BARC/2013/E/013

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GOVERNMENT OF INDIA
ATOMIC ENERGY COMMISSION

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BIBLIOGRAPHIC DESCRIPTION SHEET FOR TECHNICAL REPORT
(as per IS : 9400 - 1980)

01	*Security classification :*	Unclassified
02	*Distribution :*	External
03	*Report status :*	New
04	*Series :*	BARC Exernal
05	*Report type :*	Technical Report
06	*Report No. :*	BARC/2013/E/013
07	*Part No. or Volume No. :*	
08	*Contract No. :*	
10	*Title and subtitle :*	Experiments in a natural circulation loop with supercritical water at low powers
11	*Collation :*	43 p., 25 figs., 11 tabs., 1 ill.
13	*Project No. :*	
20	*Personal author(s) :*	D.S. Pilkhwal; Manish Sharma; S.S. Jana; P.K. Vijayan
21	*Affiliation of author(s) :*	Reactor Engineering Division, Bhabha Atomic Research Centre, Mumbai
22	Corporate author(s) :	Bhabha Atomic Research Centre, Mumbai - 400 085
23	*Originating unit :*	Reactor Engineering Division, BARC, Mumbai
24	*Sponsor(s) Name :* *Type :*	Department of Atomic Energy Government

Contd...

30	*Date of submission :*	April 2013
31	*Publication/Issue date :*	May 2013
40	*Publisher/Distributor :*	Head, Scientific Information Resource Division, Bhabha Atomic Research Centre, Mumbai
42	*Form of distribution :*	Hard copy
50	*Language of text :*	English
51	*Language of summary :*	English
52	*No. of references :*	19 refs.
53	*Gives data on :*	

60

Abstract : Earlier, 1/2" uniform diameter Supercritical Pressure Natural Circulation Loop (SPNL) was set-up in hall-7, BARC for carrying out experiments related to supercritical fluids. The loop is a rectangular loop having two heaters and two coolers. Experiments were carried out with CO_2 under supercritical conditions for various pressures and different combinations of heater and cooler orientations. Since, the design conditions are more severe for supercritical water (SCW) experiments, the loop was modified for SCW by installing new test sections, pressurizer and power supply for operation with supercritical water. Experimental data were generated on steady state, heat transfer and stability under natural circulation conditions for the horizontal heater and horizontal cooler (HHHC) orientation with SCW up to a heater power of 8.5 kW. The flow rate data and instability data were compared with the predictions of in-house developed 1-D code NOLSTA, which showed reasonable agreement. The heat transfer coefficient data were also compared with the predictions of various correlations exhibit peak at bulk temperature lower than that obtained in the experiments. Most of these correlations predicted experimental data well in the pseudo-critical region. However, all correlations are matching well with experimental data beyond the pseudo-critical region. The details of the experimental facility, Experiments carried out and the results presented in this report.

70 *Keywords/Descriptors :* TURBUENT FLOW; COOLANT LOOPS; HEAT TRANSFER; CARBON DIOXIDE; DESIGN; STAINLESS STEEL-347; INCONEL 625; SAFETY; STEADY-STATE CONDITIONS

71 *INIS Subject Category :* S22

99 *Supplementary elements :*

Abstract

Earlier, ½" uniform diameter Supercritical Pressure Natural Circulation Loop (SPNL) was set-up in hall-7, BARC for carrying out experiments related to supercritical fluids. The loop is a rectangular loop having two heaters and two coolers. Experiments were carried out with CO_2 *under supercritical conditions for various pressures and different combinations of heater and cooler orientations. Since, the design conditions are more severe for supercritical water (SCW) experiments, the loop was modified for SCW by installing new test sections, pressurizer and power supply for operation with supercritical water. Experimental data were generated on steady state, heat transfer and stability under natural circulation conditions for the horizontal heater and horizontal cooler (HHHC) orientation with SCW up to a heater power of 8.5 kW. The flow rate data and instability data were compared with the predictions of in-house developed 1-D code NOLSTA, which showed reasonable agreement. The heat transfer coefficient data were also compared with the predictions of various correlations. The experiments show a peak heat transfer coefficient at 381* ^{O}*C. All correlations exhibit peak at bulk temperature lower than that obtained in the experiments. Most of these correlations predicted experimental data well in the pseudo-critical region. However, all correlations are matching well with experimental data beyond the pseudo-critical region. The details of the experimental facility, Experiments carried out and the results presented in this report.*

CONTENTS

List of tables

List of figures

List of Appendices

1. INTRODUCTION

Supercritical water natural circulation loops (operating above critical points) are capable of generating density gradients comparable to two-phase water natural circulation loops. Hence, supercritical water is being considered as a coolant in some advanced nuclear reactor designs. Because of the higher operating temperatures with supercritical fluids, the thermodynamic efficiency is larger. The critical heat flux phenomenon is eliminated raising the possibility of higher power density. The supercritical fluids can be directly sent to the turbine eliminating the requirement of steam generator, steam-water separator and dryer. The higher power density achieved in such reactors could result in the lower core size. These many advantages suggest that the supercritical reactor could be far more competitive economically compared to the current LWRs.

Supercritical fluids undergo significant property changes in the pseudo-critical region. A few studies have been made to extend the generalized dimensionless parameters applicable for stability analysis of two-phase flows to supercritical fluids [1 & 2]. Some of these studies were carried out in natural circulation systems [3-6]. However, very few experimental studies are reported in the open literature. To our knowledge, the supercritical test data are reported in rectangular loops by Lomperski et al. [7] and Holman and Boggs [8] with supercritical CO_2 and Freon-12 respectively. Besides Yoshikawa et al. [9] studied the performance of a supercritical CO_2 natural circulation in a somewhat complex loop. Due to the large property variations in the pseudocritical region, traditional single-phase heat transfer correlations are not adequate to predict the heat transfer for supercritical fluids. Several investigators have also reported deterioration in heat transfer in the pseudocritical region similar to that observed in two-phase flows following the occurrence of CHF [10-11].

Safety is a key issue in the design of advanced reactors and considerable emphasis is placed on passive safety. Hence, steady state and stability behaviour of natural circulation with supercritical fluids is of interest for a number of new reactor systems. In the context of the above, an experimental investigation of the steady state and stability behavior was planned. A ½” diameter supercritical pressure natural circulation loop (SPNCL) was designed, installed and operated with supercritical CO_2 as working fluid, at hall no. 7, BARC [12 & 13]. Experiments were carried out for different supercritical pressures with different combinations of heaters and coolers orientations with chilled water as coolant.

Subsequent to the completion of the experiments with CO_2 the existing supercritical pressure natural circulation loop (SPNCL) was modified by installing new test sections, pressurizer and a new power supply. Besides, the instrumentation and the secondary system of the loop were also modified. Two inconel-625 heater test-sections were fabricated and installed in place of the SS-347 test sections. The cooler is the same as in CO_2 loop. However, provision was made for cooling with air flowing in the annulus. The instrumentations and safety devices of the loop were upgraded to supercritical water conditions.

Experiments were carried out for the horizontal heater and horizontal cooler (HHHC) orientation for steady state natural circulation flow and instability. These experiments were carried out up to 8.5

kW heater power and up to a pressure of 241 bar. The experimental data generated were compared with in-housed developed code and were found in reasonable agreement. The heat transfer coefficient data was also compared with the predictions of various correlations. The details of the experimental set-up, experiments carried out and the results of the analysis are presented in this report.

2.0 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

3.0 EXPERIMENTAL LOOP FOR SUPERCRITICAL WATER

Earlier, experiments were carried out with supercritical CO2 in a supercritical pressure natural circulation loop (SPNCL) [12 & 13]. The test facility is a uniform diameter (13.88 mm ID & 21.34 mm OD) rectangular loop, which can be operated with SC-CO2. 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.

Since, the design conditions are more severe for supercritical water (SCW) experiments and the loop for SC-CO2 was modified for SCW experiments. The loop was modified by installing new test sections, pressurizer and power supply for operation with supercritical water. Fig. 1 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. The schematic of the loop as fabricated length scales are given in Fig. 2. 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 vent valve is located at the highest elevation of the loop. The filling and draining operations in the loop are carried out through valves located at the bottom horizontal section. A pressurizer (with safety devices) is provided at the highest elevation of the loop to take care of thermal expansion of the fluid. Nitrogen is used as a cover gas in the system.

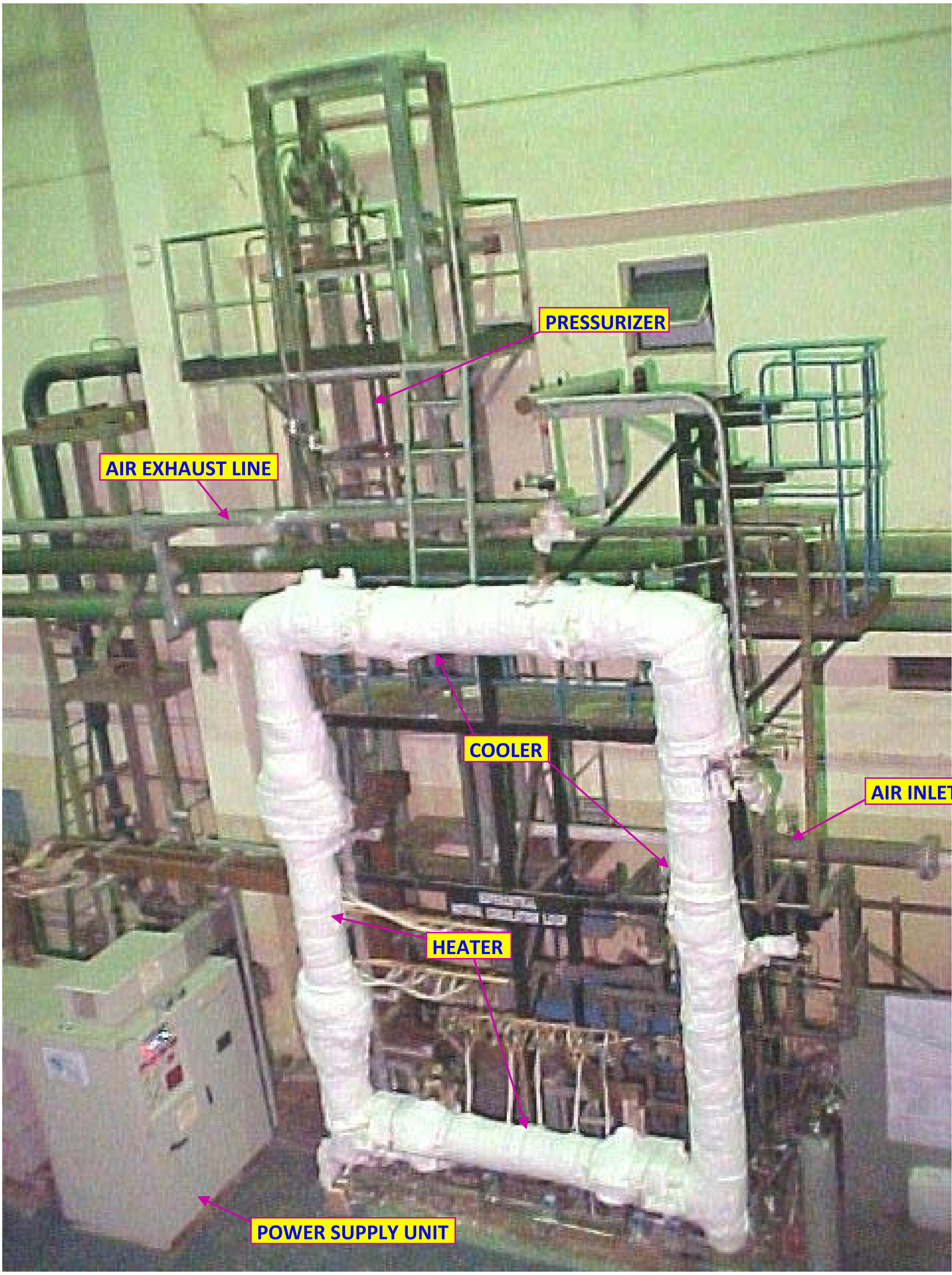


Fig. 1: Photograph of SPNCL

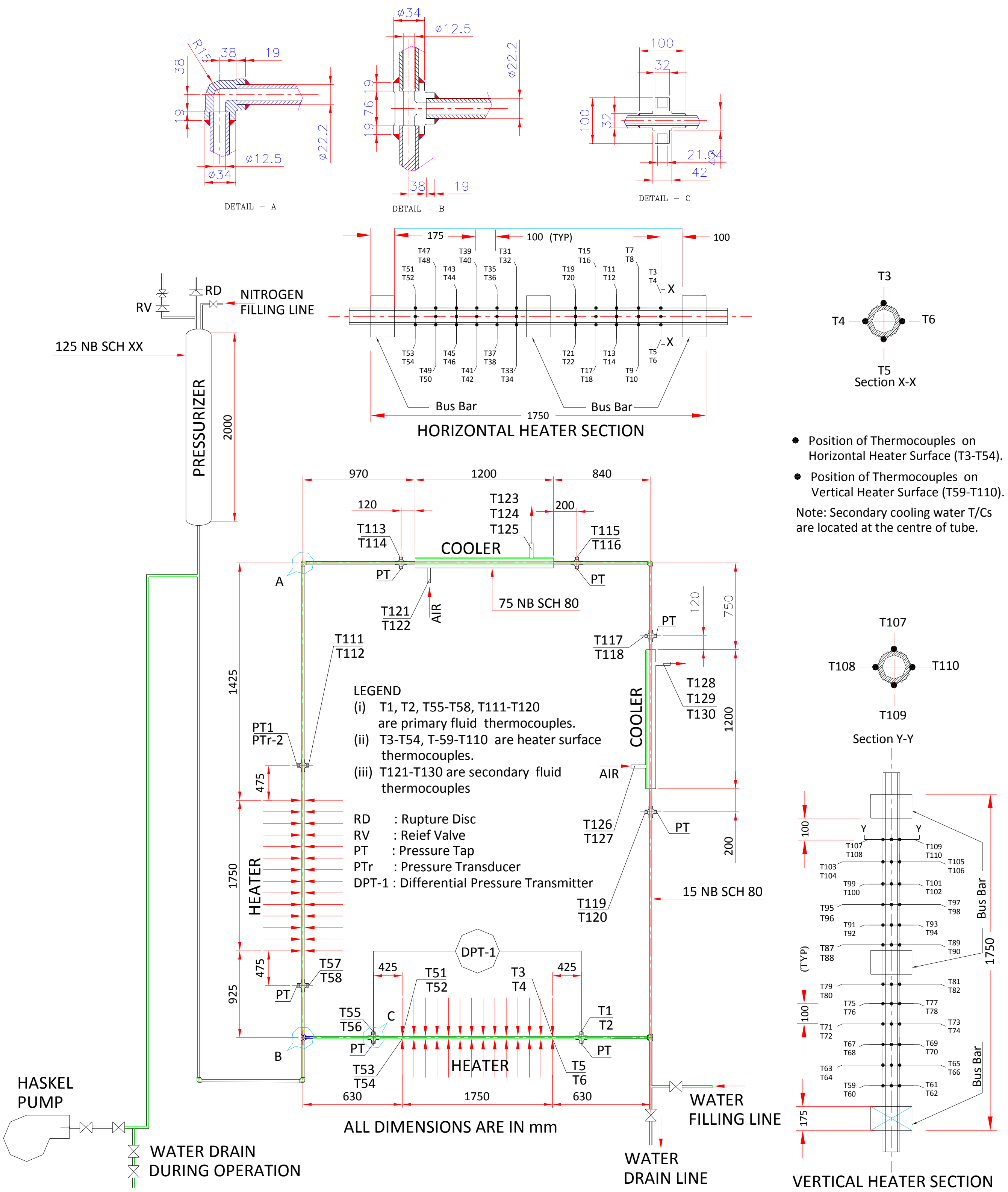


Fig. 2: Schematic of the SPNCL for SCW

The new test sections are direct electrically heated ones. For this, a 200 kW low voltage high current (25 V & 8000 A) power supply was procured and installed. Fig. 3 shows the photograph of new power supply unit. It could be connected to either the horizontal or the vertical heater test sections by flexible silver coated copper busbars. A haskel pump was also installed to pressurize the loop. The cooler is tube in tube type which is the same as in CO_2 loop. However, provision was made for cooling with air flowing in the annulus. For this a large capacity blower (i.e. 45,300 lpm at 20 m WC head) was installed. An anubar was installed in the 150 mm line for the air flow measurement. Two hot air exit lines from the horizontal and vertical coolers were fabricated and installed. Steam exit lines from the outlet of rupture disc to the outside of building were fabricated. The loop along with impulse lines was hydro tested at 60 MPa. A new pressurizer for high pressure (designed for 30 MPa) operation required for the supercritical water conditions was designed and fabricated. Besides, the instrumentation and the secondary system of the loop were also modified. This also necessitated the use of a new data logger. Fig 4 shows the photograph of control panel with data logger.

