparted to the R-134a working fluid in the test section through Joule heating of the portions of the test-section walls that are in contact with the fluid. A 4 kW flexible preheater wrapped around the tubing just upstream of the test section inlet allows precise control over the temperature of the fluid entering the test section.

Three gear pumps (Micropump™ GN Series) collectively generate flow rates in the range of 0.021 to 2.1 kg/s at a pressure rise of 560 kPa, operating at speeds of up to 1750 rpm. Since the pumps are connected in parallel and each pump is driven by its own dedicated variable frequency drive (VFD), the flow of the R-134a through the test-section can be finely regulated (to within ±0.005 kg/s). The choice of gear-type pumps is compatible with the desired ranges of flow rates and the corresponding pressure losses along the length of the loop (up to 560 kPa), and reduces the amplitude of pressure fluctuations at the pump outlet compared to other pump types.

The flow of R-134a is monitored by a turbine-type flow meter (Blancett™ 1100) with a flow range of 1.1 m^3/hr to 11.4 m^3/hr (5 to 50 GPM), and an accuracy of ±1% of the reading. To realize this measurement accuracy, the turbine flow meter is installed with a 63 diameter straight section upstream and 10 diameter straight section downstream of the meter. The flow meter uses a tungsten carbide rotor shaft and it is equipped with a magnetic pick-off sensor rated to 177 °C. A turbine flow meter was selected over other methods of flow measurement for its ease of installation, good accuracy and economical considerations.

A plate-and-shell heat exchanger (manufactured by Vahterus™) located downstream of the test-section lowers the temperature of R-134a in order to meet the temperature rating requirements of the pump and achieve the desired test-section inlet temperature. The heat exchanger is designed to lower the R-134a temperature to a minimum of 40 °C, which is required for experiments in the subcritical range. The heat exchanger is sized to match the maximum Joule heating capability of

300 kW of the loop. To achieve this heat transfer rate, a total heat transfer surface area of 9.33 m^2 is required for a coolant mass flow rate and inlet temperature of 15 kg/s and 29.5 °C, respectively. It is designed to operate at a maximum pressure of 6.2 MPa at a maximum temperature of 149 °C.

