A TEST FACILITY FOR HEAT TRANSFER, PRESSURE DROP AND STABILITY STUDIES UNDER SUPERCRITICAL CONDITIONS

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Manish Sharma, D.S. Pilkwal, S.S. Jana and P.K. Vijayan

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Supercritical water (SCW) exhibits excellent heat transfer characteristics and high volumetric expansion coefficient (hence high mass flow rates in natural circulation systems) near pseudo-critical temperature. SCW is being considered as a coolant in some advanced nuclear reactor designs on account of its potential to offer high thermal efficiency, compact size, elimination of steam generator, separator and dryer, making it economically competitive. The elimination of phase change results in elimination of the Critical Heat Flux (CHF) phenomenon. Cooling a reactor at full power with natural instead of forced circulation is generally considered as enhancement of passive safety. In view of this, it is essential to study natural circulation, heat transfer and pressure drop characteristics of supercritical fluids. Carbon-dioxide can be considered to be a good simulant of water for natural circulation at supercritical conditions since the density and viscosity variation of carbon-dioxide follows a parallel curve as that of water at supercritical conditions. Hence, a supercritical pressure natural circulation loop (SPNCL) has been set up in Hall-7, BARC to investigate the heat transfer, pressure drop and stability characteristics of supercritical carbon-dioxide under natural circulation conditions. The details of the experimental facility are presented in this report.

**Abstract**

Supercritical water (SCW) exhibits excellent heat transfer characteristics and high volumetric expansion coefficient (hence high mass flow rates in natural circulation systems) near pseudo-critical temperature. SCW is being considered as a coolant in some advanced nuclear reactor designs on account of its potential to offer high thermal efficiency, compact size, elimination of steam generator, separator and dryer, making it economically competitive. The elimination of phase change results in elimination of the Critical Heat Flux (CHF) phenomenon. Cooling a reactor at full power with natural instead of forced circulation is generally considered as enhancement of passive safety. In view of this, it is essential to study natural circulation, heat transfer and pressure drop characteristics of supercritical fluids. Carbon-dioxide can be considered to be a good simulant of water for natural circulation at supercritical conditions since the density and viscosity variation of carbon-dioxide follows a parallel curve as that of water at supercritical conditions. Hence, a supercritical pressure natural circulation loop (SPNCL) has been set up in Hall-7, BARC to investigate the heat transfer, pressure drop and stability characteristics of supercritical carbon-dioxide under natural circulation conditions. The details of the experimental facility are presented in this report.
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1.0 INTRODUCTION

Supercritical water is being considered as a coolant in some advanced nuclear reactor designs on account of its potential to offer high thermal efficiency, compact size, elimination of steam generator, separator & dryer, making it economically competitive. Several Supercritical Water Cooled Reactors (SCWRs) designs with forced circulation of primary coolant have been proposed in the past. Supercritical water natural circulation loops are capable of generating density gradients comparable to two-phase natural circulation loops. Hence, natural circulation is also considered as a viable option of heat removal in supercritical water cooled reactors. Natural circulation can also be used for passive decay heat removal after reactor shutdown. Hence, the behaviour of steady state natural circulation with supercritical fluids is of interest for a number of new reactor systems. Besides stable steady state, operation with unstable natural circulation is undesirable as it can lead to power oscillations in natural circulation based supercritical water reactors. Moreover, it can also cause mechanical vibration of components and failure of control systems.

Since supercritical fluids experience drastic change in their thermodynamic and transport properties near the pseudo-critical temperature, the heat transfer behaviour is quite different from sub-critical convective heat transfer and flow may be susceptible to density wave instability. Dramatic reduction in density near the pseudo-critical temperature results in strong buoyancy and acceleration effects across the cross-section causing unusual flow and heat transfer behaviour. Hence normal heat transfer correlations developed for turbulent flow of conventional fluids with small or moderate property variations like Dittus-Boelter correlation may not be applicable at supercritical conditions. Hence, the knowledge of heat transfer characteristics of supercritical fluids under natural circulation conditions is also important.

In view of the above, a supercritical pressure natural circulation loop (SPNCL) has been set up in Hall-7, BARC. The experiments are proposed to be conducted with carbon-dioxide at supercritical conditions. Carbon-dioxide can be considered as a good simulant.
fluid for water at supercritical conditions because of analogous change of properties particularly density and viscosity across the pseudo-critical point as shown in Figure 1a & 1b.

