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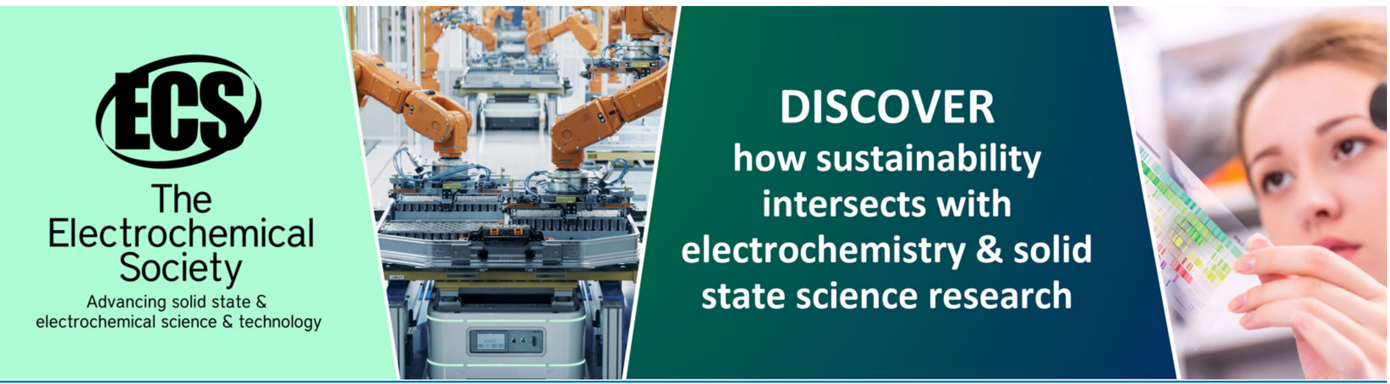

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Design realization towards the qualification test of ITER cold circulator

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Abstract. Cold circulators, part of ITER Cryo-distribution system, have now reached to a stage of final qualification to demonstrate the design to cater the maximum mass flow and operational demands of the toroidal field (TF) superconducting magnet of ITER with a very high isentropic efficiency. The design for the two numbers of TF cold circulators are now complete gratifying additionally the operational requirements of poloidal field & central solenoid superconducting magnet as well as the cryopumps towards the fulfilment of standardization aspects. Management of physical and functional interfaces has been identified as one the most critical aspect towards the performance of cold circulator. All the interfaces of cold circulators have been analysed with the help of optimized interfacing parameters of Test Auxiliary Cold Box (TACB) and cryogenic test facility at JAEA, Japan during the course of design finalization. Testing at the warm conditions after completion of precise manufacturing of cold circulators has been performed before integrating into the TACB to fulfil the Japanese as well as European regulatory requirements simultaneously. The paper elaborates the methodology of interface management and control, analysis performed towards the interface management and preliminary test results towards the qualification test of the ITER cold circulator.

1. Introduction

Cold Circulator, a cryogenic centrifugal type pump, is the most critical state-of-the art item for the ITER cryo-distribution system. The main function of the cold circulator [1, 2] is to establish and maintain forced-flow supercritical helium (SHe) flow in to the flow-path of the superconducting magnet of ITER. The major challenging tasks of cold circulator are to operate at vigorous operating regime of superconducting magnet having an isentropic efficiency of 70%. Two cold circulators have been designed, manufactured by two industrial partners in order to perform the qualification test prior to the final design of ITER cryo-distribution system. The main objective of the qualification test is to assess the wide operating capabilities during normal and off-normal design condition accomplishing the isentropic efficiency requirements. Both the cold circulators will be installed at Test Auxiliary Cold Box (TACB) and the qualification test is to be performed at the cryogenic test facility at JAEA-Naka, Japan in order to evaluate the performance of the cold circulators.

The integrated design realization for the cold circulators and TACB is the prime important factor for the qualification test. Hence, at the beginning of the design work, interface management has been identified as the high-risk area for the project involving three industrial partners; M/s. IHI Corporation, Japan, M/s. Barber-Nichols Inc., USA for Cold Circulators, M/s. Taiyo-Nippon Sanso Corporation, Japan for TACB as well as the cryogenic test facility at JAEA-Naka, Japan.

2. Design of Interfaces for Cold Circulators

The methodology of interface management and control has been implemented by (i) identifying all the interface points, (ii) defining design responsibilities of the respective interface points, (iii) updating the counter-interface design suiting to the original interface and (iv) verifying the complete system by integrated analysis, which reduces the design iterations. The interfaces for each of the cold circulators with the TACB and the cryogenic test facility have been identified. Mechanical, instrumentation and control as well as utilities are recognized as physical interfaces; whereas, operating modes of the cold circulator as an integrated component of TACB have been defined as the functional interface. Table 1 shows the detailed assessments on the interfaces.