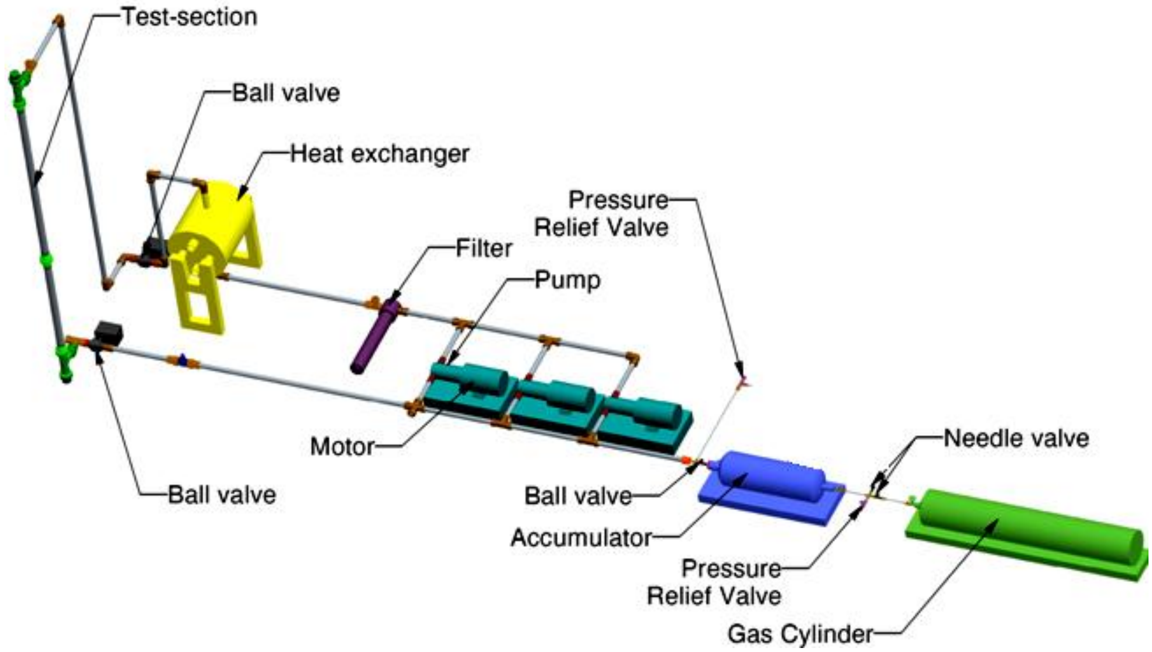

Figure 2 Layout and major components of the R-134a loop

Pressurization of the R-134a loop is achieved with the help of a high-pressure nitrogen gas cylinder and accumulator combination. A 19 litre (5 US gallons) bladder type accumulator with a transfer barrier to protect the bladder against extrusion is selected for use on the loop. Bladder type accumulators have excellent pulsation dampening capabilities, and are readily available in the size and pressure rating required for the loop. The pressure in the loop is regulated by allowing nitrogen gas to flow into the accumulator and by venting off excessive gas to the atmosphere. The accumulator also helps to moderate the pressure oscillations created by the pumps and/or any flow instabilities in the loop. Two electrically-actuated control valves, CV 3 and CV 4 as shown in Figure 3, are used to assist in the pressure regulation.

Before the working fluid returns to the pump, it is passed through an in-line filter (United Filtration™ Model 160) to protect the gear pumps from corrosion and/or erosion particulate that may be dislodged from the tubing, in particular the test-section where direct Joule heating of the tubes is carried out. The filter has a 5 micron stainless steel mesh.

The loop is instrumented with static pressure taps connected to absolute (Honeywell FP2000) and differential (Honeywell Model TJE) pressure transducers, and with ungrounded (1.5 mm sheath