Fig. 3: Photograph of Power Supply Unit

Fig. 4: Photograph of Control Pannel for SPNCL

3. 1 Design and Operating Conditions

The loop design parameters have been listed in Table-1. Heater test sections (horizontal & vertical) in the loop are made of Inconel-625 which can with stand high temperatures up to 600^{o}C, while SS-347 valves and fittings of standard 6000 lbs (41.3 MPa) rating have been used. The design of loop piping has been done as per ASME-B31.1.

The loop operating parameters have been listed in Table-2.

Table-1: Design conditions for the Loop and the pressurizer

Primary /Secondary side	Description	Operating Fluid	Material	Design Pressure (bar)	Design Temp. (^{o}C)	Design Mass Flux ($kg/m^2/s$)
Primary side	Loop piping	H2O	SS-347	300	450	2000
	Heater	H2O	Inconel-625	300	600	2000
	Pressurizer*	H_2O	SS-347	300	150	Water (with N2 cover gas)
Secondary side	Cooler	Air	SS-316	50	250	3000
	Piping	Air	SS-316	50	250	3000

* The pressurizer will not experience high temperature as it is connected by U-bend to the main loop, hence the same has been designed for low temperature e.g. $150^{o}C$

Table-2: Operating conditions for the Loop and the pressurizer

Primary / Secondary side	Description	Pressure (bar)	Max. Temp. (^{o}C)	Mass Flux ($kg/m^2/s$)	Remarks
Primary side	Loop	220-250	445	100-1000	SCW
	Heater	220-250	575	-	Surface temp.
	Pressurizer	220-250	60	-	Water
Secondary side	Cooler	1.02	50-100	3000	Air
	Piping	1.05	50-100	3000	Inlet & outlet

3.2 Heaters

The loop has two heaters (direct electrically heated) one each on bottom horizontal and left vertical legs. Each heater section consists of Inconel-625 pipe (13.88 mm ID with 3.73 mm wall thickness & 1.75 m length) is capable of operation at 25 MPa and 575 ^{o}C was fabricated and installed in place of the SS-347 test sections. Thermocouples were brazed on the outside surface of each heater test section, at thirteen different axial locations. At each location, four thermocouples were provided at 90^{o} angular distance (each at top, bottom, side-ways). A total of 124 thermocouples were installed in the water loop compared to 44 thermocouples in the CO_2 loop. The photograph of the installed horizontal heater with thermocouples is shown in Fig. 5.

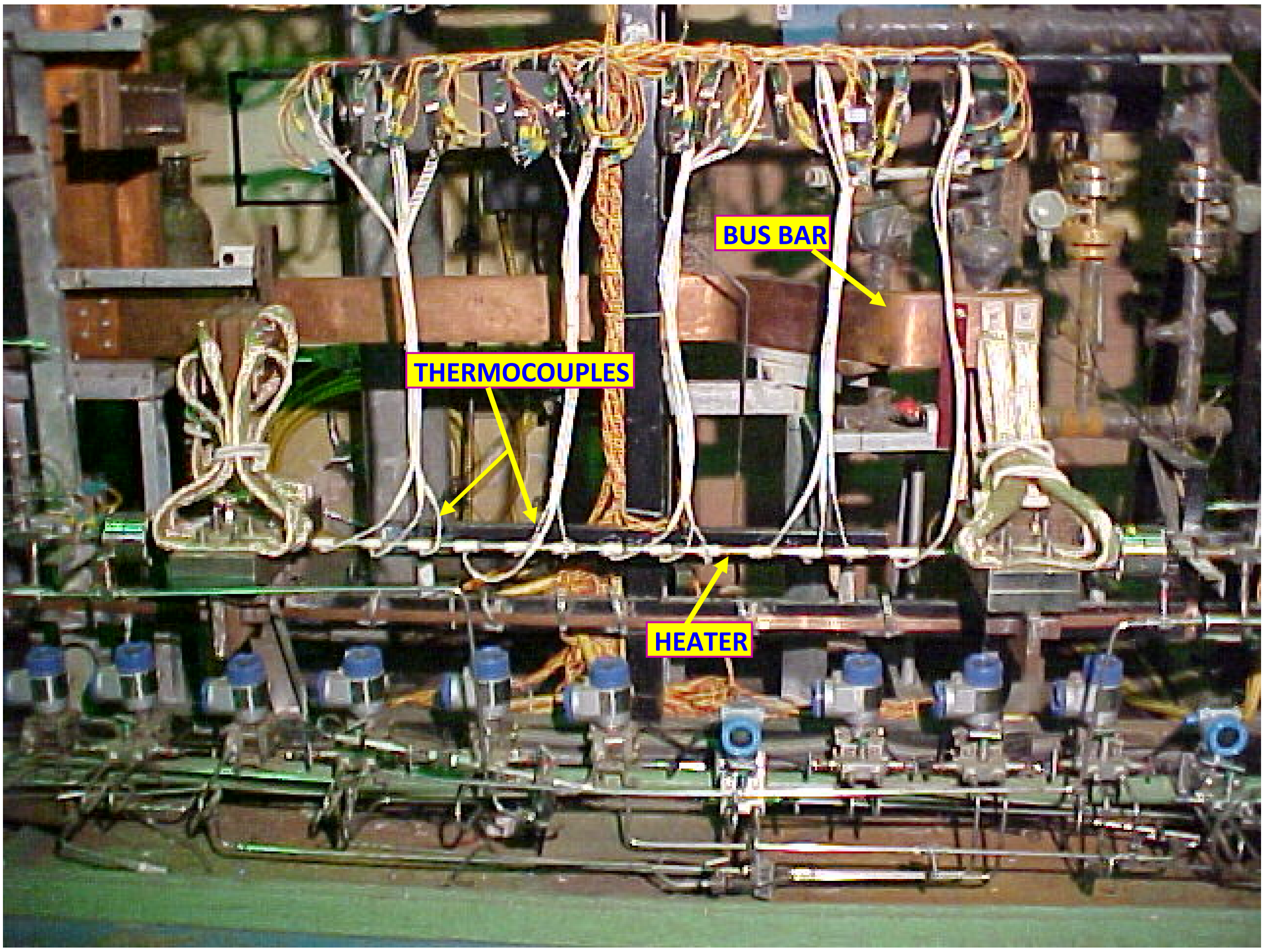


Fig. 5: Photograph of horizontal heater with thermocouples

3.3 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). The air flows in the secondary side of the cooler from a blower and the air exit line goes out of the Hall-7. The main design details of each cooler are as given in the Table-3. Fig. 6 shows the schematic of the cooler.

Table-3: Details of Cooler

Description	Material	ID (mm)	OD (mm)	Design Pressure (bar)	Design Temp. (^oC)	Fuid
Inner tube	SS-347	13.88	21.34	300	450	SC-H_2O
Outer tube	SS-347	77.90	89.90	5	100	Air

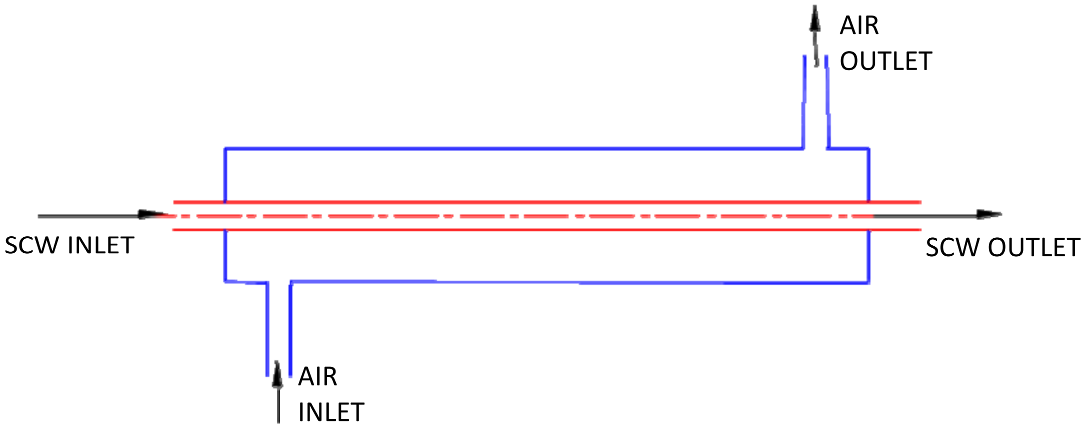


Fig. 6: Schematic of the cooler for SPNCL

3.4 Pressurizer

A new pressurizer for high pressure operation required for the supercritical water conditions was designed (30 MPa, 150 ^{O}C) and fabricated. It is made up of SS-347 pipe and ellipsoidal caps having a capacity of 16.7 litres (103.2 mm ID and 141.3 mm OD) is connected by U-bend at the bottom horizontal leg of the loop. The safety devices (rupture discs) required for the higher pressure rating were procured and installed on the pressurizer. The pressurizer also had provisions for gas filling (nitrogen). A new support structure was also fabricated for the pressurizer installation at the site. The temperature of the pressurizer is not expected to go beyond 100 ^{O}C. Since the pressurizer is connected to main loop using U-bend (See Fig. 2), it provides a water seal at the lower portion of the loop and pressurizer. The pressurizer has been designed as per ASME Section VIII Division I, for 300 bar and 150 ^{O}C. Fig. 7 shows the schematic of the new pressurizer without supports.

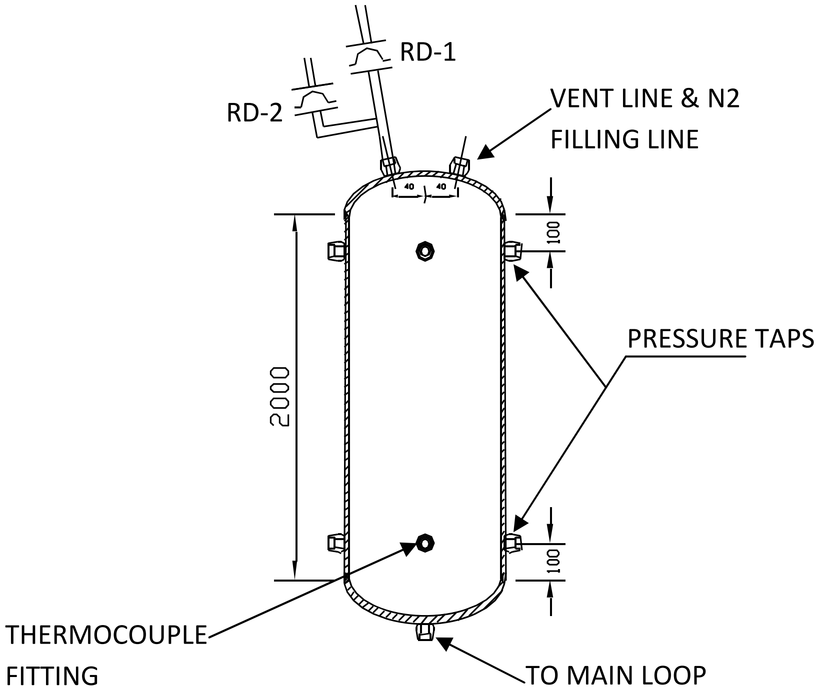


Fig. 7: Pressurizer of SPNCL

4.0 HYDROSTATIC PRESSURE TEST REQUIREMENT

The hydrotest pressure required for the loop design pressure (considering temperature correction for allowable stress) is shown in table-4 and calculated as follows

Hydro test pressure (P_{hydro}) = 1.3 x Design Pressure x ($S_{ambient\ temp}$ / $S_{design\ temp}$)
$S_{ambient\ temp}$ = Allowable stress for loop material at ambient temperature
$S_{design\ temp}$ = Allowable stress for loop material at design temperature of loop

Table-4: Hydro test pressure requirement for the loop and pressurizer

Description	Material	Design Pressure (bar)	Design Temp. (^{O}C)	S_{design} Temp (ksi)	$S_{ambient}$ Temp (ksi)	P_{hydro} (bar)
Loop (Except pressurizer)	SS-347	300	450	13.5	20	577.8
Pressurizer	SS-347	300	150	17.1	20	456.1

* Ambient temperature considered is 30^{o}C

5.0 INSTRUMENTATION

The Process and Instrumentation (P & I) diagram of the SPNCL is shown in Fig. 8. All the process parameters are transmitted electronically to the Supervisory Control and Data Acquisition (SCADA) system. 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 station 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, SS-316 sheathed; K-Type thermocouples along with 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 114 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. 2) from the inside wall whereas secondary fluid temperatures were measured by a single thermocouple located at the tube centre. 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 44 thermocouples at elevation axial distances installed at 90^{O} angular locations (as shown in Fig. 2).

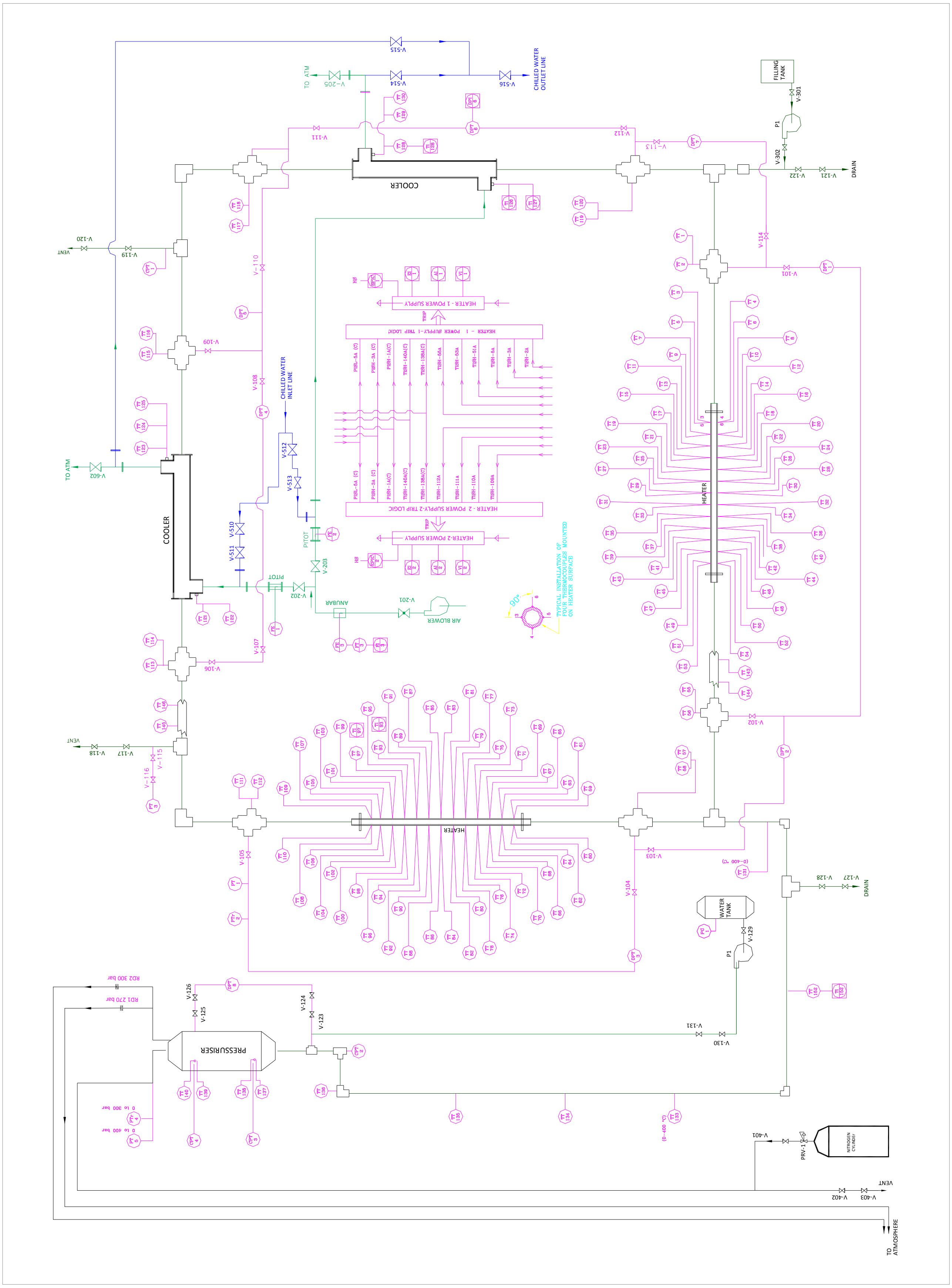


Fig. 8: P & I Diagram for SPNCL (for SCW)

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.