2.0 DESCRIPTION OF THE TEST FACILITY

The test facility is a uniform diameter (13.88 mm ID & 21.34 mm OD) rectangular loop, which can be operated with SC-CO\textsubscript{2}. The loop can operate with different possible orientations of heater and cooler, viz. Horizontal Heater Horizontal Cooler (HHHC), Horizontal Heater Vertical Cooler (HHVC), Vertical Heater Horizontal Cooler (VHHC) and Vertical Heater Vertical Cooler (VHVC) to study the effect of orientation on natural circulation behaviour at supercritical conditions. Figure 2a shows the photograph of the experimental facility. There are two heater locations (one at the bottom horizontal section and another in the left vertical leg) and two cooler locations (one at the top horizontal section and another in the right vertical leg) in the loop. Any of the above combinations (HHHC, HHVC, VHVC or VHHC) can be chosen prior to the experiment. The coolers are tube-in-tube type with a cooling length of 1.2 m.

Figure 2b shows a schematic of the loop, the fluid takes up heat in the heater section and on becoming light it rises through the riser and rejects heat in the cooler and on becoming heavier goes down the down comer and reaches heater inlet thereby establishing natural circulation. A pressurizer (with safety devices) is provided at the highest elevation of the loop to take care of thermal expansion of the carbon-dioxide. Since carbon-dioxide cylinders are available at a pressure of 65 bar, Helium cylinder will be used for pressurization of the loop to the operating pressure which will be filled from top of the pressurizer. Due to significant density difference between CO\textsubscript{2} (744.3 kg/m\textsuperscript{3}) and He (13.7 kg/m\textsuperscript{3}) at 90 bar and 30°C, the two gases are not expected to mix and a level will be formed in the pressurizer.

2.1 Design and Operating Conditions

The facility has been designed for the following conditions;

Design Pressure: 300 bar
Design temperature: 450°C

With CO\textsubscript{2} maximum operating conditions will be

Pressure: 120 bar
Temperature: 100°C

The design of loop piping has been done as per ASME-B31.1. The non-standard flanges for the above conditions have been designed as per ASME Section VIII Division I, Appendix-II (Mandatory). The material for Pipes, flanges and fittings in the system is SS-347, and are designed for the above conditions. The valves and fittings of standard 6000 1b rating have been used.
Since the design conditions are more severe for supercritical water (SCW) experiments and same loop will be modified later for SCW experiments, the loop except for the pressuriser has been designed for SCW conditions i.e. 300 bar/ 450°C.

Fig. 2a. Photograph of Supercritical Pressure Natural Circulation Loop (SPNCL)
Fig. 2b. Schematic of Supercritical Pressure Natural Circulation Loop (SPNCL)
2.2 Heaters

The loop has two heaters one each on bottom horizontal and left vertical legs. Each heater section consists of a SS-347 pipe (13.88 mm ID with 3.73 mm wall thickness & 1.22 m length) uniformly wound with 1 mm diameter Nichrome wire over a layer of fibre glass insulation. The maximum heat flux for heater test section is 143.3 kW/m². Flanged joints have been provided at the ends of each heater test sections. Tongue and groove Flanges (SS-347) have been designed for 300 bar and 450°C.

2.3 Coolers

There are two tube-in-tube type coolers in the loop (one at the top horizontal leg and other at the right vertical leg) with a heat removal capacity of 7.5 kW each. The chilled water flows in the secondary side of the cooler for which a connection has been taken from chilled water inlet line (9-12 °C) and the outlet is sent back to the chilled water return line going out of Hall-7. The main design details of each cooler are as given in the Table-1.

<table>
<thead>
<tr>
<th>Description</th>
<th>ID (mm)</th>
<th>OD (mm)</th>
<th>Design Pressure (bar)</th>
<th>Design Temp. (°C)</th>
<th>Fluid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner tube</td>
<td>13.88</td>
<td>21.34</td>
<td>300</td>
<td>450</td>
<td>SC-CO2</td>
</tr>
<tr>
<td>Outer tube</td>
<td>77.90</td>
<td>89.90</td>
<td>5</td>
<td>100</td>
<td>Chilled water</td>
</tr>
</tbody>
</table>

2.4 Pressurizer

The pressurizer (with safety devices) having a capacity of 30 litres (182.6 mm ID and 219.1 mm OD) is connected by U-bend at the bottom horizontal leg of the loop. Hence, the temperature of the pressurizer is not expected to go beyond 100 °C. The pressurizer has been designed as per ASME Section VIII Division I, for 200 bar and 100 °C.