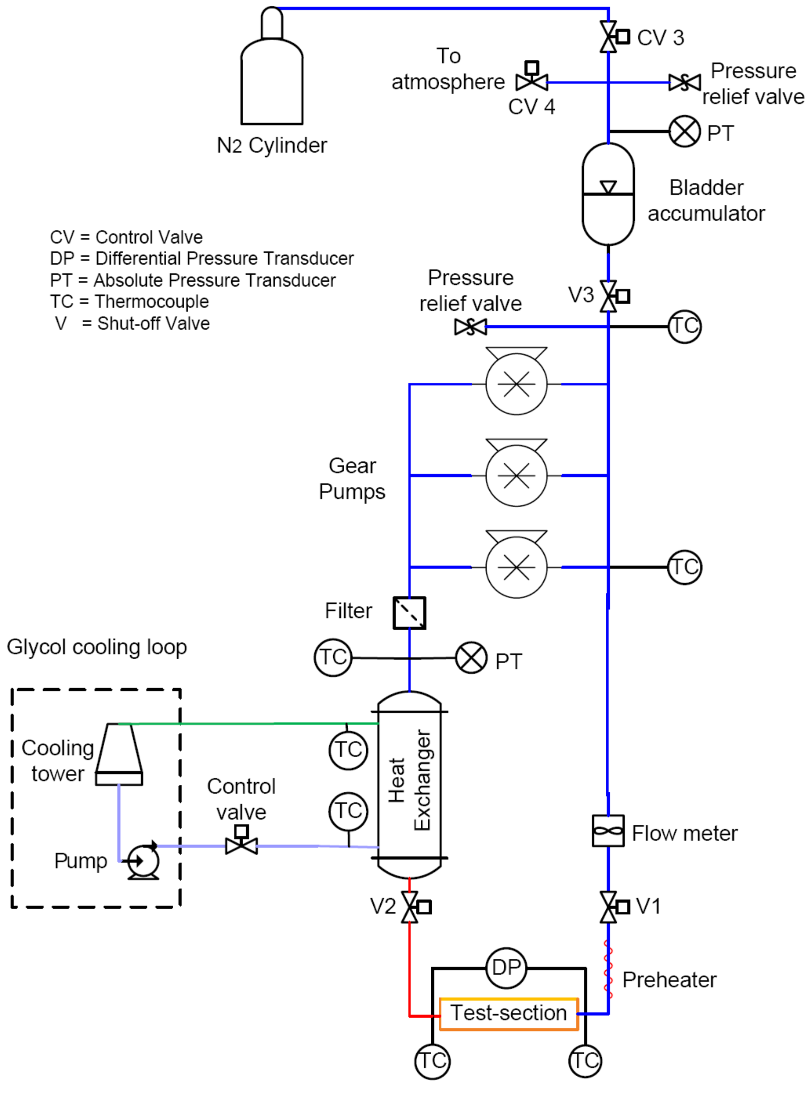

Figure 3 Piping and instrumentation diagram of the R-134a loop

diameter N- and T-type sheathed) thermocouples, at locations noted in Figure 3. The absolute pressure transducer has a measurement range of up to 10.3 MPa (1500 psi) and can operate at temperatures up to 116 °C. The differential pressure transducer is rated for a maximum differential pressure of ±345 kPa (±50 psid) with an operating temperature of up to 85 °C. Both pressure transducers are accurate to within 0.1% of the full scale and the thermocouples are accurate to 0.6 - 1.1 °C, depending on the type of the thermocouple. These sensors are used for both health monitoring and for studying the heat transfer and flow development processes in the test section. At locations (noted in Figure 3) where thermocouples have to pass through the pressure boundary to measure fluid bulk temperatures, Swagelok™ fittings are used to accomplish the leak-tight insertion of the sheathed thermocouples into the fluid flow stream. A thermocouple traverse system is used to measure the temperature distribution along the length and the circumference of the heated boundaries of the test section.

To reduce heat loss from the loop to the facility, the entire loop including the test section is thermally insulated. Up to 350 mm thick alumina silica fibre thermal insulation is used on the test section, whereas the rest of the loop is insulated with 60 mm thick mineral wool fibre thermal insulation. An estimated 250 W of stray heat will be transferred to the facility.

4. Test sections

One of the main purposes of undertaking experiments at Carleton University with R-134a in parallel with similar tests utilizing water as the working fluid is to establish a physically-sound framework for fluid-to-fluid modelling in relation to forced-convection heat transfer when the working fluid is at a supercritical thermodynamic state. To ensure that any observed variations in the heat transfer properties between the two fluids in the pending experiments are due to differences in the thermophysical properties of the fluids and not a result of subtle differences between the test sections, the same test sections are used on the R-134a and SCW loops. This requires that the test sections be designed for the structurally more challenging temperature and pressure ranges of the SCW loop.

Three different test-section geometries, the cross-sections of which are shown in Figure 4, are planned for the initial set of experiments. The annular and bundle designs are used to simulate the CANDU-SCWR fuel pin and fuel bundle arrangements, respectively, while the tubular configuration is used to study the forced convective heat transfer phenomenon in a more fundamental setting and to quantify the overall accuracy of the experimental facility/setup in comparison with established data from other facilities.

The temperature of the fluid in the test section is raised to the desired level by direct Joule heating of the selected test-section walls. In the bundle and annular test sections, the inner heater rod(s) are energized, whereas in the tubular test section, the tube itself is heated.

The design of the test sections involves the balancing of a number of competing factors. This includes the selection of a suitable high-temperature material with a reasonable cost, sizing of the test-section wall thickness to withstand exerted pressure while having an electrical resistance as close to the internal electrical resistance of the power supply as achievable, and ensuring that the hydraulic diameter of the test section is as close to the hydraulic diameter of the CANDU-SCWR as possible [7]. In the case of the annular and bundle test sections, the design also includes the challenge of transmitting the power to the heater rods through the pressure boundary while minimizing the leakage of the current through undesirable paths.