Pressure is measured by FUJI Make electronic smart transmitters and Keller make transducers with fast response (Rating up to 300 ºC) located on the pressurizer 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 2) across 2.6 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.

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.

6.0 ELECTRICAL

The new test sections are direct electrically heated ones. For this, a 200 kW low voltage high current (25 V & 8000 A) power supply was procured and installed. The power supply can be connected to only one heater at a time.

7.0 SAFETY SYSTEMS

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-5.

Table-5: Set points for rupture discs and maximum operating pressure*

Operating Fluid	Design Pressure (bar)	Design Temp. (^{O}C)	Max. Operating Pressure (bar)	Set Pressure for RD-2 (bar)	Set Pressure for RD-1 (bar)
SC-H_2O	300	450	250	300	270

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

8.0 VALVES LIST

The different valves which are in the SPNCL are listed in Table-6 with their functions and locations.

Table-6: Listing of valves

Sl. No.	Valve No.	Size of valve	Function	Location
1	V-101 & 102	3/8”	To isolate DPT1	Across horizontal heater
2	V-103	3/8”	To isolate DPT2	Before vertical heater
3	V-104 & 105	3/8”	To isolate DPT3	Across vertical heater
4	V-106, 107, 108 & 109	3/8”	To isolate DPT4	Across horizontal cooler
5	V-110	3/8”	To isolate DPT5	Before vertical cooler
6	V-111 & 112	3/8”	To isolate DPT6	Across vertical cooler
7	V-113 & 144	3/8”	To isolate DPT7	Across vertical cooler
8	V-115 & 116	3/8”	To isolate PT3	After left side tee on top horizontal pipe
9	V-117 & 118	3/8”	Venting of loop	After left side tee on top horizontal pipe
10	V-119 & 120	3/8”	Venting of loop	After right side tee on top horizontal pipe
11	V-121 & 122	3/8”	For draining the loop	After right side tee on bottom horizontal pipe
12	V-123, 124 & 125, 126	3/8”	To isolate DPT8	Level measurement in pressurizer
13	V-127 & 128	3/8”	For draining the loop	After left side tee on bottom horizontal pipe
14	V-201	3/8”	Blower discharge side	Blower discharge side
15	V-202	3/8”	Isolation for horizontal cooler	After blower on horizontal cooler line

Table-6: Listing of valves (Contd.)

Sl. No.	Valve No.	Size of valve	Function	Location
16	V-203	3/8”	Isolation for vertical cooler	After blower on vertical cooler line
17	V-301	3/8”	For filling the loop	Pump suction
18	V-302	3/8”	For filling the loop	Pump discharge
19	V-401	3/8”	For isolating N2 cylinder	After PRV-1
20	V-402 & 403	3/8”	Venting of pressurizer	On top of presssurizer near ground
21	V-510, 511 & 515	3/8”	For isolating secondary side of horizontal cooler	Inlet and outlet of secondary side of horizontal cooler for chilled water (for SC-CO2)
22	V-512, 513 & 514	3/8”	For isolating secondary side of vertical cooler	Inlet and outlet of secondary side of vertical cooler for chilled water (for SC-CO2)
23	V-516	3/8”	Common outlet line of coolers	Return line of chilled water from hall-7 for chilled water (for SC-CO2)
24	PRV-1	3/8”	For setting discharge pressure from CO2 cylinder	On top of Nitrogen cylinder

9.0 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.

10.0 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.

10.1 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

ΔT_{heater} = (Qx time)/ m_{heater} x $(C_p)_{heater}$
Time = 0.50 second or 500 milliseconds
$\rho_{inconel}$ = 7900 kg/m^3
$m_{heater} = \rho_{heater}$ x $[(\pi/4)\ (d_0^2 - d_i^2) l]$
$(C_p)_{inconel}$ = 0.48 kJ/kg K

The temperature rise (ΔT) in 0.5 s for the loop is given in Table-7 below.

Table-7: Criterion for high temperature trip

Operating fluid	Max. Power (kW)	Heater Design Temp. (°C)	ΔT_{heater} (°C) in 0.5s	Alarm for high temp trip (°C)	High temp trip Value (°C)
SC-H_2O	20.0	575	7.7	575	585

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

10.2 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-8 below. For conservative calculation an instrument time delay of 500 milliseconds is considered. The basis is that at no time the pressure exceeds the lower threshold of RD1 set point. ΔP shown in the Table-8 has been estimated considering the loop operation at 250 bar and 575°C and fluid expansion due to enthalpy rise (because of instrumentation 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-8: High Pressure trip set point value

Power (kW)	Max. Operating Pressure (bar)	High Pressure Alarm Value (bar)	High Pressure Trip Value (bar)	Pressure Rise (ΔP) in 0.5 s (bar)	Set Pressure for RD(bar)	
					Lower Threshold	Upper Threshold
7.5	250	252	252	2.1	268	254.6

10.3 Low Pressure trip

Since the loop will be operated between 220-250 bar. The low pressure alarm and trip set points for the loop are kept below the minimum operating condition and are given in Table-9.

Table-9: Low Pressure trip set point value

Oper. fluid	Max. Operating Pressure (bar)	Low Pressure Alarm Value (bar)	Low Pressure Trip Value (bar)
H_2O	250	115	110

11.0 INSULATION

For maximum power of 20.0 kW, the maximum loop operating temperature is 575°C with SCW. The entire loop has been insulated with 5” thick ceramic mats except the pressurizer (since pressurizer will not experience high temperature) because of U-bend provided at the bottom of the loop which connects the main loop to the pressurizer).

12.0 LOOP OPERATION

12.1 Experimental procedure with Supercritical Water

To achieve supercritical pressure the following operating procedure is followed

i) The loop is filled up with water to the required level in the pressurizer.

ii) Nitrogen is filled at the top of the pressurizer and the loop pressure is increased to 11 MPa.

iii) Further pressurization to 22 MPa and beyond is achieved by injecting more water at the bottom of the pressurizer with the Haskel pump which increases the water level in the pressurizer. Then the Haskell pump is isolated.

iv) Now power is switched on and due to thermal expansion of water in the rectangular loop the loop gets pressurized above 22.1 MPa (i.e. the supercritical pressure).

v) To get desired pressure at an operating power, water inventory in the pressurizer is changed by either injecting water with haskel pump or draining water from drain line near the outlet of haskel pump. The pressurizer leg remains cold as it is connected by a U-bend to the main loop, facilitating cold water injection in to the system without concerns of thermal stress.

12.2 Experiments with Supercritical Water

The facility was commissioned for operation with supercritical water with air as secondary coolant. The steady state and stability experiments were carried out for HHHC orientation. The ranges of parameters covered during the experiments are given in Table-10.

Table-10: Range of parameters for SCW Operation

Parameter	HHHC
Pressure, Mpa	20.0-24.1
Power, kW	0.5-8.5
Cold leg temperature, ^{o}C	30 – 403
Hot leg temperature, ^{o}C	199 - 424
Secondary coolant inlet temperature, ^{o}C	44 – 47
Secondary coolant outlet temperature, ^{o}C	70 – 95

12.3 Steady state Experiments with H2O

Steady state experiments were carried out for HHHC for different heater powers and secondary air flow rates. The experimental steady state mass flow rate, heater inlet and outlet temperatures versus power for HHHC orientation with constant secondary side air flow rate are shown in Fig. 9 a & b respectively. Appendix-1 shows the complete set of steady state data generated with H2O.

The heat transfer coefficient corresponding to steady state experimental data were determined. The measured heat transfer coefficients were compared with various heat transfer correlations (McAdams [14], Jackson [15], Bringer- Smith [16], Shitsman [17], Jackson-Fewester [18] and Bishop [19]) available in literature for supercritical fluids (Pl. see Fig. 10). The peak heat transfer coefficient is observed near the pseudo-critical temperature. All correlations are predicting well in the range of experiments carried out except pseudo-critical region, where only McAdams [14], Jackson [15], Bringer- Smith [16] and Shitsman [17] correlations are in good agreement.

12.4 Instability Experiments with H_2O

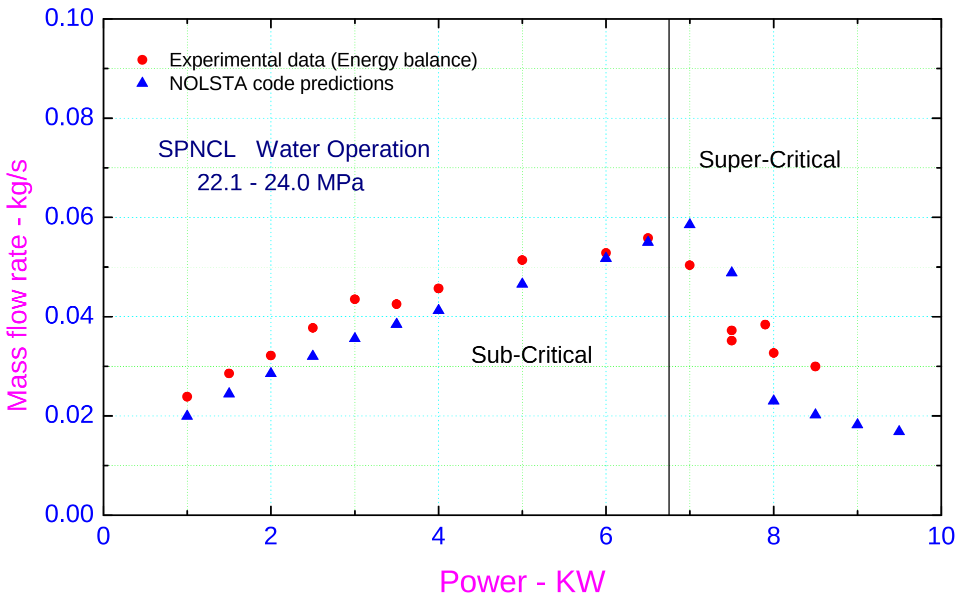
Table-11 lists all the instability data that was generated in the facility. As seen from the table most instability data are for 7.5-8.5 kW of heater power. Figures 11-19 show the time series plots for different parameters during the experimental observations of instability.

Table-11: Summary of instability data (H_2O) for HHHC Orientation

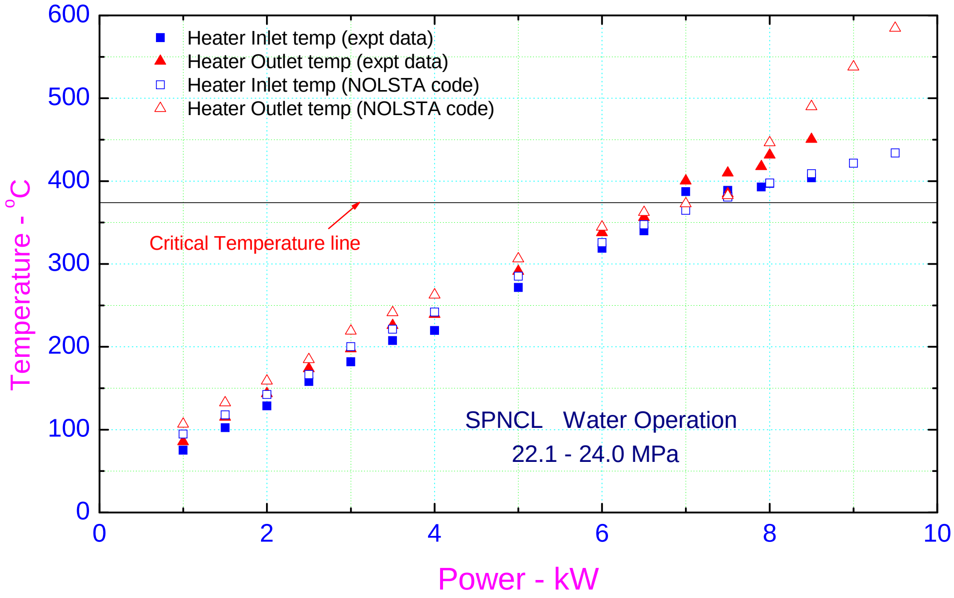
File name	Pressure (MPa)	Power (kW)	Flow rate (LPM)	Coolant inlet temp. (^oC)	Remark
Stab_220_7.5_12875_41_SC-H2O	22.0-23.0	7.5	12875	41-46	Instability at 7.5 k W (Figure 11)
Stab_220_7.5_9635_41_SC-H2O	22.0-23.0	7.5-8.0	9423-9635	41-46	Instability during power crease from 7.5 kW to 8.0 kW (Figure 12)
Stab_221_7.5_8956_38_SC-H2O	22.2-22.8	7.5	8956	38-45	Instability at 7.5 k W (Figure 13)
Stab_222_7.5_8256_41_SC-H2O	22.0-23.0	7.5	8256	41-45	Instability at 7.5 k W (Figure 14)
Stab_217_7.5_8225_42_SC-H2O	21.7-22.9	7.5-7.0	8179-8225	42-46	Instability during power decrease from 7.5 kW to 7.0 kW (Figure 15)
Stab_217_7.5_8179_44_SC-H2O	21.7-22.7	7.5-7.0	8179	44-47	Instability at 7.0 k W (Figure 16)
Stab_224_7.5_6935_51_SC-H2O	22.4-24.1	7.5-8.5	6935	51	Instability during power crease from 7.5 kW to 8.0 kW (Figure 17)
Stab_224_8.0_7682_51_SC-H2O	22.4-23.4	8.0	7682	51	Instability at 8.0 k W (Figure 18)
Stab_221_7.7_7665_51_SC-H2O	20.1-23.6	7.7-8.3	7665	51	Instability at 8.3 k W (Figure 19)

* The stability file names are given in such a way that they represent the operating conditions. For example in case of the first file,

Stab_220_7.5_12875_41_SC-H2O.xls: 220 represents pressure in bar,
7.5 represents power in kW,
12875 represent the coolant flow rate in LPM,
41 represent coolant inlet temperature in ^OC
SC-H2O represents for supercritical water