2.5 Primary storage tank details

The primary loop will be charged using CO₂ cylinder having following specifications
Purity-99.8%
Pressure – 65 bar
Temperature – ambient
Capacity – 22 litres
Location – ground
3.0 OBJECTIVES

The objectives of the proposed experimental facility is to generate data base for
(a) heat transfer coefficient,
(b) friction pressure drop,
(c) steady state natural circulation performance,
(d) transient and stability performance

4.0 RANGE OF EXPERIMENTS

The experiments will be carried out with supercritical carbon dioxide. Measurements are to be carried out at different pressures ranging from 80-100 bar with supercritical carbon dioxide as working fluid. The heater section power will vary from 0- 7.5 KW during first phase of experiments with SC-CO₂.

4.1 Operating Parameters

- Primary operating conditions for SC-CO₂ operation
  Operating Pressure – 74 – 100 bar
  Operating Temperature – 200°C (maximum)
  Operating mass flow – 100 - 1000 kg/m²/s

- Secondary Operating conditions for SC-CO₂ operation
  Operating Pressure – 1 bar
  Operating Temperature –15°C (maximum)
  Operating mass flux – 100 - 3800 kg/m²/s

5.0 HYDRO-TEST PRESSURE REQUIREMENT

The hydro test pressure, $P_h$, required for SPNCL is estimated as below;

$$P_h = 1.3 \times P_d \times \frac{S_a}{S_d}$$

Where, $P_d$ is Design Pressure of the loop/equipment,
$S_a$ is Allowable stress for material at ambient temperature of 30 °C and is 20 ksi
$S_d$ is Allowable stress for material at design temperature of 450 °C and is 13.5 ksi

Since the loop and pressurizer are designed for two different conditions, hence these were hydro tested separately. The values of hydro test pressures required are shown in Table-2.

The loop was hydro tested for a pressure of 580 bar, while the pressurizer was hydro tested at 340 bar. The loop along with the pressurizer has also been hydro tested at 340 bar.
Table-2: Hydro test pressure requirement for the loop

<table>
<thead>
<tr>
<th>Description</th>
<th>material</th>
<th>Design Pressure (bar)</th>
<th>Design Temp. (°C)</th>
<th>$S_d$ (ksi)</th>
<th>$S_a$ (ksi)</th>
<th>$P_h$ (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loop</td>
<td>SS-347</td>
<td>300</td>
<td>450</td>
<td>13.5</td>
<td>20</td>
<td>577.8</td>
</tr>
<tr>
<td>Pressurizer</td>
<td>SS-316</td>
<td>200</td>
<td>100</td>
<td>15.6</td>
<td>20</td>
<td>333.3</td>
</tr>
</tbody>
</table>

6.0 INSTRUMENTATION

The Process and Instrumentation (P & I) diagram of the SPNCL is shown in Fig. 3. All the process parameters are transmitted electronically to the Supervisory Control and Data Acquisition (SCADA) system. All the instruments used are electronic in nature. Processing of all the electronic signals transmitted from the field transmitters is performed by the SCADA system. The SCADA control system digitizes the analog signals and computes the control signals. The system also communicates with operator for uploading data to database and receiving operator commands. The supervisory computer serves as operator interface and database server.

All the temperatures in the loop are measured by mineral insulated, 1 mm, SS316 sheathed; K-Type thermocouples along with Astron make isolated electronic temperature transmitters giving 4 to 20 mA normalised floating signals. Temperature signals in the form of 4 to 20 mA DC from isolated field transmitters are brought to SCADA using multi-core cables. The transmitters are calibrated in groups depending on temperature zone in the process. There are 44 calibrated thermocouples to measure the primary fluid, secondary fluid and heater outside wall-temperatures. Primary fluid temperatures at each location was measured as the average value indicated by two thermocouples inserted diametrically opposite at r/2 (see detail-D in Fig. 2b) from the inside wall whereas secondary fluid temperatures were measured by a single thermocouple located at the tube centre. This was adequate to obtain the average temperature as the temperature rise in the secondary fluid was small (< 4 °C). The thermocouples used to measure the heater outside wall temperature were installed flush with the outside surface. To enable this, a longitudinal slot of 0.2 mm deep and width equal to the diameter of the thermocouple was cut on the outside surface and the thermocouple was inserted in this groove and brazed. There were 12 thermocouples at six axial distances installed at diametrically opposite locations.