Since the test sections have to be certified by the relevant government authority as part of the entire high-pressure system, the design has to be carried out in accordance with the codes and standards stipulated by law. As parts of the test sections are being directly heated, it would be an over-simplification to consider them as mere pipes. Instead, the directly heated parts of the test sections are designed according to the rules stipulated in ASME Section VIII, Division 1 [8].

As a first step in the design process, from a range of materials, including Inconel 617 and N06230, Inconel 625 (UNS 06625, SB-444) is selected as the suitable material, primarily for the heated parts of the test sections. This material possesses excellent high-temperature strength and a relatively constant electrical resistivity as a function of temperature [7].

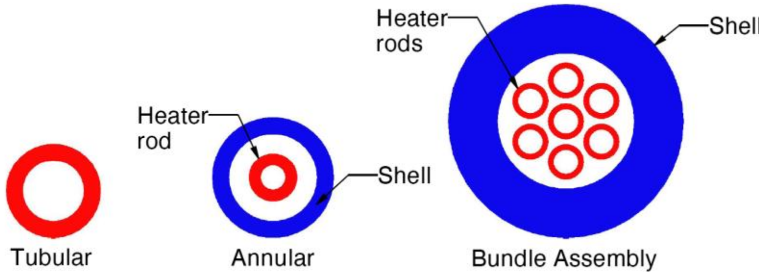

Figure 4 Cross-sections of the three test-section geometries

Using the mechanical properties of the selected material and expected operating conditions to which the test sections will be subjected, the required wall thicknesses are calculated for predetermined inner or outer diameters. The wall thickness of the tubular test section under internal pressure is calculated using the following formula [8]:

For $P > 0.385 S_f E$: $$t_p = R\left(Z_p^{1/2} - 1\right) \tag{1}$$

where, $$Z_p = \frac{S_f E + P}{S_f E - P}$$

P is the design pressure, R is the internal radius of the test section, S_f is the maximum allowable stress at the design temperature from ASME Section II Part D [9], E is the weld joint efficiency (unity for seamless tube/pipe), and t_p is the minimum required wall thickness of the test section at the design temperature and pressure.

The inner hollow heater rods are subjected to external pressure. Determination of the wall thickness for external pressure requires an iterative procedure, which is dependent on the magnitude of the pressure and the concurrent temperature.

The maximum allowable pressure (the lesser of P_{a1} or P_{a2}) that can be accommodated for a given wall thickness is calculated by the following equations [8]:

$$P_{a1} = \left(\frac{2.167}{D/t} - 0.0833\right) B \tag{2}$$

$$P_{a2} = \frac{2S}{D/t}\left(1 - \frac{1}{D/t}\right) \tag{3}$$

where, *D* is the outside diameter of the tube/shell, *t* represents the wall thickness, *B* is a factor determined from applicable material chart in ASME Section II, Part D Subpart 3 and *S* is the allowable stress value determined according to the rules of UG-28(c)(2).

Utilizing the above mentioned procedure and formulae, the specifications of the test sections are as follows.

The tubular test section has an internal diameter of 12.5 mm and a wall thickness of 3.5 mm. The heated length of the test section is 2000 mm. Based on the available DC amperage of 2000 A, a heat flux of 760 kW/m^2 is achievable.

The inner heater rod of the annular test-section design has inner and outer diameters of 5 mm and 10 mm, respectively, with a total heated length of 2000 mm. The outer shell has an inner diameter of 18 mm. This results in a hydraulic diameter of 8 mm. Heat fluxes of up to 2.5 MW/m^2 can be achieved with the annular test section.

The achievable heat flux for the bundle test section is 197 kW/m^2. The heater rods of the bundle test section have a wall thickness of 1.2 mm and an outer diameter of 7.4 mm with an approximate heated length of 2000 mm. The outer shell has an inner diameter of approximately 28 mm. This results in a hydraulic diameter of 5 mm.