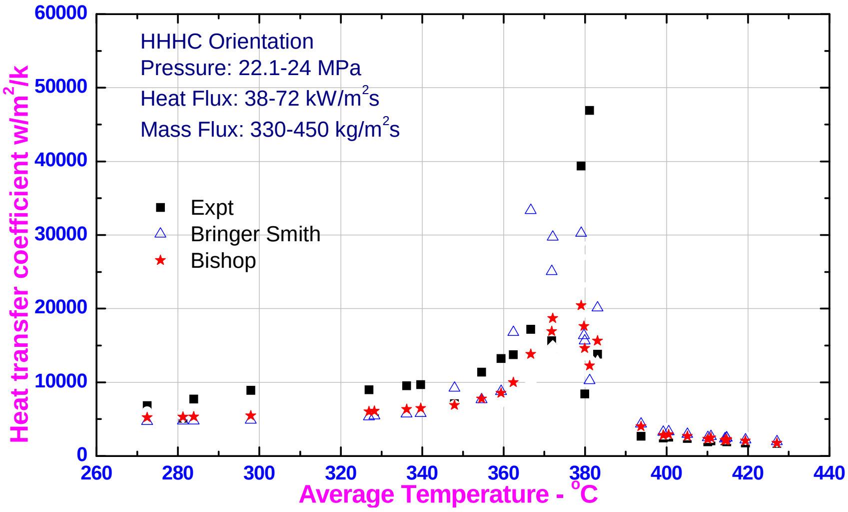


(a) Steady state flow rate

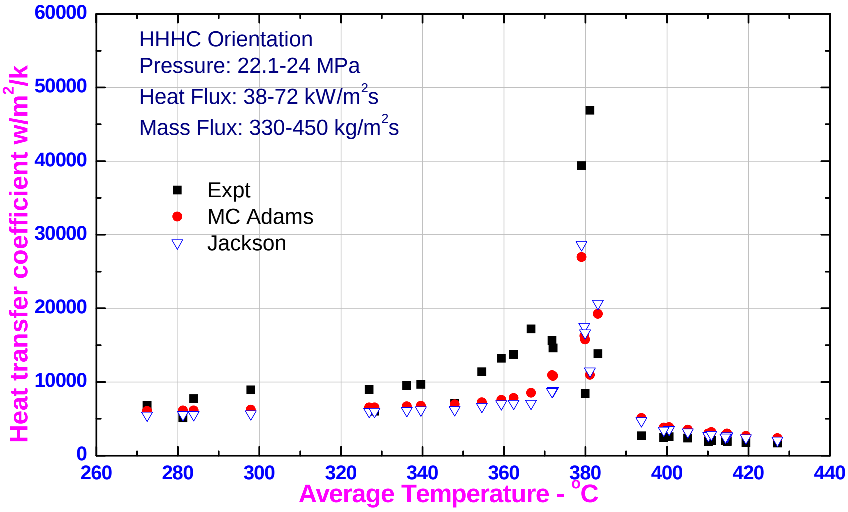


(b) Heater inlet and outlet temperatures

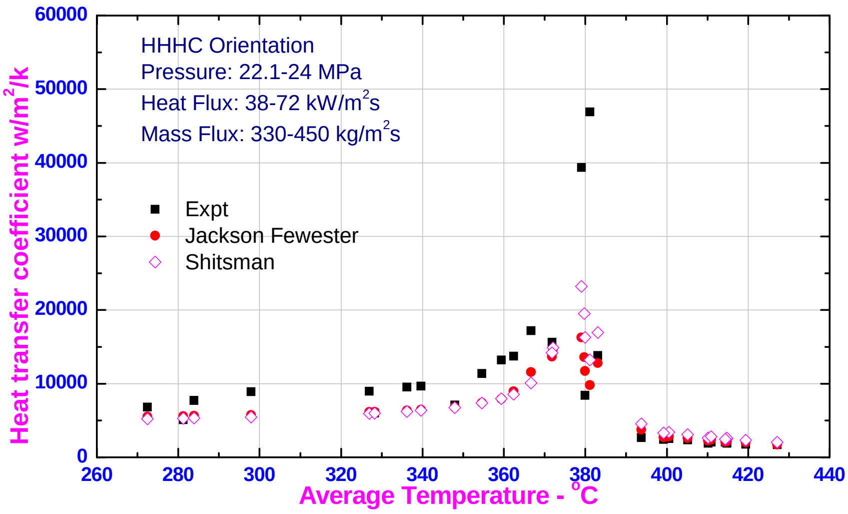
Fig. 9: Steady state flow rate data and temperatures with supercritical water for HHHC orientation



(a) Comparison of Bringer-Smith and Bishop correlations with experimental data

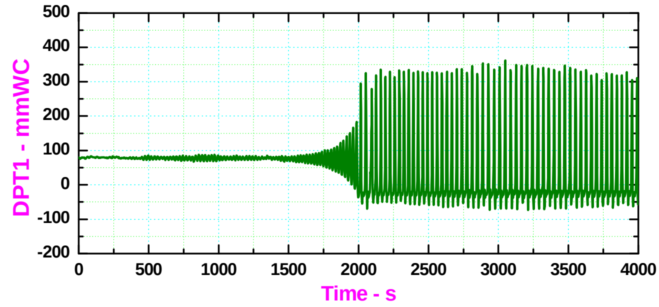


(b) Comparison of McAdams, Jackson correlations with experimental data

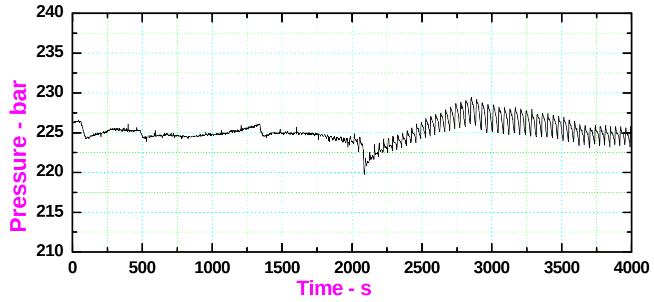


(c) Comparison of Jackson-Fewester and Shitman correlations with experimental data

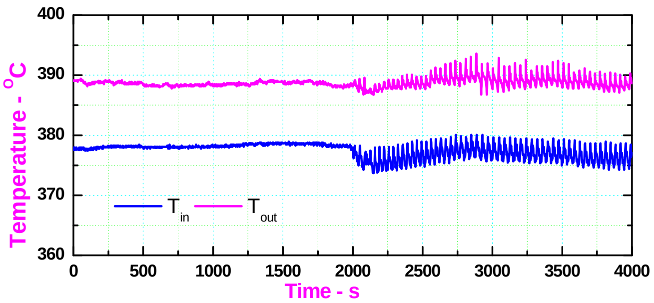
Fig. 10: Comparison of experimental heat transfer coefficient data with various correlations for HHHC orientation



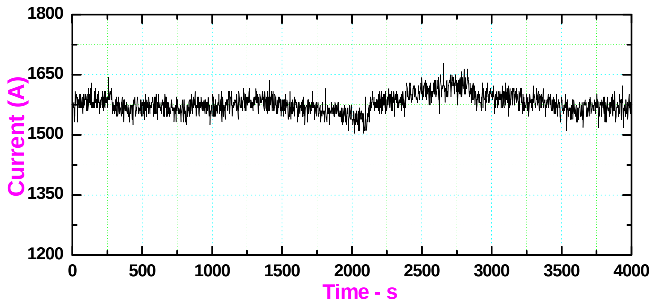
(a) Pressure drop variation across horizontal heater



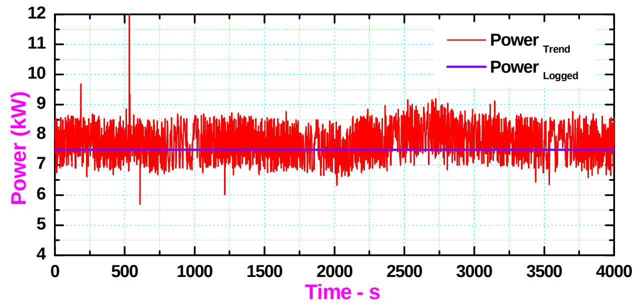
(b) Variation of loop pressure



(c) Variation of heater inlet/ outlet temperatures

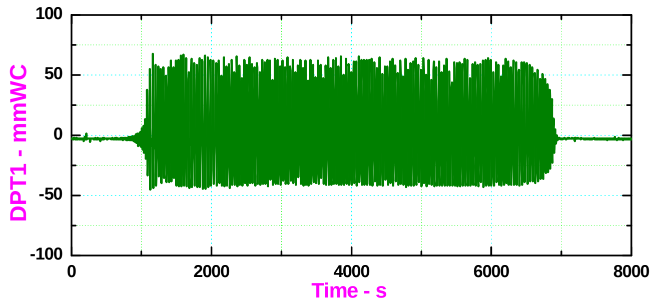


(d) Variation of heater current

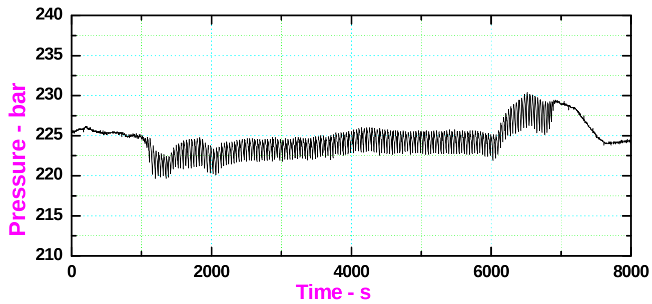


(e) Variation of heater power

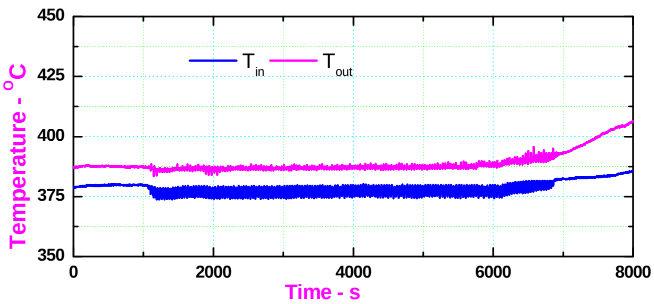
Fig. 11: Instability observed at 7.5 kW with air flow of 12875 lpm (at 22.0-23.0 MPa)



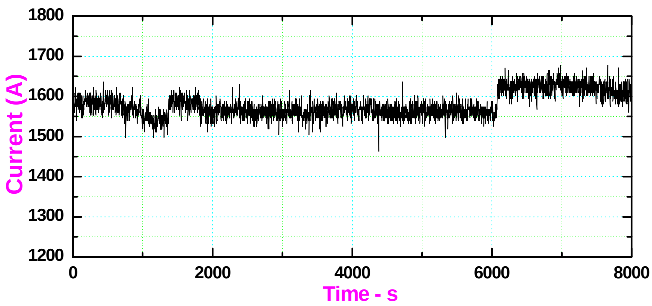
(a) Pressure drop variation across horizontal heater



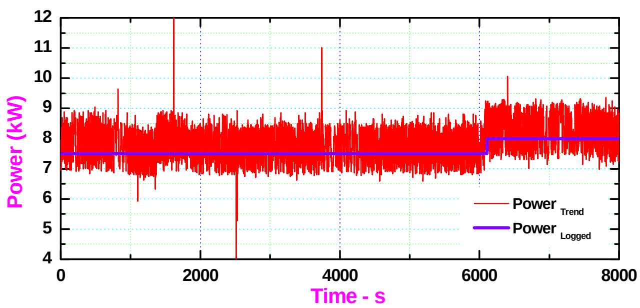
(b) Variation of loop pressure



(c) Variation of heater inlet/ outlet temperatures

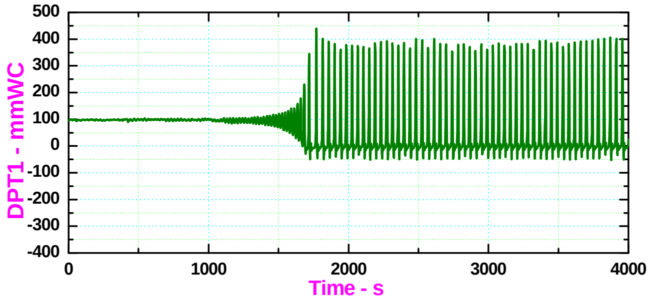


(d) Variation of heater current

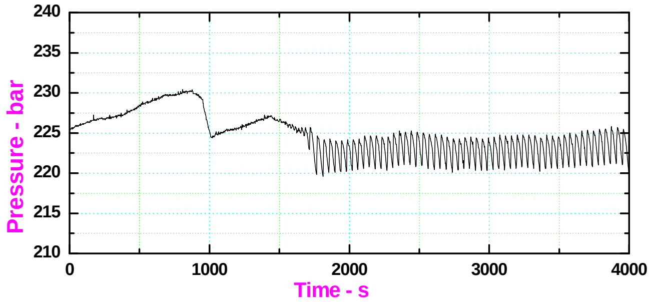


(e) Variation of heater power

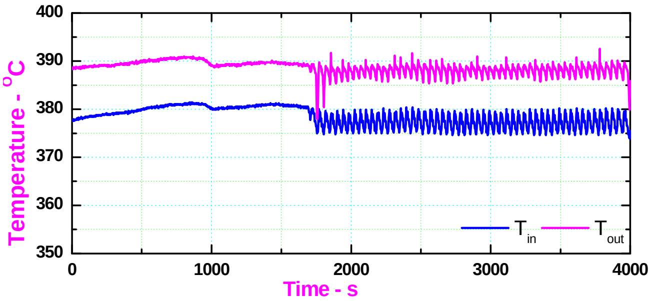
Fig. 12: Instability observed at 7.5 kW with air flow of 9635 lpm (at 22.0-23.0 MPa)



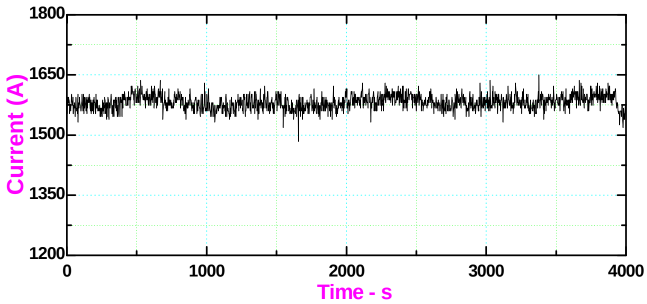
(a) Pressure drop variation across horizontal heater



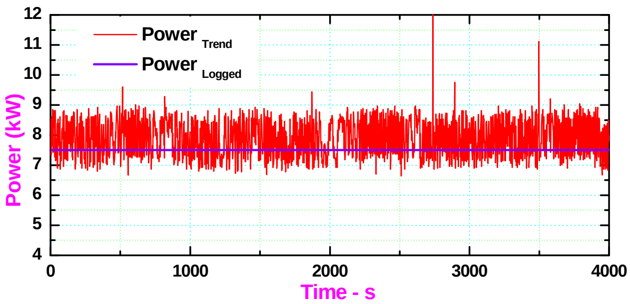
(b) Variation of loop pressure



(c) Variation of heater inlet/ outlet temperatures

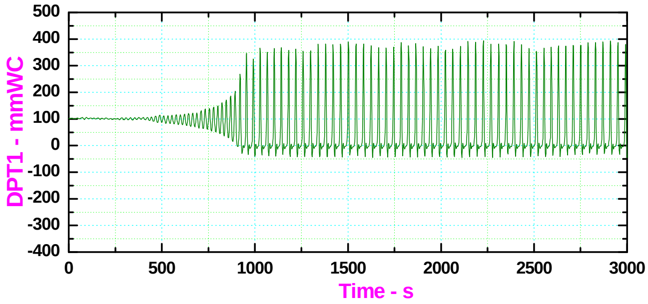


(d) Variation of heater current

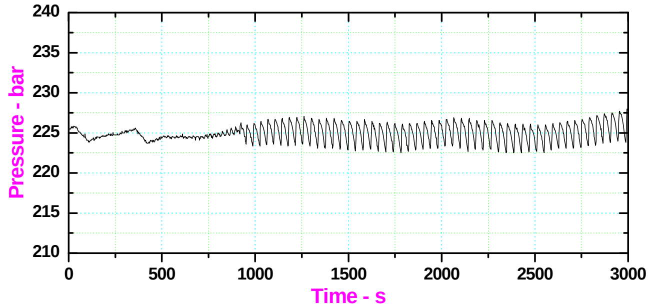


(e) Variation of heater power

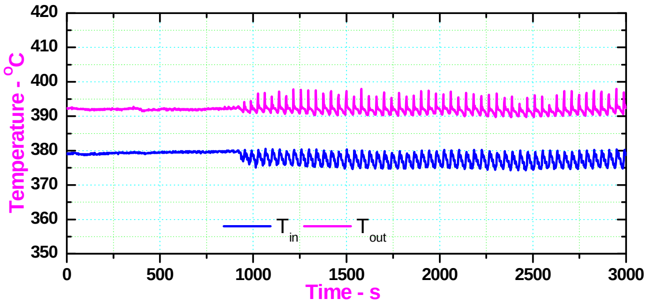
Fig. 13: Instability observed at 7.5 kW with air flow of 8956 lpm (at 22.0-23.0 MPa)



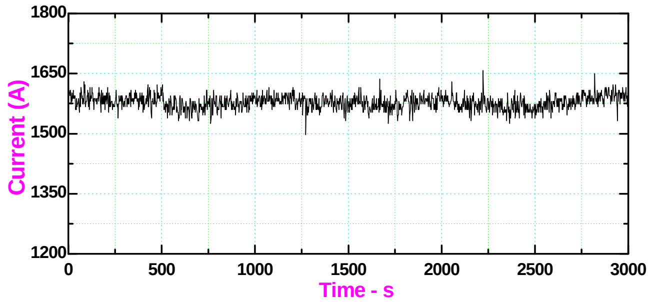
(a) Pressure drop variation across horizontal heater