Differential Pressure and Level of the supercritical fluid are measured by FUJI Make electronic smart transmitters capable of withstanding high static pressure (420 bar). Pressure and differential pressure signals from field are of 4 to 20 mA normalized DC signal from transmitters energised by 24 V DC power supply located inside the control panel. Diaphragms of pressure and differential pressure/ level transmitters are rated up to 100 °C for normal operation. Hence, process connections are taken from piping and vessel with U-bends followed by long impulse tubing to protect the instruments. Dedicated hardwired trip logic has been used for tripping the heaters on over pressure and high temperature.
Fig. 3. P & I Diagram for Supercritical Test Facility
Pressure is measured by FUJI Make electronic smart transmitters and Keller make transducers with fast response (Rating up to 300 °C) located on the pressuriser as well as at the heater outlet. Electronic transmitters capable of withstanding more than 500 bars are used.

The flow in the main loop is measured in the single-phase horizontal pipe with calibrated pipe taps. The flow rate in the loop is proposed to be estimated from the measured pressure drop (by DPT-1 in Figure 3) across 1.8 m length of horizontal pipe (the flow in this stretch of pipe is single phase flow) using the pipe friction chart. This method is adopted to minimise the pressure losses in the loop which has a significant influence on the natural circulation flow. To improve the accuracy of this method, this pipeline has been calibrated against the measurement by rotameter for different flow rates under forced flow.

A single-point conductance probe (CPI-1) is installed at the top of the loop for checking the presence two-phase in the loop. There is one 3-points conductance probe (CPI-2) at the bottom of the pressurizer and two single-point conductance probes (CPI-3 & CP-4) in the liquid and gas space of the pressurizer for measurement of level and to determine whether CO₂ is in liquid or vapour state during initial charging and subsequent pressurization of loop using Helium cylinder. These probes are located at different elevations in the pressurizer and the surge line.

The secondary flow rate was measured with the help of three parallel turbine flowmeters (FE1 to FE3).

The power of each heater was measured with a Wattmeter.

All instruments were connected to a data logger with a user selectable scanning rate. For all the transient and stability tests the selected scanning rate was 1 second.

7.0 ELECTRICAL

The power supply (15kw) to the heaters is taken from the switch fuse unit (SFU) of electrical panel located to MP-4 in High bay of hall-7 to the control cubical near the loop. The SFUs are rated for 63A, 415V, 50 Hz. The cubical accommodate power contactors, CTs, and digital metering system for reading of voltage, current and power parameters, etc. It has on/off push buttons and power ‘on’ indication lamps. The power supply can be varied with the help of two separate autotransformers connected to heater. Only one heater can be switched on at a time.

8.0 COOLING WATER SYSTEM

Chilled water is required as a heat sink on secondary side of the cooler. Cooling water pressure and flow requirements are given below
Pressure – 5 bar
Flow rate – 35 lpm
For this a connection from chilled water inlet line to Hall-7 is taken and fed on the secondary side of the cooler and after taking up heat from the cooler, is sent back to the return line going out of Hall-7.

9.0 SAFETY SYSTEMS

9.1 Rupture discs

Two rupture discs of different set points have been provided at the top of the pressurizer in parallel. In case of excess pressure rupture disc will break. The maximum operating pressures, the set point of rupture discs (RD-I & RD-2) are given in the following Table-3.

9.2 Relief line

For SC-CO₂ operation the relief line is the discharge line after the two rupture discs in parallel on top of the pressurizer. The discharge rate required for SC-CO₂ operation, as given in Table-4 is the minimum flow required through this discharge line. The relief line for SC-CO₂ operation will be routed outside Hall-7.

<table>
<thead>
<tr>
<th>Operating Fluid</th>
<th>Design Pressure * (bar)</th>
<th>Design Temp.* (°C)</th>
<th>Max. Operating Pressure (bar)</th>
<th>Set Pressure for RD-2 (bar)</th>
<th>Set Pressure for RD-1 (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC-CO₂</td>
<td>300</td>
<td>450</td>
<td>100</td>
<td>125</td>
<td>110.0</td>
</tr>
</tbody>
</table>

* The design values are for the loop excluding the pressurizer.

