Experimental results of ITER cold circulators towards the performance demonstration

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Abstract. The cold circulators, the most challenging component of ITER cryo-distribution system, have been designed, manufactured and tested successfully at factory. The design point for the cold circulator has been specified as 2.21 kg/s at 4.3 K inlet temperature having 0.155 MPa pressure head, dedicated for the nominal operation of toroidal field (TF) superconducting magnet of ITER. The expected isentropic efficiency has been defined as 70% or more suitable to cater the demands of the cryo-distribution system. Two cold circulators for TF superconducting magnet have been installed in the Test Auxiliary Cold Box (TACB) followed by the integration of TACB system with the 5.0 kW at 4.5 K class cryogenic test facility at Japan. Final cold acceptance test of the complete system has been performed in order to validate the design conditions of TACB and cold circulators. Qualification tests of two cold circulators have been executed at closed loop operating condition. The cool-down of cold circulators down to 4.6 K temperature level and normal operating results as well as the experimental validation of performance along with the obtained isentropic efficiencies at the operating conditions have been demonstrated meeting the system level requirements of ITER cryo-distribution.

1. Introduction

The supercritical helium (SHe) cold circulators, part of ITER cryo-distribution system [1], are required to fulfil the cooling function of the ITER superconducting magnets of Central Solenoid (CS), Toroidal Field (TF), Poloidal Field & Correction Coil (PF&CC) and magnet support structure (ST) as well as the cryopumps (CP). The first of its kind requirement [2, 3] of cold circulator includes largest mass flow rates with guarantee on the performance under transient operating condition [4]. Two numbers of cold circulators with identical design condition as 2.21 kg/s at 4.3 K mass flow and 0.155 MPa pressure head have been designed, manufactured and factory tested by two independent world leading suppliers. Both the cold circulators have been installed into the Test Auxiliary Cold Box (TACB). Entire TACB has been installed, commissioned at one of the largest cryogenic test facility situated at Atomic Energy Agency (JAEA), Japan [5]. Complete control system including cold circulators, TACB has been installed and integrated with JAEA test facility. The inception of qualification test and associated concept has been generated in order to mitigate technical and schedule risks as well as to generate sufficient experimental results suitable for the detailed design of overall cryo-distribution system. Qualification test of the cold circulator has been performed in closed loop operating condition.
at the 4.5 K temperature level at JAEA test facility under the ‘Arrangement for ITER Cold Circulator Test’ dated June 2013.

2. Qualification test objective and methodology
The design of cold circulators has been standardized in compliance with the operational requirement and performance guarantee of TF, CS, PF&CC and CP. The test objectives for the qualification of cold circulators have been evaluated based on the requirement and are summarized as follows

(i). Controlled cool-down of cold circulator including TACB along with refrigerator/liquefier
(ii). Operation and performance assessment at nominal condition (100 % rotational speed) of TF, CS, PF&CC and CP
(iii). Operation and performance assessment at maximum condition (110 % rotational speed) of TF, CS, PF&CC and CP
(iv). Finding of extreme operational limits at 100 % and 110% rotational speed operations of TF, CS, PF&CC and CP
(v). Performance assessment by alternative efficiency measurement methods at design point

Control methodology and test modes during the qualification test [3] has been developed and implemented during the entire qualification test at JAEA, Japan.

3. System description

3.1. ITER Cold Circulator
ITER cold circulators [6] have been designed and manufactured in parallel by IHI Corporation, Japan and Barber Nichols Inc. (BNI), USA, which has been referred as Cold Circulator -1 (CC-1) and Cold Circulator -2 (CC-2) respectively now onwards in this paper. The rotors have been sustained by two competitive technologies, such as, active magnetic bearing (AMB) and hybrid ceramic ball bearing for CC-1 as well as CC-2 respectively. Each of the two cold circulators has been equipped with (i) Rotational speed probe, (ii) Vibration probes, (iii) Electrical power measurement, (iv) Electrical motor temperature sensor, (v) Start/stop counter, (vi) Operation hours counter, (vii) Bearing temperature measurement for CC-2, (viii) Touch – down counter for CC-1 and (ix) Rotor floating hours for CC-1.

Dedicated electrical cabinets of each cold circulator have been developed to house majorly programmable logic controller, variable frequency drives, power filters, panel human-machine interface (HMI) and AMB controller for CC-1. Intermediate signal and power cables have been designed and installed with the length of 100 m in order to verify the performance as per actual ITER condition. Table 1 illustrates nominal operating condition of cold circulator during qualification test.