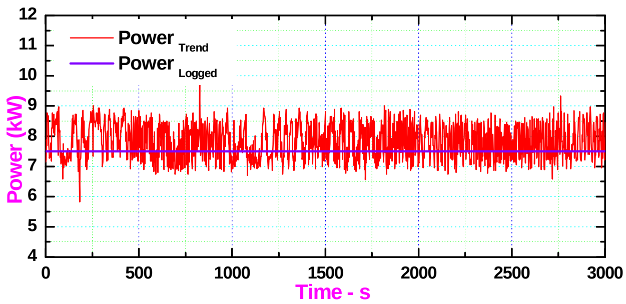
(b) Variation of loop pressure



(c) Variation of heater inlet/ outlet temperatures

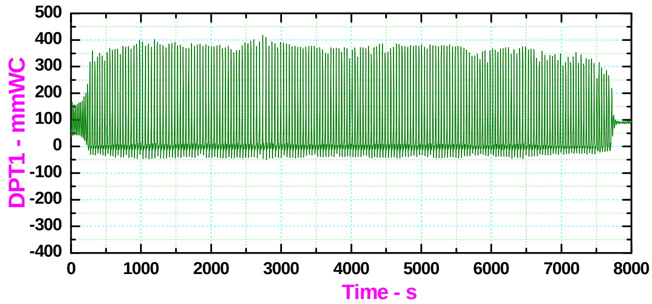


(d) Variation of heater current

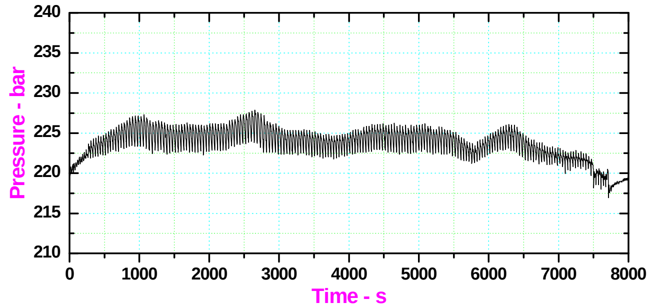


(e) Variation of heater power

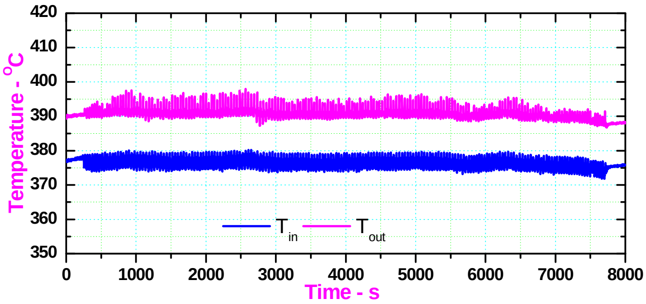
Fig. 14: Instability observed at 7.5 kW with air flow of 8256 lpm (at 22.2-22.8 MPa)



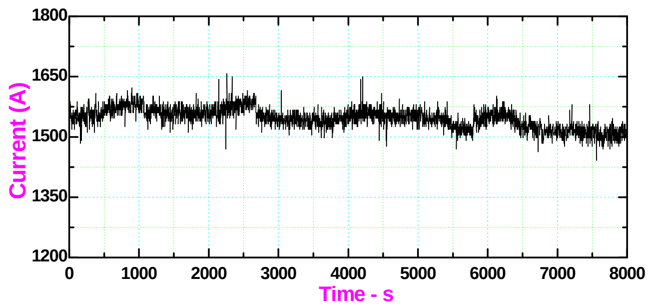
(a) Pressure drop variation across horizontal heater



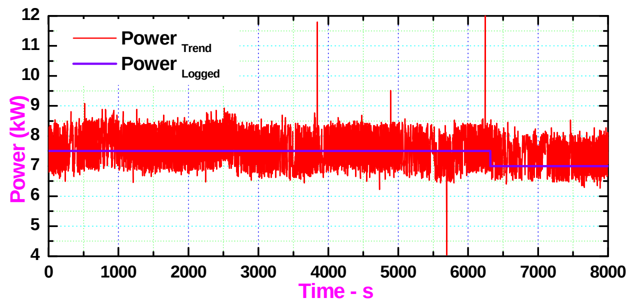
(b) Variation of loop pressure



(c) Variation of heater inlet/ outlet temperatures

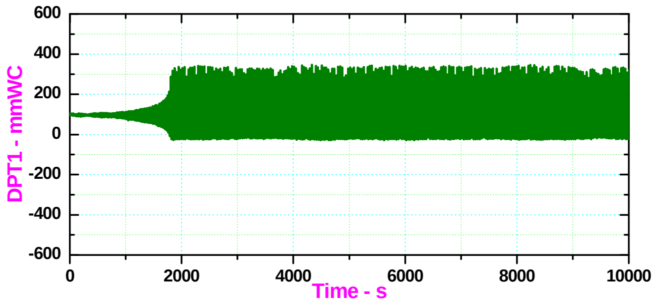


(d) Variation of heater current

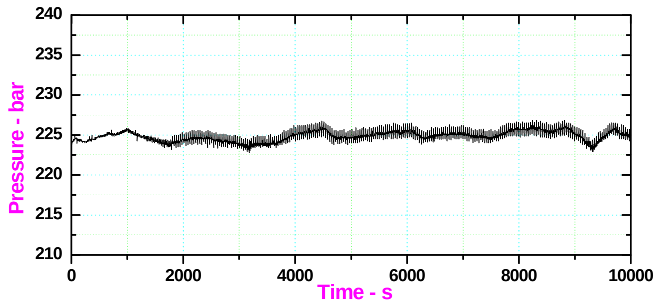


(e) Variation of heater power

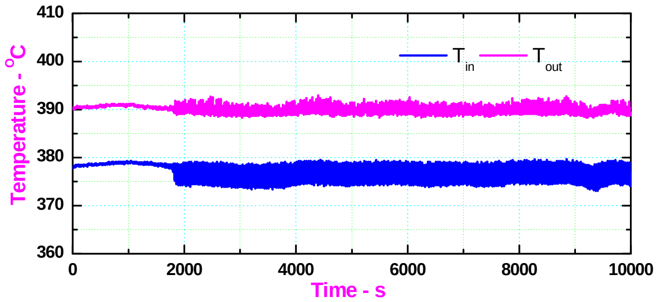
Fig. 15: Instability during power reduction from 7.5 kW to 7.0 kW with air flow of 8225 lpm (at 21.7-22.9 MPa)



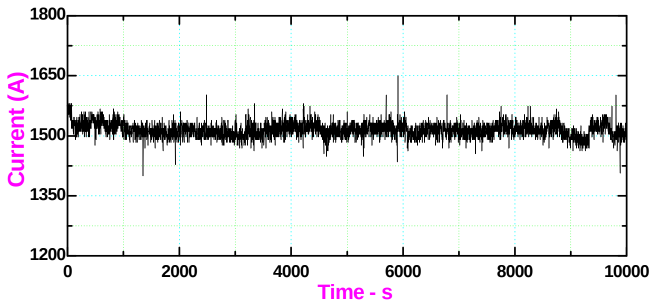
(a) Pressure drop variation across horizontal heater



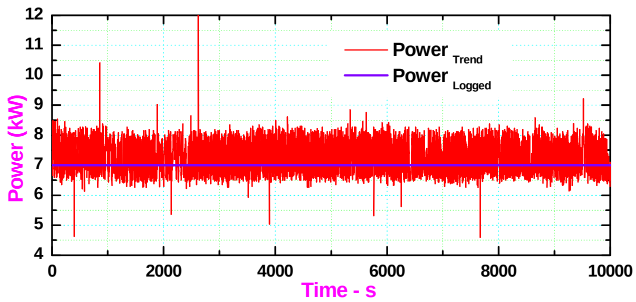
(b) Variation of loop pressure



(c) Variation of heater inlet/ outlet temperatures

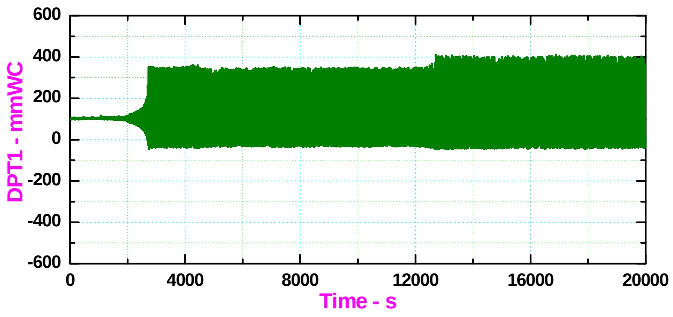


(d) Variation of heater current

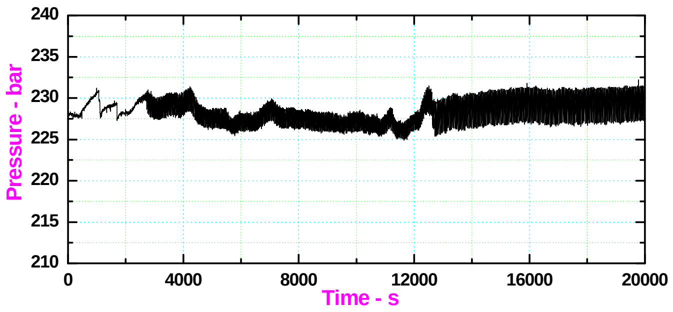


(e) Variation of heater power

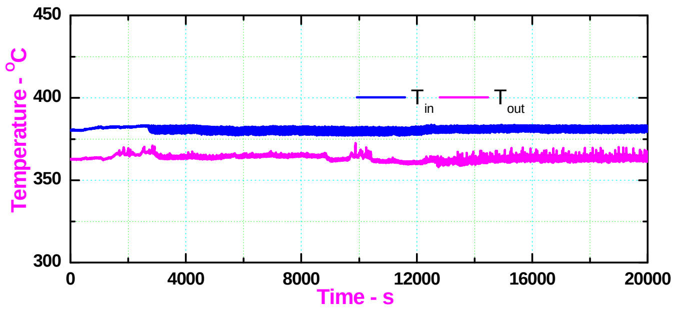
Fig. 16: Instability observed at 7.0 kW with air flow of 8179 lpm (at 21.7-22.7 MPa)



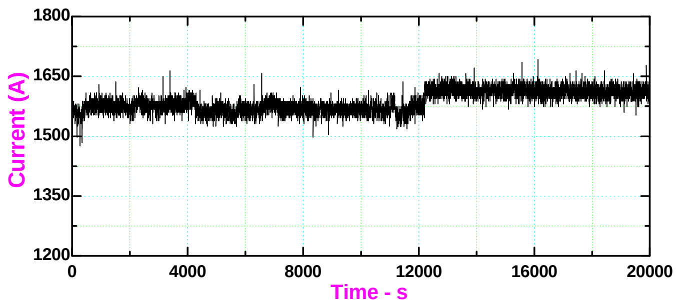
(f) Pressure drop variation across horizontal heater



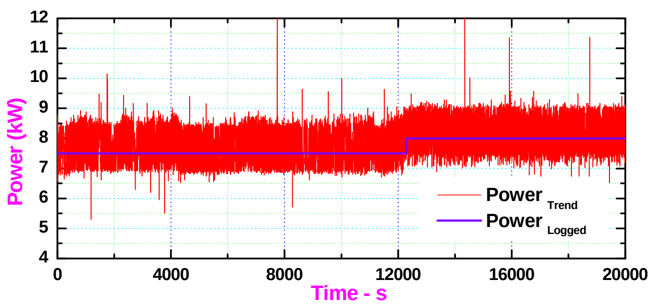
(g) Variation of loop pressure



(h) Variation of heater inlet/ outlet temperatures

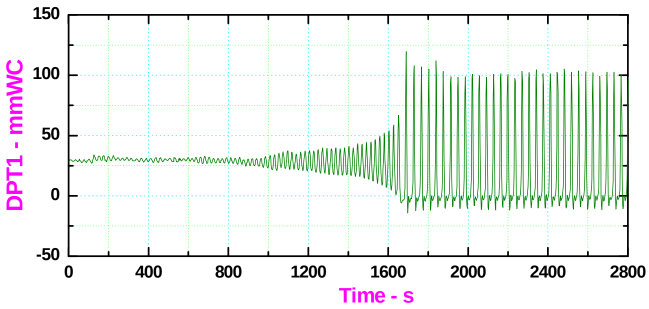


(i) Variation of heater current

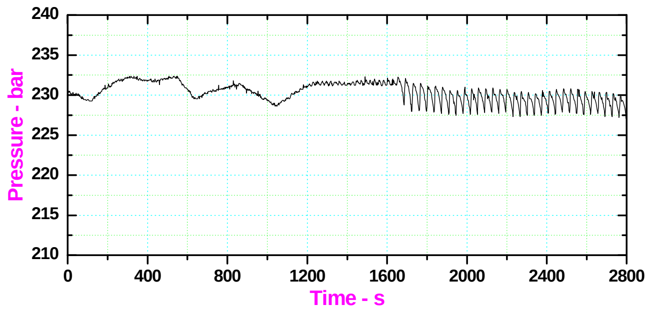


(j) Variation of heater power

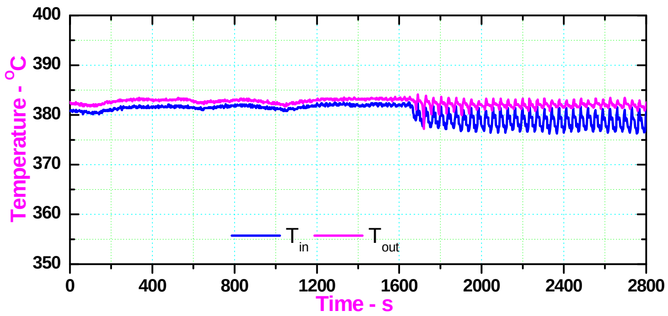
Fig. 17: Instability during power rise from 7.5 kW to 8.0 kW with air flow of 6935 lpm (at 22.4-24.1 MPa)



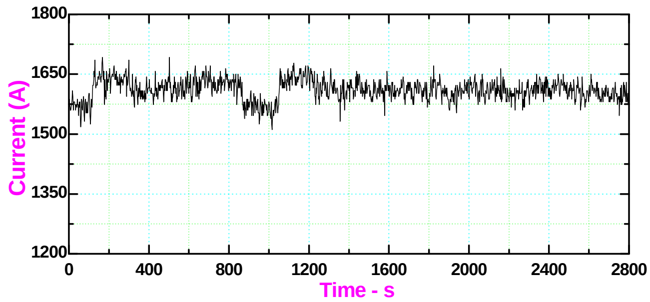
(a) Pressure drop variation across horizontal heater



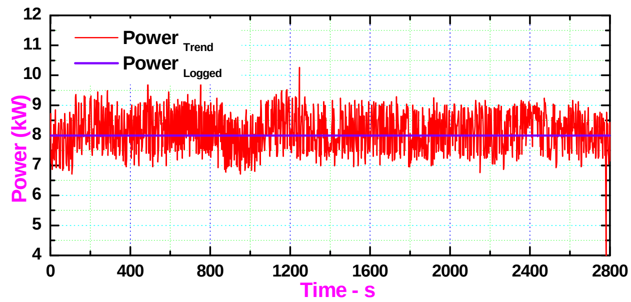
(b) Variation of loop pressure



(c) Variation of heater inlet/ outlet temperatures

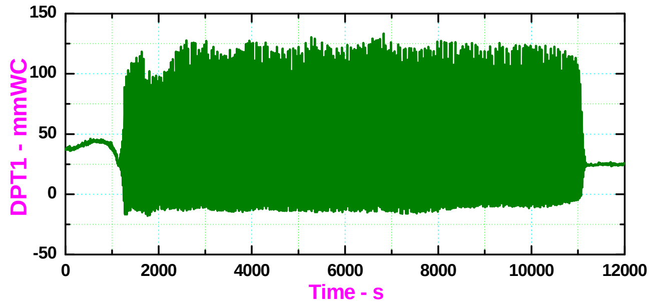


(d) Variation of heater current

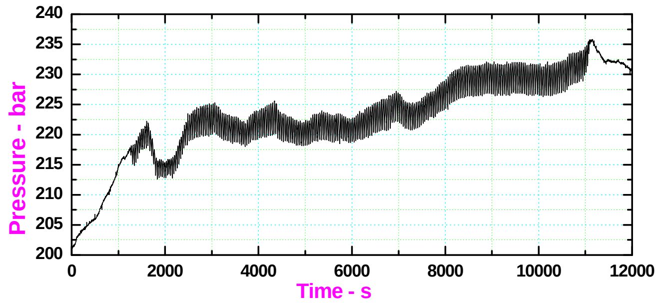


(e) Variation of heater power

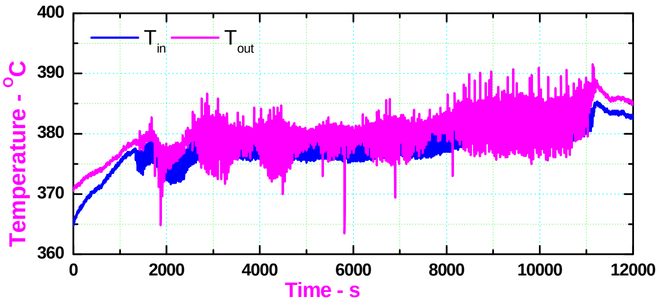
Fig. 18: Instability observed at 8.0 kW with air flow of 7682 lpm (22.4-23.4 MPa)