Early on in the design process, it was determined that the required wall thicknesses would be driven by the magnitude of the exerted pressures. Therefore, the internal electrical resistance of the power supply could not be used as a sizing criterion for the wall thickness of the test sections.

Once the required wall thicknesses have been determined, the method of transmitting the power to the heated parts and the setup of the test sections are established. Electric power to the tubular test section is transmitted by simply connecting two bus bars to the test section 2 m apart. The method of transmitting power to the heater rod(s) of the annular and bundle test sections is more complicated. Figure 5 shows the cross section of the annular test section.

Power is transmitted to the heater rod via a blind flange bus bar on one terminal and the Grayloc™ bus bar on the other. To avoid inadvertent heating of the outer shell, the blind flange is dielectrically isolated from the rest of the test section with the help of a dielectric gasket kit. One of the ends of the heater rod is accessible from the outside, which allows the use of a traverse mechanism, equipped with four 0.25 mm ungrounded N-type Inconel sheathed thermocouples, to map the internal wall temperature of the heater rod. A sealing block on the other end of the heater rod allows access for the installation of the traverse mechanism and creates a compression-type seal during operation.

The method of transmitting power to the heater rods of the bundle test section is similar to the one described for the annular test section, except that the bundle test section has seven heater rods and they are all connected to the bus bars on either ends. In the same way, a dielectric gasket kit isolates the blind flange from the rest of the test section.

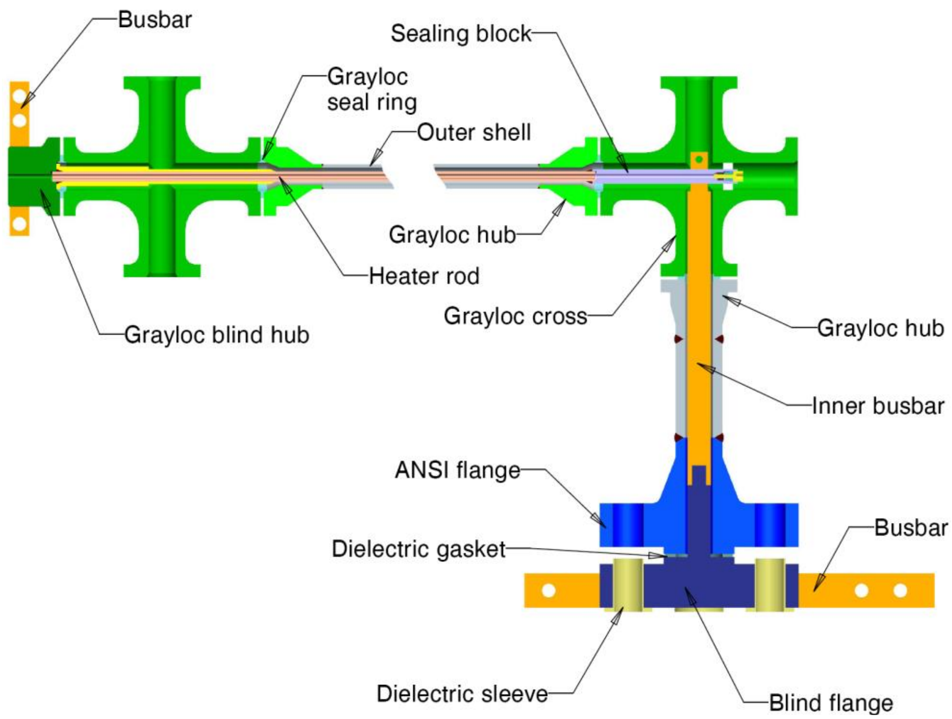

Figure 5 Cross section of the annular test section

5. Data acquisition and control system

The facility is operated through a LabVIEW™ program that provides an efficient user interface for a single user to control the experimental test parameters, perform the test section measurements, and simultaneously monitor the health of the facility and the test loop. The health-monitoring information, loop-operation parameters, and the test section measurements are set and displayed on three separate monitors. Furthermore, a nine-view camera system allows the operator to remotely maintain visual contact with the test loop during the measurements.