Table-4: Required discharge rate of relief line for SPNCL

<table>
<thead>
<tr>
<th>Operating fluid</th>
<th>Max. Power (kW)</th>
<th>Max. Operating Pressure (bar)</th>
<th>Discharge rate required (kg/s)</th>
<th>Actual Discharge rate (kg/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC-CO₂</td>
<td>7.5</td>
<td>100</td>
<td>0.01905</td>
<td>1.2</td>
</tr>
</tbody>
</table>

10.0 VALVES LIST

The different valves which are in the SPNCL are listed in Table-5 with their functions and locations.
<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Valve No.</th>
<th>Size of valve</th>
<th>Function</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>V-101 &amp; 102</td>
<td>3/8”</td>
<td>To isolate DPT1</td>
<td>Across horizontal heater</td>
</tr>
<tr>
<td>2</td>
<td>V-103</td>
<td>3/8”</td>
<td>To isolate DPT2</td>
<td>Before vertical heater</td>
</tr>
<tr>
<td>3</td>
<td>V-104 &amp; 105</td>
<td>3/8”</td>
<td>To isolate DPT3</td>
<td>Across vertical heater</td>
</tr>
<tr>
<td>4</td>
<td>V-106, 107, 108 &amp; 109</td>
<td>3/8”</td>
<td>To isolate DPT4</td>
<td>Across horizontal cooler</td>
</tr>
<tr>
<td>5</td>
<td>V-110</td>
<td>3/8”</td>
<td>To isolate DPT5</td>
<td>Before vertical cooler</td>
</tr>
<tr>
<td>6</td>
<td>V-111 &amp; 112</td>
<td>3/8”</td>
<td>To isolate DPT6</td>
<td>Across vertical cooler</td>
</tr>
<tr>
<td>7</td>
<td>V-113</td>
<td>3/8”</td>
<td>To isolate DPT7</td>
<td>After vertical cooler</td>
</tr>
<tr>
<td>8</td>
<td>V-114</td>
<td>3/8”</td>
<td>To isolate DPT7</td>
<td>Before horizontal cooler</td>
</tr>
<tr>
<td>9</td>
<td>V-115 &amp; 116</td>
<td>3/8”</td>
<td>To isolate PT3</td>
<td>After left side tee on top horizontal pipe</td>
</tr>
<tr>
<td>10</td>
<td>V-117 &amp; 118</td>
<td>3/8”</td>
<td>Venting of loop</td>
<td>After left side tee on top horizontal pipe</td>
</tr>
<tr>
<td>11</td>
<td>V-119 &amp; 120</td>
<td>3/8”</td>
<td>Venting of loop</td>
<td>After right side tee on top horizontal pipe</td>
</tr>
<tr>
<td>12</td>
<td>V-121 &amp; 122</td>
<td>3/8”</td>
<td>Venting of U tube</td>
<td>Before U bend connecting main loop to the pressurizer</td>
</tr>
<tr>
<td>13</td>
<td>V-123, 124 &amp; 125, 126</td>
<td>3/8”</td>
<td>To isolate DPT8</td>
<td>Level measurement in pressurizer</td>
</tr>
<tr>
<td>14</td>
<td>V-127 &amp; 128</td>
<td>3/8”</td>
<td>For draining the loop</td>
<td>After right side tee on bottom horizontal pipe</td>
</tr>
<tr>
<td>15</td>
<td>V-301</td>
<td>3/8”</td>
<td>For filling the loop</td>
<td>After PRV-1</td>
</tr>
<tr>
<td>16</td>
<td>V-302 &amp; 303</td>
<td>3/8”</td>
<td>For CO2 venting</td>
<td>Across horizontal cooler</td>
</tr>
<tr>
<td>17</td>
<td>V-304</td>
<td>3/8”</td>
<td>For CO2 venting</td>
<td>In the U bend before pressurizer</td>
</tr>
<tr>
<td>18</td>
<td>V-401</td>
<td>3/8”</td>
<td>For isolating Helium cylinder</td>
<td>After PRV-2</td>
</tr>
<tr>
<td>19</td>
<td>V-402 &amp; 403</td>
<td>3/8”</td>
<td>Venting of pressurizer</td>
<td>On top of pressurizer</td>
</tr>
<tr>
<td>20</td>
<td>V-501</td>
<td>1 ½”</td>
<td>For isolating secondary side</td>
<td>Inlet line of chilled water to hall-7</td>
</tr>
<tr>
<td>21</td>
<td>V-502 to V-509</td>
<td>½”</td>
<td>For isolating the flowmeters</td>
<td>Inlet and outlet of flowmeters</td>
</tr>
<tr>
<td>22</td>
<td>V-510, 511 &amp; 515</td>
<td>3/8”</td>
<td>For isolating secondary side of horizontal cooler</td>
<td>Inlet and outlet of secondary side of horizontal cooler</td>
</tr>
<tr>
<td>23</td>
<td>V-512, 513 &amp; 514</td>
<td>3/8”</td>
<td>For isolating secondary side of vertical cooler</td>
<td>Inlet and outlet of secondary side of vertical cooler</td>
</tr>
<tr>
<td>24</td>
<td>V-516</td>
<td>3/8”</td>
<td>Coommon outlet line of coolers</td>
<td>Return line of chilled water from hall-7</td>
</tr>
<tr>
<td>25</td>
<td>PRV-1</td>
<td>3/8”</td>
<td>For setting discharge pressure from CO2 cylinder</td>
<td>On top of CO2 cylinder</td>
</tr>
<tr>
<td>26</td>
<td>PRV-2</td>
<td>3/8”</td>
<td>For setting discharge pressure from Helium cylinder</td>
<td>On top of Helium cylinder</td>
</tr>
</tbody>
</table>
11.0 SAFETY ANALYSIS