Table 1. Nominal operating condition of cold circulator during qualification test.

| Operating Condition | Parameter          | CS-cold circulator | TF-cold circulator | PF&CC-cold circulator | CP-cold circulator |
|---------------------|--------------------|--------------------|--------------------|------------------------|--------------------|
| Inlet conditions    | Pin (MPa)          | 0.51               | 0.46               | 0.51                   | 0.34               |
| during operations   | Tin (K)            | 4.55               | 4.55               | 4.55                   | 4.55               |
| Nominal operation   | Mass flow (kg/s)   | 2.07               | 2.21               | 1.93                   | 1.36               |
|                     | ΔP (MPa)           | 0.105              | 0.155              | 0.105                  | 0.075              |

3.1.1. ITER Cold Circulator -1. Figure 1 shows the outer view of cartridge, which includes rotor shaft, impeller with shroud, warm motor casing with utility and signal interfaces, electrical motor, active magnetic bearings (radial and axial) with sensors, touch-down bearings (upper and lower) as well as thermal insulator with 80 K thermal anchor. Figure 2 shows the outer view of cartridge as installed into the cold casing, which includes volute with diffuser, suction and discharge process interface, cryostat mounting flange as well as the 80 K cooling facility with its interfaces.
Additionally, specially designed thermal shield at 80 K has been applied to protect the direct radiation on the 4.5 K surfaces of cold casing.

3.1.2. ITER Cold Circulator -2. The cartridge, as shown in Figure 3, includes rotor shaft, impeller with shroud, warm motor casing, electrical motor, ball bearings (upper and lower), sensors, as well as electrical junction boxes including amplifiers. Figure 4 shows the cold casing, which includes volute, suction and discharge process interface, cryostat mounting flange as well as the 80 K intercept cooling facility with its interfaces.

3.2. Test Auxiliary Cold Box
The process and control scheme of TACB has been described in the Figure 5, in which, cold circulators have been installed in parallel with suction and discharge side heat exchanger suitable for the complete operation. The cool-down has been achieved by control valve CV 10 and CV30 for the liquid helium (LHe) bath and cold circulator SHe loop respectively. Pressure in the LHe bath has been controlled by the pressure controller PIC113 whereas the SHe loop pressure has been controlled by pressure controller PIC107. Submerged electrical heater HE2 was responsible for the level control
with the controller LIC100. DPIC200 has been used for the pressure head measurement either for cold circulator - 1 or for cold circulator - 2.

![Figure 5. TACB process and control scheme.](image)

4. Qualification Test and the Facility

4.1. Efficiency measurement methods

The enthalpy (H) rise of the SHe flow has been measured by the detection of pressure and temperature at the inlet and outlet of the cold circulator. The isentropic efficiency ($\eta$) has been evaluated as in equation (1) and it has been termed as direct method of measurement.

$$\eta = \frac{\Delta H_{\text{isentropic}}}{\Delta H_{\text{actual}}}$$ (1)

Alternative method for efficiency measurement has been adopted, in which rotational speed of the cold circulator has been reduced to nearly zero from the design point speed. At the same time, injected power to the heater (HE2) at the liquid helium bath has been increased in a manner to keep the liquid level constant. During the entire operation, inlet condition of control valve CV10, such as temperature, pressure as well as the percentage opening of CV10 has been kept condition. The isentropic efficiency ($\eta$) has been evaluated as in equation (2) in which $m_{cc}$ is the mass flow rate; $Q_{cc}$ and $Q_{HE2}$ are the heat flow by the cold circulator and the heater, HE2 respectively and it has been termed as alternative method of measurement.

$$\eta = \frac{(\Delta H_{\text{isentropic}}) m_{cc}}{Q_{cc}}; \text{ Where } Q_{cc} = Q_{HE2(\text{CC stopped})} - Q_{HE2(\text{CC running})}$$ (2)

4.2. Qualification Test Facility

The complete qualification of two cold circulators has been performed at JAEA-Naka facility as shown in Figure 6 with the help of helium refrigerator/liquefier (HRL) of 5kW at 4.5 K [5]. Liquid nitrogen (LN$_2$) has been used for the cooling of thermal shields for TACB and cold circulators.
5. Experimental results and performance evaluation

TACB along with cold circulator has been cooled down to 4.6 K simultaneously in a controlled way by refrigerator/liquefier. Figure 7 shows controlled cool down plot for the cold circulator, which is divided into three regions, such as, (i) initial cool down up to 80 K, (ii) 80 K stand-by (iii) final cool down up to 4.6 K.