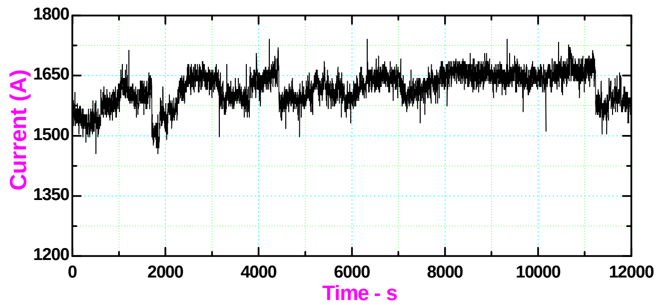
(f) Pressure drop variation across horizontal heater



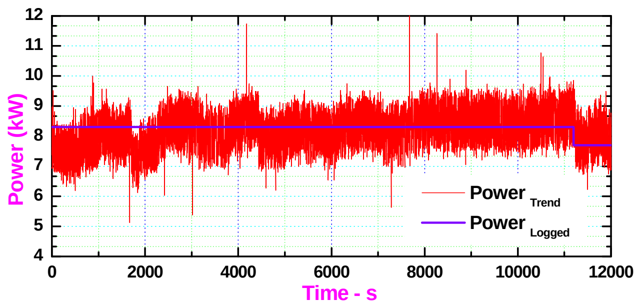
(g) Variation of loop pressure



(h) Variation of heater inlet/ outlet temperatures



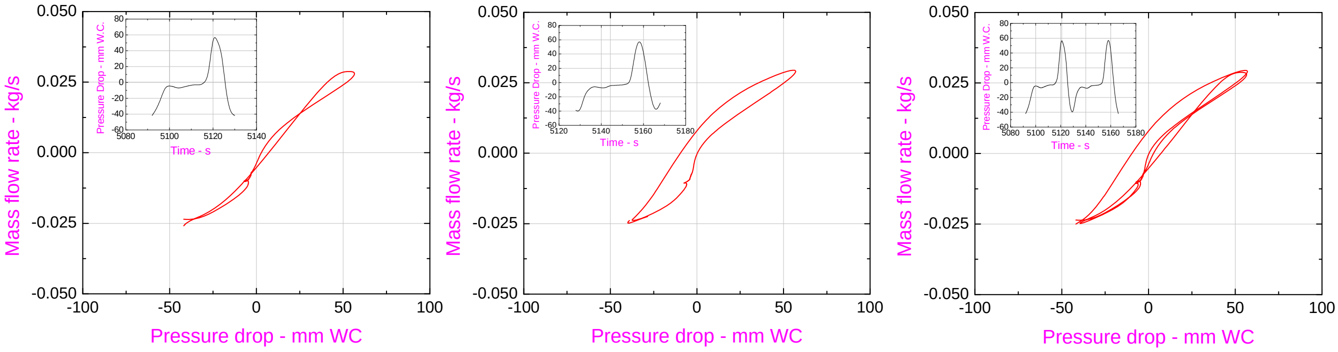
(i) Variation of heater current



(j) Variation of heater power

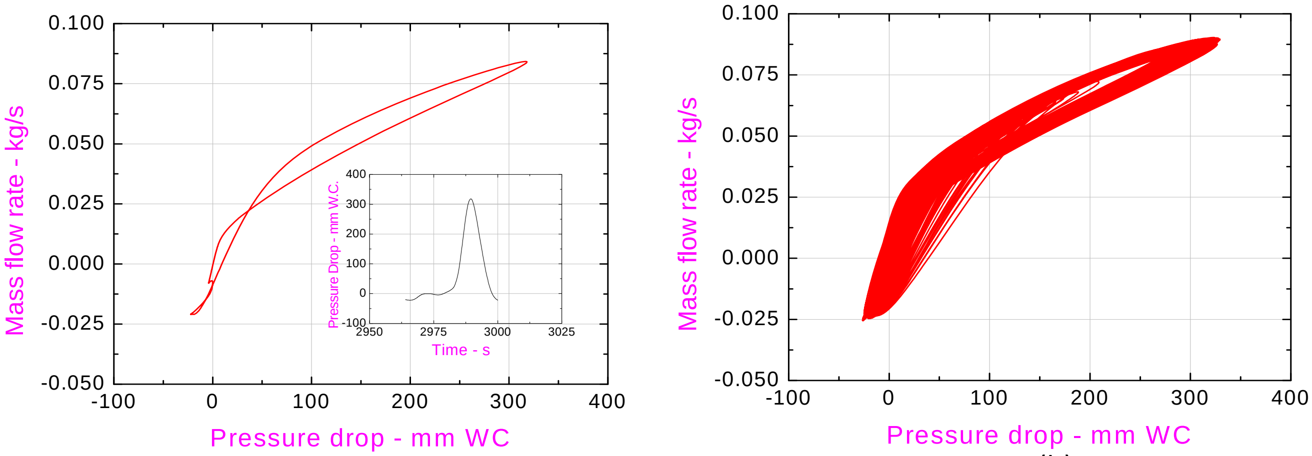
Fig. 19: Instability observed at 8.3 kW with air flow of 7665 lpm (20.1-23.6 MPa)

The phase plot corresponding to a typical oscillation observed at 7.5 kW (Fig. 12) is shown in Fig. 20a, but a different signature is obtained for a similar pressure drop oscillation observed in the same experiment (Fig. 20b) and the phase plot of two combined oscillations is shown in Fig. 20c. The phase plot of a typical oscillation observed at 7 kW (Fig. 16) is shown in Fig. 21a. Fig. 21b shows the phase plot of complete instability oscillations observed in the Fig. 16. It shows a highly chaotic behavior of oscillations. Similarly the phase plots of time series oscillations observed at 7.5 kW & 8 kW (Fig. 17) are shown in Fig. 22 & 23 respectively.



(a) (b) (c)

Fig. 20: Phase plot for Instability observed at 7.5 kW (Fig. 12)



(a) (b)

Fig. 21: Phase plot for Instability observed at 7.0 kW (Fig. 16)

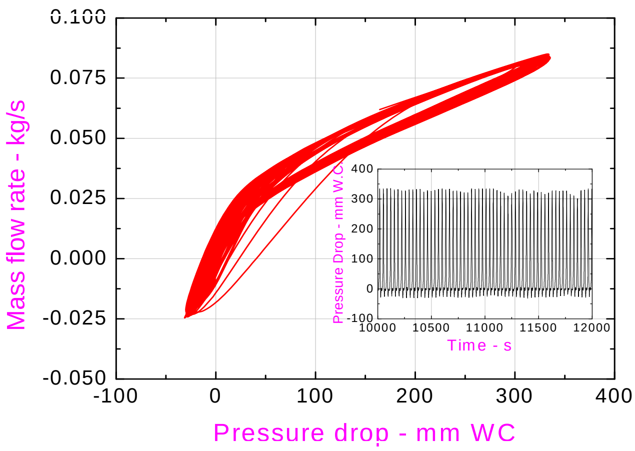


Fig. 22: Phase plot for Instability observed at 7.5 kW (Fig. 16)

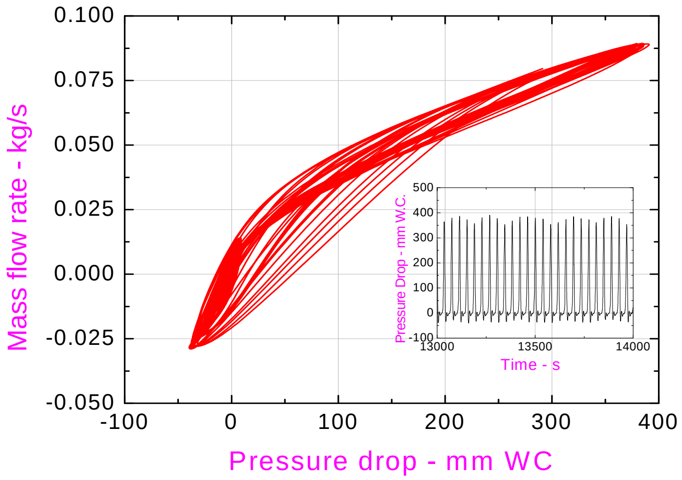
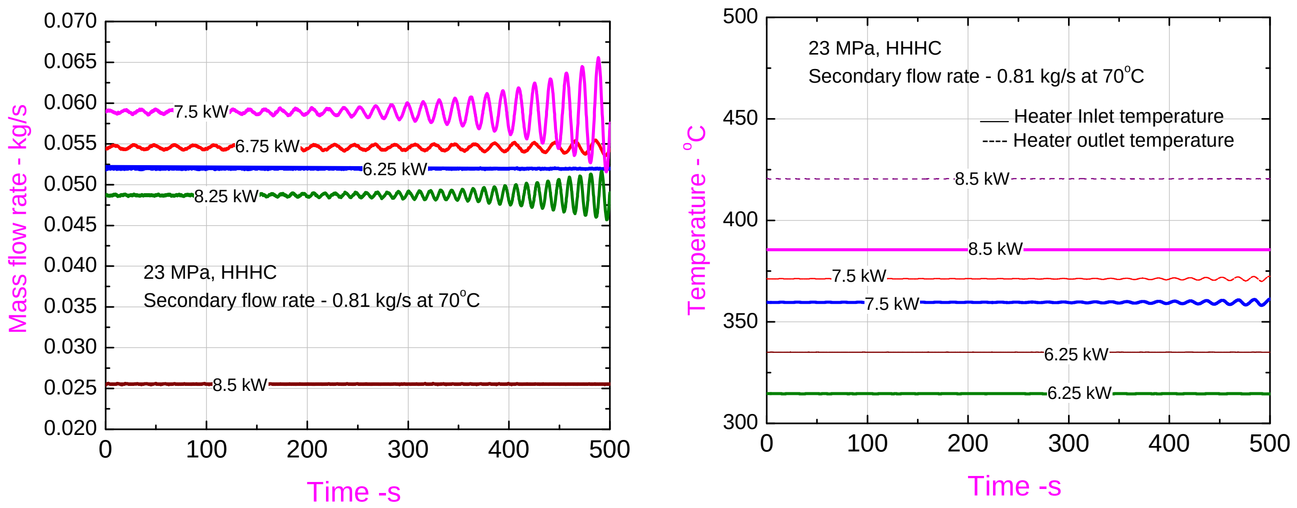


Fig. 23: Phase plot for Instability observed at 8 kW (Fig. 17)

13.0 STABILITY ANALYSIS WITH NOLSTA

The stability analysis of SPNCL with SCW is carried out with NOLSTA code at 23 MPa operating pressure. The loop is stable at 6.25 kW, becomes unstable at 6.75 kW and continues to be unstable till 8.25 kW as shown in Figs. 24 a & b. The loop again becomes stable at 8.5 kW. The experiments show a smaller unstable zone varying from 7.5 to 8 kW at 230 bar. The stability map for the experimental loop using NOLSTA code for SCW operation at 230 bar is shown in Fig. 25. The threshold power of instability is increasing with secondary coolant (air) flow rate but the unstable zone is limited to a narrow range of the heater power.



(a) Mass flow rate variation (b) Heater inlet/outlet temperature variation

Fig. 24: Stability analysis of SPNCL with NOLSTA Code for SC-H_2O

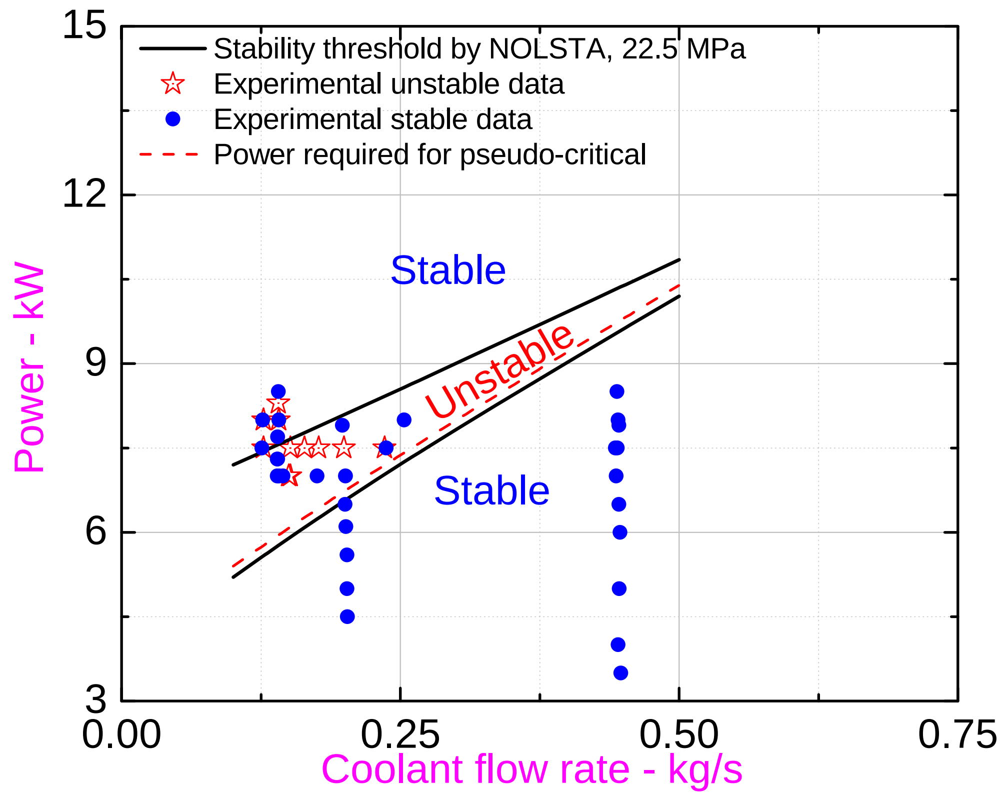


Fig. 25: Stability analysis of SPNCL with NOLSTA Code for SC-H2O

14.0 CONCLUDING REMARKS

Supercritical pressure natural circulation experiments were carried out in with CO_2 in a loop for different combinations of heaters and coolers orientations for different powers and pressures [12 &13]. Subsequently, the SPNCL test loop was modified for operation with supercritical water. Steady state natural circulation experiments were carried out for the HHHC orientation and the flow rate data showed reasonable agreement with code predictions. Experiments on instability were also carried out up to 8.5 kW power. Instability was observed in a narrow window of power i.e. at 7.5 & 8 kW with average pressure of 230 bar. NOLSTA code predicted a larger unstable zone i.e. 6.5 to 8.25 kW for 230 bar operating pressure. The heat transfer coefficient data was also compared with the predictions of various correlations. The experiments show a peak heat transfer coefficient of 47 $kW/m^2/K$ at 381 ^{O}C. All correlations exhibit peak at bulk temperature lower than experiment i.e. 379 ^{O}C. Mc Adams [14], Jackson [15], and Shitsman [17] correlations seem to predict experimental data well in the pseudo-critical region. However, all correlations are matching well with experimental data beyond the pseudo-critical region.

ACKNOWLEDGEMENT:

The help received from various officers and staff personnel of RED during various stages of fabrication, installation, commissioning and operation of the loop is gratefully acknowledged. Thanks are also due to the local safety committee for their valuable suggestions.

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Appendix-1: Steady state natural circulation data with Supercritical H_2O

Steady state natural circulation data generated with H_2O for the HHHC orientations are given in Tables A1.