a) In case of **power failure** there will be no heating in the loop, so there will be no rise in pressure & temperature, hence it is safe.

b) In case of **secondary side fluid flow failure**, the heat transfer to secondary will reduce and pressure & temperature on primary side will increase. The heater power will trip on high pressure signal or high temperature signal, whichever comes first. Thus loop will be again in safe conditions.

c) In case of **pipe/ flange failure** the loop pressure will decrease and low pressure trip signal will switch off the heater power and there will be no unsafe condition. In case of pipe/ flange failure with CO₂ operation, the CO₂ concentration will be well below allowable limit of 5000 ppm. The loop will be operated with two pedestal fans to prevent high concentration of CO₂ in the loop area.

12.0 ALARM AND SET POINTS

Signals indicating high pressure and high temperature of the process fluid are used for tripping the heater power supplies and window based alarm indication. Redundant signals analog circuits have been used for achieving this trip action.

12.1 High temperature trip

The temperature rise due to the time delay in the high temperature trip signal and trip action is to be accounted in the high temperature trip set point. The temperature rise is taken care by selecting high temperature trip set point in such a way that this rise in temperature is within the design limits of the heater test section. The calculation details are given below. Total time delay involves 100 ms for sensor (thermocouple), 250 ms for transmitter and 100 ms for scanning time which adds up to total of 450 milliseconds. For conservative calculation an instrument time delay of 500 milliseconds is considered and heat transfer to the carbon-dioxide inside the heater section is also not considered. The temperature rise in the heater test section can be estimated as

\[
\Delta T_{\text{heater}} = \frac{(Q \times \text{time})}{m_{\text{heater}} \times (C_p)_{\text{heater}}}
\]

Time = 0.50 second or 500 milliseconds
\(\rho_{\text{steel}} = 7817 \text{ kg/m}^3\)
\(m_{\text{heater}} = \rho_{\text{heater}} \times [(\pi/4) (d_0^2 - d_i^2)]\)
\((C_p)_{\text{steel}} = 0.461 \text{ kJ/kg K}\)

The temperature rise (ΔT) in 0.5 s for the loop is given in Table-6 below.
Table-6: Criterion for high temperature trip

<table>
<thead>
<tr>
<th>Operating fluid</th>
<th>Max. Power (kW)</th>
<th>Heater Design Temp. (°C)</th>
<th>ΔT_{heater} in 0.5s</th>
<th>Alarm for high temp trip (°C)</th>
<th>High temp trip Value (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SC-CO₂</td>
<td>7.5</td>
<td>450</td>
<td>4.04</td>
<td>440</td>
<td>445</td>
</tr>
</tbody>
</table>

Hence, the shutdown of the SPNCL due to high temperature trip can be carried out safely.