Data acquisition from all sensors is performed though a USB-2416 A/D converter manufactured by Measurement Computing. This 24 bit A/D converter is capable of higher sampling rates than the time response of the sensors warrants, thus the slowest sensor is used to determine the data acquisition rate for the measurement and control system. The slowest sensors on the test loop are the thermocouples with a time response of 0.26 seconds. Therefore, sampling of all 23 health-monitoring channels is performed at 4 Hz, with the frequency of test section sampling being left adjustable. No analog filtering is currently implemented, but the commissioning plan includes tests to verify that the RF-induced sensor noise does not require the installation of such filters.

The LabVIEW™ main control program controls the test loop and facility through sub-system control modules. The controlled sub-systems include pressurization, flow rate, test section heating, environmental conditions, and coolant flow. Each sub-system control module is capable of providing fully automatic or manual operation of its respective sub-system. For example, the flow rate control module utilizes data from the flow meter, VFDs, and the user interface panel to control the VFDs running the three pumps on the loop to achieve either a desired flow rate or manually selected pump speed.

After performing the control logic in the individual sub-system control modules, the control outputs and sensor inputs are both fed to an extensive set of fault detection modules. These modules perform no control, but instead use logic gate techniques to detect faults in the operational state of all the controlled systems. Depending on the severity of fault, the system either generates warnings to the operator or executes a control override to safely shut down the loop.

The loop startup procedure commences with the operator performing a diagnostic check of all health-monitoring sensors against their respective expected values. Next, a pressure level of about half of the final target value is set in the LabVIEW™ control program, which will then pressurize the loop to the set value by automatic control of the two nitrogen control valves (CV3 and CV4 in Figure 3). Pressurization is performed in an over-damped manner to minimize nitrogen waste and avoid loop damage. Once the set pressure is achieved, the target mass flow rate is set. The control program determines how many gear pumps to activate to provide the largest control range around the set target. Mass flow rate is also controlled in an over-damped fashion to reduce the risk of temperature excursions as a result of flow rate changes or oscillations. Once the target flow rate is achieved, the target temperature values for the test-section inlet and outlet are input in the control program. To achieve the target temperatures, the control program can adjust the test section heating, the preheater heating, and the coolant flow rate through the heat exchanger. This is done in a manner that minimizes energy waste from over-cooling in the heat exchanger then reheating in the preheater. Temperature ramping is constrained to 1 °C/min in the control program to avoid thermal shocks. While temperature ramping is occurring, the pressure and pump speed are adjusted as required to achieve the target pressure and maintain the target mass flux, respectively.

The shut down procedure is commenced by phasing out heat input to the test section and preheater while ramping down the temperature at a rate of 1 °C/min by adjusting the coolant flow rate through the heat exchanger. Once the fluid bulk temperature equals the wall temperature at the heated locations, heat input is turned off and the loop is allowed to cool down at the set rate.

6. Conclusions

The paper presents the design of an R-134a loop and the capabilities of the Carleton University supercritical forced-convection heat-transfer test facility. Also discussed in the paper is the design of three different test section geometries for heat transfer experiments at subcritical and supercritical conditions involving R-134a as the working fluid.

The facility is shown to provide unique features that will enable the study of flows in thermal ranges and geometric configurations that are substantially broader than those that have been performed by other research groups to date. Detail on the infrastructure and design choices are 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 R-134a loop and test sections, and provides rationale for the choices of structural components, layout selections, instrumentation, control strategies, and data acquisition arrangements.

7. Acknowledgements

The contributions of Anne Mason, Yi-Li Jin and Alex Pickard on the sensor, data acquisition and control systems described herein are acknowledged.

8. References

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