5.1. Experimental Characterization

Two cold circulators have been operated in closed loop condition one by one. The discharge pressure of the cold circulator has been controlled at 0.6 MPa during the entire characterization except for the CP which has been controlled at 0.413 MPa. Nominal operating condition (mass flow and head) of TF, CS, PF&CC and CP as in Table 1 has been reached by increasing the rotational speed of cold circulator keeping opening of control valve CV80 as constant. Maximum operating condition has been obtained by increasing further the rotational speed up to 110 % of the experimentally obtained nominal speed. Characterization at nominal as well as maximum rotational speed has been experimentally performed by changing the opening of control valve CV80. Figure 8 shows the experimentally obtained pressure head vs. SHe mass flow rate characteristic curve of cold circulator-1.
Very stable operation has been achieved during entire window of operation. Maximum SHE mass flow rate has been achieved as 3.066 kg/s with consumption of 5.32 kW of electrical power; whereas, maximum stable pressure head as 218.88 kPa has been acquired. Speed ramp up from start-up up to design point has been performed and shown in Figure 8.

Experimental characterization of pressure head vs. mass flow rate for cold circulator-2 has been performed and shown in Figure 9 for TF, CS, PF&CC and CP.

![Figure 8](image1.png) **Figure 8.** Experimental pressure head Vs. mass flow characteristic of cold circulator-1, where ‘nominal’ and ‘maximum’ denote 100% and 110% rotational speed respectively.

![Figure 9](image2.png) **Figure 9.** Experimental pressure head Vs. mass flow characteristic of cold circulator-2, where ‘nominal’ and ‘maximum’ denote 100% and 110% rotational speed respectively.

The largest possible SHE mass flow at this stage has been achieved as 3.42 kg/s and the maximum pressure head has been obtained as 192.8 kPa at the highest rotational speed operation. The characteristic of cold circulator-2 has lower slope while comparing the slope in the characteristic of cold circulator-1 as shown in Figure 8 and Figure 9. Hence, for a very small change in the pressure head at a constant rotation speed, very large change in mass flow rate has been observed in cold circulator-2.
5.2. Performance evaluation as efficiency measurement

Performance of two cold circulators has been measured and examined as direct method of measurement as in equation (1). Figure 10 shows the experimentally attained isentropic efficiencies of cold circulator – 1 and 2 for the CP nominal and maximum operating condition. Similarly, isentropic efficiencies as shown in Figure 11 Figure 12 Figure 13 have been measured for the PF&CC, CS and TF operating condition respectively, which includes the nominal and maximum rotational speed.

![Figure 10. Isentropic efficiency of cold circulator-1 and 2 for CP operating condition.](image1)

![Figure 11. Isentropic efficiency of cold circulator-1 and 2 for PF&CC operating condition.](image2)

![Figure 12. Isentropic efficiency of cold circulator-1 and 2 for CS operating condition.](image3)

![Figure 13. Isentropic efficiency assessment of cold circulator-1 and 2 for TF operating condition.](image4)

It has been observed that cold circulator – 1 has demonstrated better isentropic efficiencies for the entire operating regime than that of cold circulator - 2. The highest efficiency of cold circulator -1 has recorded as 78 % for CP operating condition whereas 72 % efficiencies during TF operating condition has been recorded for the cold circulator -2. The average isentropic efficiencies of cold circulator – 1 has been analyzed as 73.8 % excluding the operational limit (at surge and choke) point. Similar assessment for the cold circulator – 2 has been made and 62.9 % of efficiencies have been noted excluding the operational limit points. Higher average efficiency as 67.3 % has been observed during
large mass flow operation (only at choke) than that of nominal operating areas in case of cold circulator -2.

Further, performance of two cold circulators has been measured only for the TF nominal operating condition as design point as per alternative method of measurement described in equation (2). The resultant efficiencies have been obtained as 73.45 % and 61.86 % for the cold circulator - 1 and cold circulator - 2 respectively. The result using alternative method of measurement has very good agreement with the efficiency obtained by direct method of measurement as in equation (2).

6. Conclusion
Both the cold circulators have been operated in a very stable condition over the entire range of characteristic area. Very large supercritical helium mass flow rates more than 3.0 kg/s have been achieved for both the cold circulators. The detailed experimentation for the efficiency measurement has been performed followed by the complete assessment on the performance. High efficiency more than 62 % has been achieved by the cold circulators. Qualification test facility at JAEA has been operated very successfully in tune with the various process needs, some of which are highly transient in nature.

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Disclaimer
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