Table-A1: Steady State data for HHHC orientation with Supercritical H_2O

Sl. No.	Logged Power (kW)	Flow (lpm)	DPT-1 (mmWC)	PT-1 (bar)	PTr-2 (bar)	TT-1 (^oC)	TT-2 (^oC)	TT-3 (^oC)	TT-4 (^oC)	TT-5 (^oC)	TT-6 (^oC)	TT-7 (^oC)	TT-8 (^oC)	TT-9 (^oC)	TT-10 (^oC)	TT-11 (^oC)	TT-12 (^oC)	TT-13 (^oC)	TT-14 (^oC)
1	7.0	9563.0	-3.5	224.4	223.2	363.2	359.8	388.6	388.2	388.3	385.6	389.4	387.4	387.9	388.9	394.5	388.2	384.5	386.0
2	8.0	13824.0	-133.7	233.9	232.4	402.7	401.1	499.6	472.9	460.7	472.7	489.8	467.8	455.5	470.4	488.1	464.8	447.5	461.3
3	7.5	12937.0	-135.1	230.0	229.2	396.4	395.1	488.6	461.3	449.5	461.5	479.3	467.8	444.9	459.1	478.1	455.2	438.2	451.2
4	5.0	11025.0	31.4	229.2	228.0	275.7	275.5	300.8	300.2	299.8	298.1	303.2	309.4	300.0	301.1	309.2	301.9	297.5	300.2
5	5.6	11025.0	30.7	228.1	227.1	290.1	289.5	316.0	315.1	314.7	313.5	318.7	324.8	315.6	316.5	324.6	316.6	312.2	314.9
6	6.1	10978.0	42.5	228.3	227.8	319.8	318.5	347.3	346.0	346.1	344.6	349.8	356.5	346.5	347.5	355.8	347.8	343.3	346.0
7	6.5	10932.0	48.8	229.7	228.4	332.8	331.8	361.2	357.9	360.6	358.3	363.3	370.3	360.4	361.7	369.1	361.7	356.7	359.1
8	7.0	10947.0	66.9	232.0	230.5	368.4	367.1	393.3	390.4	392.8	390.6	392.7	402.4	392.5	392.6	398.6	392.4	389.1	390.2
9	4.5	11056.0	28.6	230.0	228.8	264.9	264.0	288.6	287.6	287.4	286.1	291.0	297.3	288.2	289.3	296.7	289.7	285.3	287.6
10	7.9	10807.0	50.9	229.5	228.0	390.5	389.2	458.2	452.5	453.6	452.8	467.1	473.7	451.3	456.6	473.5	456.8	446.6	453.7
11	8.0	7682.0	28.7	231.1	230.5	377.4	377.3	398.9	395.6	398.2	395.2	399.9	394.7	397.3	397.6	405.7	395.7	394.1	395.2
12	8.0	7682.0	24.5	230.3	229.9	378.8	378.2	398.0	395.6	397.8	394.8	397.3	393.9	396.5	397.2	403.2	395.2	393.3	394.4
13	8.5	7673.0	27.6	231.1	230.5	397.7	397.5	490.8	484.3	482.6	482.7	502.5	483.8	480.1	488.8	509.7	486.3	475.2	485.2
14	8.5	7673.0	28.0	230.3	229.7	398.0	397.9	486.2	480.9	478.8	478.9	497.8	480.1	476.7	485.4	504.7	482.5	472.7	481.9
15	7.0	7620.0	23.5	229.7	228.8	353.9	353.4	380.3	378.1	379.2	377.3	382.2	377.2	379.2	380.5	387.4	377.6	375.6	377.6
16	7.0	7620.0	23.5	228.3	227.8	357.0	357.1	383.3	381.4	382.9	380.2	384.7	380.2	382.6	383.8	390.3	381.0	379.0	380.5
17	7.3	7635.0	21.6	230.0	229.7	328.0	327.7	359.7	357.3	358.9	356.2	363.7	356.8	358.5	360.4	369.5	357.9	355.0	357.8
18	7.3	7635.0	23.0	230.6	230.3	347.9	347.9	377.4	374.7	376.3	373.6	379.7	374.3	375.8	377.1	385.3	375.1	372.3	374.6
19	7.7	7635.0	25.8	230.3	229.4	361.3	361.3	389.6	387.2	388.7	385.2	390.2	386.0	387.6	388.9	395.7	386.9	384.5	386.0
20	7.7	7635.0	29.3	232.0	231.5	366.9	366.8	395.9	393.1	395.3	392.3	396.9	391.8	394.4	395.1	402.8	392.7	391.2	392.7
21	7.3	7620.0	-27.2	230.9	229.9	375.3	374.8	419.1	395.1	393.3	393.9	413.3	392.6	392.7	396.0	414.4	392.7	389.5	392.7
22	7.3	7620.0	-27.6	230.3	229.7	374.6	374.8	420.8	395.6	393.7	394.3	414.6	393.5	393.1	396.4	415.3	393.6	389.5	393.1
23	7.0	7899.0	92.7	228.6	227.1	379.3	375.2	398.3	395.0	397.0	394.3	397.8	400.3	396.8	396.8	403.6	396.6	392.9	394.0
24	7.0	7899.0	96.1	228.3	226.9	381.4	377.3	398.3	396.3	398.2	395.6	398.2	401.1	397.2	397.2	403.6	397.1	393.3	394.8
25	7.0	7712.0	66.2	228.1	227.1	399.2	394.1	472.6	465.8	462.7	464.8	481.0	474.9	463.1	470.0	491.4	472.0	460.9	469.2
26	8.0	6904.0	97.5	227.5	226.1	402.4	400.0	494.1	487.1	485.9	486.4	505.4	489.1	484.7	493.0	512.6	493.9	480.3	489.8
27	7.5	6858.0	92.7	229.5	228.2	398.9	396.2	474.3	467.9	467.3	467.7	484.0	469.1	465.6	472.9	491.0	473.3	461.3	470.1
28	1.0	25159.0	5.0	225.3	224.0	74.9	75.5	89.5	85.4	84.4	86.3	92.1	86.7	84.9	87.4	93.6	88.8	87.0	faulty
29	1.5	25035.0	5.4	225.8	224.2	102.2	102.8	121.1	116.7	115.0	117.8	123.2	117.2	115.8	118.3	126.1	119.6	117.7	faulty
30	2.0	24973.0	7.3	226.7	225.3	128.4	129.0	147.7	144.6	144.7	145.1	151.0	145.5	145.4	147.2	155.6	148.2	145.8	faulty
31	2.5	24693.0	8.1	226.9	226.3	157.8	158.0	176.0	173.8	174.9	174.2	178.7	174.7	175.8	177.3	183.5	176.4	174.8	faulty
32	3.0	24320.0	7.5	228.3	227.4	181.6	182.2	201.3	197.9	200.1	198.2	203.5	198.9	200.7	202.0	208.0	200.8	199.2	faulty
33	3.5	24413.0	10.9	229.5	228.6	207.1	207.7	230.0	227.1	229.1	227.2	232.9	228.5	229.9	231.2	238.0	230.3	227.7	faulty
34	4.0	24289.0	11.7	230.6	229.7	219.4	219.9	243.9	240.8	242.7	241.3	246.8	242.3	243.8	245.0	251.7	244.2	241.6	faulty
35	5.0	24351.0	14.6	234.8	233.8	271.2	271.7	297.9	294.6	297.3	295.2	301.1	296.9	298.3	299.8	307.1	298.1	295.8	faulty
36	6.0	24382.0	18.2	225.5	224.4	318.4	319.2	347.7	344.6	347.4	345.0	350.7	346.5	348.2	349.6	356.6	347.4	345.0	faulty
37	6.5	24320.0	20.5	231.1	230.3	339.4	340.2	368.4	365.8	368.9	366.1	371.7	367.3	369.7	370.9	377.4	368.0	366.0	faulty
38	7.5	24164.0	30.7	241.7	240.0	380.7	382.2	403.4	399.6	403.6	400.3	404.8	400.4	402.8	403.2	409.8	401.4	399.7	faulty
39	7.9	24326.0	34.7	229.7	228.0	393.6	392.0	465.4	458.8	459.8	459.0	474.7	480.3	458.5	463.7	481.0	463.6	453.4	461.3
40	8.0	24289.0	36.3	230.6	230.7	398.5	395.8	481.0	474.2	473.5	473.5	490.7	474.9	471.6	479.2	498.1	479.6	466.8	475.5
41	8.5	24235.0	40.9	235.3	233.9	405.2	402.8	508.0	500.4	498.7	499.2	520.1	502.4	497.8	506.3	528.4	507.4	492.9	503.3
42	7.5	24257.0	37.1	229.0	227.4	390.8	386.7	455.3	449.6	449.1	449.5	463.4	451.6	447.9	454.1	471.4	454.3	443.7	451.2
43	7.0	24195.0	30.2	225.3	224.9	389.2	385.4	444.3	438.8	436.7	437.9	450.3	446.6	436.1	441.5	459.0	443.0	433.2	439.8

Table-A1: Steady State data for HHHC orientation with Supercritical H_2O (Contd.)

Sl. No.	TT-15 (°C)	TT-16 (°C)	TT-17 (°C)	TT-18 (°C)	TT-19 (°C)	TT-20 (°C)	TT-21 (°C)	TT-22 (°C)	TT-31 (°C)	TT-32 (°C)	TT-33 (°C)	TT-34 (°C)	TT-35 (°C)	TT-36 (°C)	TT-37 (°C)	TT-38 (°C)	TT-39 (°C)	TT-40 (°C)	TT-41 (°C)
1	393.4	387.1	386.6	392.7	401.1	388.7	387.9	363.4	405.0	387.0	383.7	faulty	393.7	421.7	387.9	381.7	400.8	390.1	388.9
2	476.9	458.5	449.2	464.9	476.3	459.4	451.9	457.3	460.4	445.5	434.3	faulty	467.8	473.4	438.6	440.6	464.1	445.9	438.3
3	466.8	448.9	439.4	454.3	465.7	448.5	442.1	453.2	452.5	437.1	426.7	faulty	457.3	459.8	429.3	431.6	454.4	436.7	429.4
4	308.9	301.1	300.0	306.1	315.4	303.4	301.7	305.5	304.6	301.1	296.0	faulty	311.3	329.0	303.8	300.6	316.5	307.4	304.4
5	323.8	316.2	314.8	320.9	330.2	318.0	316.2	317.6	320.4	315.8	310.8	faulty	326.4	344.7	318.6	315.0	332.1	322.5	319.6
6	355.2	347.2	346.1	352.2	361.9	349.0	347.4	342.8	351.7	346.5	341.5	faulty	357.3	376.4	349.0	345.1	363.3	353.1	350.0
7	368.7	360.7	359.2	365.7	375.0	362.3	360.6	357.1	365.0	360.4	355.0	faulty	370.7	380.2	362.1	358.3	376.4	365.7	363.1
8	397.2	390.9	391.3	396.5	405.4	392.1	392.2	378.5	392.9	391.2	387.1	faulty	397.1	407.3	390.9	384.2	405.1	393.4	391.4
9	296.6	289.3	288.2	294.3	302.7	291.2	289.8	282.0	293.3	288.4	284.2	faulty	299.6	315.5	291.6	288.3	303.8	295.6	293.0
10	477.8	458.9	450.0	466.2	489.0	463.6	454.1	458.6	460.8	448.8	436.0	faulty	489.1	491.6	463.1	467.4	497.1	475.7	463.6
11	405.8	394.4	395.2	faulty	413.1	faulty	394.6	395.9	398.5	396.9	393.3	faulty	402.4	396.3	395.9	398.3	410.8	396.7	394.7
12	402.4	394.0	394.4	faulty	408.4	faulty	393.8	401.0	396.8	396.1	392.4	faulty	399.9	395.5	395.1	397.1	405.8	395.4	393.8
13	517.6	493.4	481.8	faulty	532.1	faulty	487.3	500.7	491.1	480.3	462.3	faulty	533.6	515.3	501.8	521.2	544.8	518.7	503.4
14	512.9	489.2	478.8	faulty	526.2	faulty	483.9	503.3	488.2	477.0	459.8	faulty	528.1	511.5	498.4	517.4	539.3	514.5	500.1
15	386.7	377.6	378.3	faulty	392.8	faulty	378.0	382.7	383.5	380.5	374.7	faulty	387.3	382.4	381.2	384.5	392.7	383.2	380.7
16	388.8	380.6	381.3	faulty	395.8	faulty	381.4	381.1	387.2	383.4	377.7	faulty	389.4	384.9	383.7	387.0	396.1	385.7	383.3
17	369.3	357.9	358.1	faulty	377.6	faulty	358.5	359.8	365.9	361.1	353.3	faulty	371.5	364.6	361.8	366.9	378.8	365.6	361.8
18	385.0	374.7	375.0	faulty	392.0	faulty	375.5	376.4	381.0	377.1	371.0	faulty	385.7	379.8	377.8	382.0	391.9	380.7	377.4
19	394.8	386.4	386.4	faulty	402.1	faulty	387.0	390.8	391.4	388.9	382.7	faulty	394.0	389.6	387.9	391.2	402.4	390.4	387.9
20	402.8	392.3	393.1	faulty	411.4	faulty	393.3	397.6	397.2	394.4	389.5	faulty	401.5	394.2	393.8	396.7	412.9	395.4	393.0
21	405.0	391.1	392.3	faulty	402.1	faulty	391.6	390.0	405.6	392.3	389.5	faulty	402.0	390.8	390.9	392.9	400.3	390.4	389.6
22	405.8	391.5	392.3	faulty	402.1	faulty	392.1	394.6	406.0	701.1	389.1	faulty	402.4	391.3	390.0	392.9	400.3	390.8	390.0
23	403.5	395.1	395.1	faulty	411.7	395.8	395.6	379.7	401.3	395.0	393.0	faulty	400.8	425.1	394.7	392.9	408.9	396.4	395.2
24	403.5	395.5	395.9	faulty	411.7	396.7	396.0	391.1	402.5	395.8	393.4	faulty	400.8	425.6	395.5	393.7	406.8	396.8	395.6
25	498.2	478.2	466.9	faulty	509.6	482.9	472.0	492.6	483.3	461.1	448.6	faulty	507.1	534.8	481.3	491.3	515.2	493.4	481.4
26	520.7	500.1	487.2	faulty	535.0	506.7	494.6	502.2	495.8	481.3	466.8	faulty	538.1	566.1	509.2	525.1	549.0	526.5	511.3
27	497.3	477.8	467.3	faulty	509.2	483.3	472.8	482.9	477.9	464.0	450.7	faulty	511.3	538.2	484.7	500.3	520.3	498.8	486.0
28	95.1	92.8	87.9	91.2	97.5	90.0	87.9	91.5	100.0	92.6	89.8	faulty	101.7	93.2	90.0	91.0	103.8	94.5	91.2
29	128.2	83.6	118.7	122.9	130.9	121.3	119.1	111.2	133.8	124.2	121.4	faulty	136.8	125.3	122.1	123.1	139.2	127.2	123.7
30	157.0	57.9	147.5	152.4	161.3	150.2	148.1	135.9	164.6	153.7	151.0	faulty	167.0	154.6	151.7	152.4	169.6	157.0	152.9
31	183.7	86.5	176.6	181.6	188.3	178.7	176.7	171.2	192.9	182.3	184.7	faulty	201.7	188.4	185.1	185.3	204.2	190.6	186.6
32	207.9	61.7	201.1	206.5	213.2	203.4	201.4	198.9	218.3	207.6	204.1	faulty	220.1	207.5	204.9	204.3	221.5	209.5	206.5
33	237.6	42.4	231.6	237.7	245.7	234.3	233.0	231.2	252.1	239.6	237.4	faulty	257.3	241.8	238.3	238.0	259.1	244.4	241.1
34	252.1	55.0	246.8	253.3	261.4	249.4	247.9	247.1	268.3	254.3	252.1	faulty	272.4	256.6	252.7	252.9	275.1	259.5	255.9
35	305.9	85.7	297.9	304.9	312.9	300.4	299.6	300.8	317.9	306.1	303.2	faulty	321.3	307.4	303.8	302.7	324.9	309.9	307.0
36	355.6	99.5	347.8	354.7	362.7	349.8	348.7	355.0	366.7	354.1	351.7	faulty	370.7	355.7	352.8	350.5	373.8	358.6	355.5
37	376.0	98.3	368.0	374.5	382.1	369.5	369.1	365.5	384.6	702.7	371.1	faulty	388.3	373.9	371.4	368.2	391.1	376.2	374.1
38	406.4	76.2	401.9	407.0	413.4	401.2	401.4	402.0	410.3	406.5	400.9	faulty	413.7	401.8	400.5	394.6	416.1	403.0	402.3
39	485.9	466.5	458.0	474.6	499.1	472.8	463.0	475.4	465.0	455.2	441.5	faulty	499.2	502.2	473.7	478.1	508.0	486.2	473.8
40	505.0	484.1	473.7	491.5	519.4	491.6	479.7	500.1	483.3	469.9	455.8	faulty	519.7	552.2	491.8	506.1	530.0	507.2	492.8
41	537.6	514.8	500.3	520.2	552.3	522.2	508.7	492.6	509.6	493.5	478.1	faulty	556.9	583.9	525.6	541.9	569.2	545.0	528.2
42	476.9	457.7	448.7	464.5	488.5	463.2	453.2	464.5	470.4	448.0	434.3	faulty	486.2	503.9	460.1	464.1	494.5	471.9	461.1
43	463.8	445.9	437.3	451.4	472.9	449.0	440.0	444.3	457.1	435.8	426.3	faulty	468.6	489.5	445.4	453.4	475.5	455.1	445.5

Table-A1: Steady State data for HHHC orientation with Supercritical H2O (Contd.)