12.2 High Pressure trip

The pressure rise due to the time delay in the high pressure trip signal and trip action is to be accounted in the high temperature trip set point. The pressure rise is taken care by selecting high pressure trip set point in such a way that this rise in pressure is within lower threshold of Rupture disc (RD1 as given in table 7) set point as shown in Table-7 below. For conservative calculation an instrument time delay of 500 milliseconds is considered. For conservative calculation an instrument time delay of 0.5 s is not allowed to go to the pressurizer. It means that ΔP is calculated without considering any inventory transfer from the primary loop to the pressurizer which is a highly conservative approach.

Table-7: High Pressure trip set point value

<table>
<thead>
<tr>
<th>Power (kW)</th>
<th>Max. Operating Pressure (bar)</th>
<th>High Pressure Alarm Value (bar)</th>
<th>High Pressure Trip Value (bar)</th>
<th>Pressure Rise (ΔP) in 0.5 s (bar)</th>
<th>Set Pressure for RD (bar)</th>
<th>Set Pressure for RD (bar)</th>
<th>Lower Threshold</th>
<th>Upper Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>100</td>
<td>101</td>
<td>102</td>
<td>0.18</td>
<td>110</td>
<td>104.5</td>
<td>115.5</td>
<td></td>
</tr>
</tbody>
</table>

12.3 Low Pressure trip

Since the loop will be operated between 80-100 bar. The low pressure alarm and trip set points for the loop are kept below the minimum operating condition and are given in Table-8.

Table-8: Low Pressure trip set point value

<table>
<thead>
<tr>
<th>Oper. fluid</th>
<th>Max. Operating Pressure (bar)</th>
<th>Low Pressure Alarm Value (bar)</th>
<th>Low Pressure Trip Value (bar)</th>
</tr>
</thead>
</table>
13.0 INSULATION

For maximum power of 7.5 kW, the maximum loop operating temperature is 100°C with SC-CO₂. The entire loop has been insulated with 3” thick ceramic mats with except the pressurizer (since pressurizer will not experience high temperature even) because of U-bend provided at the bottom of the loop which connects the main loop to the pressurizer.

14.0 LOOP OPERATION

The start up procedure for these experiments should be such that boiling should not occur while heating to supercritical conditions. The critical pressure and temperature for CO₂ are 7.4 MPa and 31°C respectively. The loop operation involves initially following operations;

14.1 Filling primary loop

First CO₂ will be filled in gaseous form in the loop from the bottom horizontal pipe of the loop (Figure 2b) at 5.5 MPa (saturation temp 18.2 °C) which is set by PRV-1. Then both horizontal and vertical coolers will be started with chilled water (9-12 °C) flowing on secondary side which will help in condensation of carbon-dioxide. During start-up of the experiments, the non-condensable gases present in the loop are vented through the vent valves (V-117 & 118, V-119 & 120) provided at the top horizontal pipe of the loop, as shown in detailed process and instrumentation diagram (figure 3). The non-condensable gases in the pressurizer surge line are vented using valves V-121 & 122. Vent valves V-402 & 403 are provided at the top of the pressurizer. For venting with SC-CO₂, all the vent lines are connected to a common outlet header at the top of the loop, from where a common outlet is led to outside Hall-7 building. During condensation loop pressure may fall and more CO₂ will be admitted from the cylinder. This process of filling and condensation will continue till there is no fall in loop pressure.

14.2 Primary side pressurization

Once the condensation in the loop is stopped, Helium can be filled on top of pressurizer at desired operating pressure (e.g. 7.0 – 10.0 MPa). Due to large density difference between CO₂ and helium, a level will be formed in the pressurizer. Once the required loop pressure is achieved the helium cylinder is isolated from the system. Sufficient time is allowed to reach a steady state. The helium cylinder is available at pressure of 165 bar, which will be connected to the top of the pressurizer through PRV-2 which can be set at desired pressure at which CO₂ needs to be pressurized.

15.0 CONCLUSION

A supercritical pressure natural circulation loop (SPNCL) has been set up in Hall-7, BARC. The loop will be utilized to conduct the experiments with carbon-dioxide at supercritical conditions.
REFERENCES


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