Sl. No.	TT-42 (^{o}C)	TT-43 (^{o}C)	TT-44 (^{o}C)	TT-45 (^{o}C)	TT-46 (^{o}C)	TT-47 (^{o}C)	TT-48 (^{o}C)	TT-49 (^{o}C)	TT-50 (^{o}C)	TT-51 (^{o}C)	TT-52 (^{o}C)	TT-53 (^{o}C)	TT-54 (^{o}C)	TT-55 (^{o}C)	TT-56 (^{o}C)	TT-57 (^{o}C)	TT-58 (^{o}C)	TT-111 (^{o}C)
1	390.6	404.2	390.2	389.1	391.5	faulty	392.0	387.2	390.2	404.8	390.3	388.9	380.3	370.6	faulty	372.3	372.4	364.3
2	446.3	454.9	440.9	436.1	441.9	faulty	441.3	437.4	441.8	451.7	440.8	440.9	429.0	392.1	faulty	390.2	389.8	387.4
3	437.4	446.1	432.5	428.1	433.2	faulty	433.3	429.8	433.0	442.4	433.7	433.2	421.2	387.8	faulty	387.4	387.4	383.4
4	308.7	319.5	308.2	305.2	309.6	faulty	311.2	306.7	311.3	322.4	312.4	309.8	304.3	292.2	faulty	292.3	291.9	286.7
5	323.4	335.4	323.7	320.3	324.6	faulty	325.9	321.5	326.0	337.6	327.6	324.3	319.2	306.3	faulty	305.9	306.0	300.2
6	353.8	366.9	354.2	350.1	355.3	faulty	356.2	351.4	356.2	368.5	357.5	354.0	348.1	334.7	faulty	335.0	334.4	328.9
7	366.9	380.3	366.8	363.5	368.2	faulty	369.3	364.5	368.8	381.6	370.1	366.8	360.5	347.4	faulty	347.2	346.7	341.8
8	393.5	408.8	393.2	391.2	394.0	faulty	394.5	391.9	394.4	410.3	394.5	393.6	384.5	377.6	faulty	376.1	376.6	371.6
9	296.4	306.9	296.9	293.5	297.5	faulty	299.0	294.9	299.2	309.3	300.6	297.5	292.4	281.3	faulty	280.0	280.8	275.5
10	477.6	502.3	478.2	465.0	479.3	faulty	483.8	469.4	485.0	508.3	491.0	477.0	479.0	411.7	faulty	411.5	410.9	403.7
11	398.5	409.9	396.7	394.7	397.9	faulty	faulty	394.4	396.4	396.9	faulty	395.2	407.1	381.1	faulty	381.3	380.2	376.7
12	397.6	405.7	395.8	393.5	396.7	faulty	faulty	393.1	395.1	395.6	faulty	394.4	406.7	381.5	faulty	381.7	380.2	377.8
13	522.4	548.8	521.3	505.5	523.2	faulty	faulty	511.3	529.3	537.8	faulty	520.9	552.1	430.6	faulty	433.0	431.0	418.8
14	518.2	543.0	517.2	501.7	519.1	faulty	faulty	507.5	524.3	533.2	faulty	516.6	545.5	429.9	faulty	430.6	432.3	419.4
15	384.5	394.5	383.3	380.9	384.2	faulty	faulty	380.9	383.8	384.6	faulty	382.5	392.0	365.0	faulty	364.4	365.7	361.0
16	387.5	397.8	386.2	383.4	386.7	faulty	faulty	383.5	386.3	387.6	faulty	385.1	394.4	367.8	faulty	366.9	368.5	363.2
17	367.7	382.0	366.5	362.1	367.6	faulty	faulty	363.3	367.9	370.2	faulty	365.6	387.9	344.0	faulty	345.2	343.7	338.0
18	383.3	394.0	381.2	378.4	382.2	faulty	385.0	378.4	382.2	383.8	faulty	380.8	399.3	360.8	faulty	361.9	360.5	355.4
19	392.1	405.3	390.0	387.6	390.9	faulty	393.4	387.7	390.5	391.0	faulty	389.7	406.7	371.3	faulty	371.4	372.7	366.6
20	398.0	415.3	395.8	393.0	396.7	faulty	398.9	393.1	396.0	396.9	faulty	394.4	412.0	376.2	faulty	376.0	377.5	371.6
21	393.4	395.3	390.4	390.1	390.9	faulty	faulty	389.8	389.7	390.1	faulty	391.0	405.1	370.3	faulty	370.2	369.3	367.2
22	393.0	395.3	390.0	389.7	390.5	faulty	faulty	389.8	389.7	389.7	faulty	391.0	406.3	369.2	faulty	368.6	369.9	367.2
23	397.3	410.1	396.9	394.6	397.4	faulty	397.9	393.1	396.1	406.5	395.8	394.9	383.2	381.5	faulty	382.1	383.2	374.4
24	397.3	407.6	396.5	395.0	397.8	faulty	397.9	393.5	396.5	403.9	395.8	394.9	383.6	382.6	faulty	383.2	382.5	375.5
25	494.9	522.9	497.8	483.9	499.7	faulty	505.3	490.0	506.0	527.8	512.0	498.7	497.6	422.6	faulty	424.8	422.5	411.0
26	532.5	555.1	528.0	512.8	530.1	faulty	536.0	519.1	535.8	560.7	544.4	526.7	530.2	437.1	faulty	437.1	438.2	447.6
27	506.7	525.8	500.8	487.2	503.1	faulty	507.0	490.9	506.4	530.3	513.7	497.0	499.7	423.7	faulty	423.7	424.9	433.6
28	97.1	105.7	95.1	92.2	97.0	faulty	96.4	92.7	97.8	105.2	97.3	93.6	95.8	82.3	faulty	85.0	85.6	79.8
29	130.5	141.7	127.7	124.5	130.7	faulty	129.3	125.1	131.8	141.6	130.5	126.4	128.8	114.3	faulty	114.7	115.4	109.6
30	159.6	171.5	157.4	153.9	160.2	faulty	158.7	155.1	161.5	172.0	160.8	156.6	158.2	143.5	faulty	143.0	143.9	137.7
31	194.2	206.7	191.8	188.3	194.7	faulty	193.3	192.1	198.9	211.3	198.7	194.0	195.7	176.9	faulty	173.1	173.7	169.8
32	212.8	223.5	211.0	207.6	213.0	faulty	212.2	211.9	216.5	225.2	216.4	213.2	212.7	196.6	faulty	197.6	197.9	190.6
33	248.7	262.1	246.2	241.9	248.8	faulty	248.0	243.5	249.2	260.3	248.8	245.1	244.9	226.4	faulty	226.3	225.5	219.8
34	263.5	278.0	261.3	256.6	264.2	faulty	263.6	258.3	264.8	276.8	264.8	260.9	261.8	240.5	faulty	238.8	239.3	233.3
35	314.1	329.1	311.9	308.2	315.0	faulty	314.1	309.3	314.7	326.6	315.0	311.5	315.9	290.1	faulty	291.6	290.6	283.9
36	362.7	378.2	360.5	356.0	363.3	faulty	362.5	358.2	364.2	377.3	363.8	360.4	364.2	336.2	faulty	338.2	337.1	330.6
37	380.4	394.6	377.7	374.0	380.3	faulty	379.8	378.4	383.1	395.9	383.2	380.0	382.8	356.2	faulty	355.2	356.8	352.5
38	406.6	418.4	403.6	401.7	406.1	faulty	404.6	401.5	404.4	414.9	403.7	402.1	402.8	384.6	faulty	383.9	385.3	382.9
39	488.1	512.4	488.2	475.1	490.2	faulty	494.3	480.8	496.4	519.7	502.7	489.4	491.0	418.1	faulty	417.8	417.2	410.4
40	511.8	535.0	507.9	493.5	509.3	faulty	514.1	497.6	514.0	538.7	521.7	504.2	507.9	425.1	faulty	427.0	436.0	415.5
41	549.2	574.0	546.0	530.0	548.4	faulty	554.5	536.8	554.7	580.6	564.2	544.9	549.6	445.5	faulty	454.9	445.6	431.2
42	474.2	499.0	474.8	461.6	476.0	faulty	480.0	465.2	480.8	503.2	485.9	472.3	474.9	408.2	faulty	409.5	409.8	399.7
43	456.9	482.6	458.9	447.4	460.6	faulty	463.6	450.0	464.1	484.7	467.8	456.2	454.2	399.0	faulty	399.9	400.6	394.7

Table-A1: Steady State data for HHHC orientation with Supercritical H_2O (Contd.)

Sl. No.	TT-112 (°C)	TT-113 (°C)	TT-114 (°C)	TT-115 (°C)	TT-116 (°C)	TT-117 (°C)	TT-118 (°C)	TT-119 (°C)	TT-120 (°C)	TT-121 (°C)	TT-122 (°C)	TT-123 (°C)	Voltage (V)	Current (A)
1	366.8	363.6	367.2	360.4	faulty	360.5	362.2	360.7	359.4	45.5	42.0	85.1	4.3	1525.1
2	390.8	385.4	388.9	400.8	faulty	398.9	402.0	403.4	396.7	46.6	42.0	89.6	5.4	1580.8
3	386.3	382.1	385.5	394.1	faulty	392.7	395.2	396.6	391.2	48.3	43.1	92.5	5.1	1601.7
4	289.2	287.4	289.3	279.0	faulty	277.6	279.2	277.5	272.7	47.7	43.6	75.5	4.6	1239.6
5	303.1	300.8	302.6	293.1	faulty	290.6	292.1	291.6	286.4	48.3	44.8	78.9	4.7	1302.2
6	331.6	329.4	332.1	322.8	faulty	320.5	322.4	320.8	316.0	48.8	44.8	82.9	4.2	1420.6
7	345.0	342.3	344.9	336.3	faulty	333.4	335.2	334.3	329.8	48.3	44.2	83.4	5.2	1406.7
8	374.6	372.5	375.5	370.5	faulty	367.8	370.0	369.1	363.8	46.6	42.5	86.8	5.2	1539
9	278.0	275.6	278.2	267.8	faulty	266.3	267.4	266.3	261.7	47.2	42.5	72.7	4.4	1197.8
10	406.4	403.4	406.7	393.5	faulty	389.8	393.0	391.0	385.7	46.6	42.5	88.5	4.6	1594.7
11	380.2	377.8	380.2	379.7	faulty	377.1	380.1	378.6	377.3	50.2	50.5	92.7	4.6	1622.6
12	380.8	378.4	380.8	381.4	faulty	378.3	382.3	379.7	377.9	50.2	50.5	91.6	5.2	1615.6
13	422.0	418.2	420.9	405.6	faulty	400.3	404.2	400.0	398.0	50.2	50.5	95.5	4.9	1692.2
14	422.0	418.2	421.4	404.5	faulty	399.7	404.2	399.4	397.5	50.2	50.5	95.5	5.6	1622.6
15	362.9	361.0	363.0	358.3	faulty	354.6	358.2	355.6	354.4	50.2	50.5	89.9	4.8	1469.4
16	365.7	363.8	366.3	362.3	faulty	358.5	361.5	358.9	357.2	50.2	50.5	89.9	4.9	1497.2
17	340.6	338.5	340.2	333.5	faulty	329.7	332.9	330.2	328.1	51.5	51.8	86.5	5.1	1518.1
18	358.5	355.9	358.5	352.7	faulty	348.9	352.0	349.9	348.2	50.6	50.9	88.2	5.4	1559.9
19	369.6	367.2	369.7	366.2	faulty	362.5	365.5	362.9	361.1	51.1	51.3	90.5	4.8	1546
20	374.1	371.6	374.7	371.8	faulty	368.1	371.1	368.5	367.2	51.1	51.3	89.9	5.8	1706.1
21	370.2	366.0	368.0	376.9	faulty	374.3	377.8	376.9	375.1	51.1	51.3	92.7	5.1	1532
22	369.6	364.9	368.0	376.9	faulty	373.7	377.8	376.4	375.1	51.5	51.8	92.2	5.4	1552.9
23	377.4	374.8	378.3	375.0	faulty	374.6	376.2	375.8	375.9	44.9	42.0	86.3	5.4	1525.1
24	378.5	375.4	378.9	376.1	faulty	376.3	378.4	377.0	377.0	44.9	42.5	88.5	4.4	1539
25	414.2	407.8	411.7	398.6	faulty	396.6	398.6	396.1	395.6	38.7	36.5	113.9	4.3	1511.1
26	427.6	421.3	425.6	402.5	faulty	399.4	402.0	399.4	392.3	51.6	41.4	93.0	4.6	1643.5
27	417.6	411.8	416.1	396.9	faulty	394.9	396.9	395.5	388.5	52.2	42.5	95.3	4.4	1552.9
28	80.9	80.7	80.7	76.9	faulty	76.7	76.8	75.3	84.0	49.4	55.8	52.4	3.1	278.6
29	110.0	109.8	110.2	103.9	faulty	104.4	104.3	102.8	112.5	49.4	55.8	55.8	3.8	362.1
30	137.9	137.8	137.4	130.8	faulty	130.9	130.6	129.8	139.4	49.4	55.8	58.6	5.1	424.8
31	170.3	168.1	168.6	160.6	faulty	160.2	159.2	158.4	169.5	49.4	56.4	62.6	5.6	536.2
32	190.4	191.0	190.8	182.5	faulty	182.2	182.2	181.5	193.1	50.0	56.4	65.4	6.1	557.1
33	220.0	219.6	219.2	210.5	faulty	210.4	209.7	209.0	221.1	49.4	55.8	68.8	6.7	612.8
34	233.4	233.1	232.5	224.0	faulty	223.4	222.6	220.8	234.8	49.4	55.8	70.5	7	654.6
35	283.0	283.5	283.2	273.4	faulty	273.1	272.5	271.9	287.0	49.4	55.8	77.2	7.5	689.4
36	329.4	330.5	328.8	321.1	faulty	321.0	319.6	319.1	335.8	48.8	55.8	84.0	7.7	793.9
37	350.0	351.8	349.9	343.6	faulty	342.5	340.9	339.9	357.2	50.0	56.4	87.4	8.3	849.6
38	380.7	383.2	381.6	381.8	faulty	381.9	379.5	380.3	398.4	50.5	56.4	94.7	8.8	893.5
39	413.1	410.1	413.4	396.9	faulty	393.8	396.4	394.9	388.5	46.0	42.0	89.1	9	950.9
40	419.3	412.3	416.7	398.0	faulty	395.5	397.5	395.5	389.0	50.5	40.9	93.6	9	940.5
41	434.9	427.5	431.2	406.5	faulty	402.8	405.3	402.8	395.6	51.1	40.9	95.3	9.3	983.6
42	401.4	396.6	400.6	388.5	faulty	387.6	389.6	387.6	386.8	44.4	39.8	89.6	8.7	960.7
43	396.9	392.7	396.1	388.5	faulty	387.6	389.6	387.1	386.8	38.7	36.5	111.1	8.1	896.2