Table 1. List of Interfaces of cold circulator.

Sr. No.	Interfaces	Interfacing Points
1.	Physical Interfaces	(i) Location of interfaces at casing (in-cryostat), mounting plate (on-cryostat), nozzles etc. along with the interfacing load specification (ii) Sizing and material of construction at the interface for a. SHe suction and discharge nozzles b. 80 K thermalization c. Mounting plate/flange of the cold casing d. Shield for magnetic field (as applicable) (iii) Interface with utilities a. Cooling Water b. Electrical Power
2.	Instrumentation and control (I&C) Interfaces	(i) I&C signal interface between the programmable logic controllers (PLC) of TACB and cold circulators (ii) Logical (software logic program) interfaces between the cold circulator and TACB (iii) Cabinet interface at the cryogenic test facility and supports as required
3.	Functional interfaces with the cryogenic test facility	Functional interface must satisfy all the operating conditions during the qualification test.

2.1. Physical Interfaces

The physical interfacing points of cold circulators are at the outer vacuum jacket of TACB where cold circulator mounting flange is welded with TACB and at internal inlet/outlet process lines as well as 80 K thermalization lines are connected, as shown in figure 1. Two utility connections namely, cooling water for motor cooling and electrical power supply, are also considered as part of the physical interfaces. The material and dimensional compatibility of two cold circulators and TACB internal piping is ensured during the design and manufacturing phase. Physical interface mismatch would lead to technical and schedule risk, therefore, the interfaces were managed with industrial partners as well as with the test facility. The intrinsic details of physical interfaces of cold circulators (defined as CC-1, CC-2 by manufacturer-1 and 2 respectively) with the TACB have been evaluated to meet the regulatory requirements of Japanese High Pressure Safety Act (JHPGSA) [3] as well as applicable European Directives towards the CE certification.

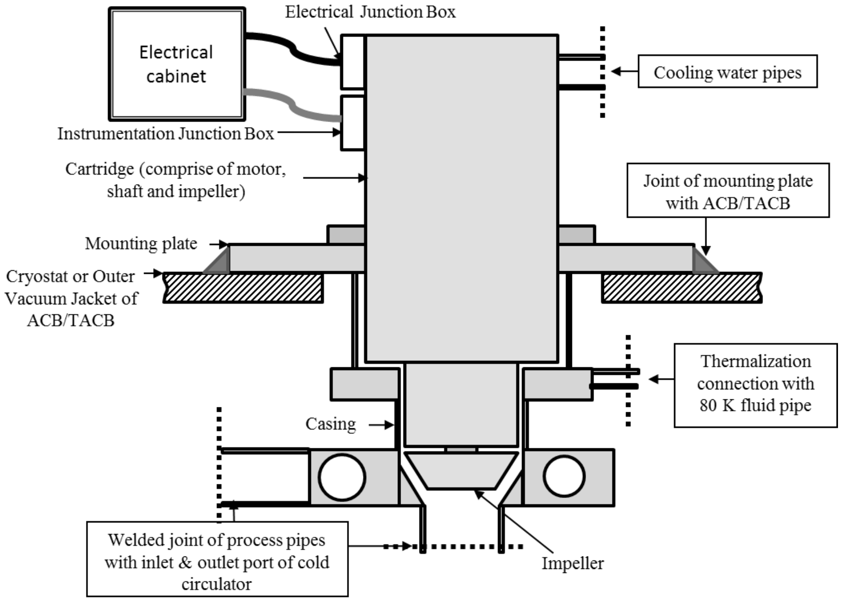

Figure 1. Schematic of cold circulator with interfaces.

2.1.1. Analysis during Design of Cold Circulator

Individual design and analysis of CC-1 and CC-2 as well as TACB system were performed as per the applicable or adopted codes and standard during the design phase with coherent design conditions. Thermo-mechanical and structural analysis has been performed on the pressure boundary of the cold circulator in order to assess and verify the safe condition with the various interfacing load cases. The regulatory requirements of JHPGSA are to be followed additionally for the piping / equipment / components bearing pressure boundary.

2.1.2. Integrated analysis with TACB

Integrated analysis of two cold circulators with TACB has been performed in order to evaluate the overall system level design compatibility under the influence of various load cases. Several iterations have been performed in order to avoid the thermal compensating devices at the suction and discharge sides of cold circulators.

2.2. Functional Interfaces with the Cryogenic Test Facility

Stable operation during the qualification test for cold circulator has been ensured by analysing the functional interfaces with the cryogenic test facility at JAEA-Naka facility with capacity of ~ 5.0 kW@4.5K or 800 l/h [4] . Functional interfaces have been evaluated based on the operating condition [5, 6] of cold circulator such as: (i) Nominal, (ii) Maximum mass flow at 110 % speed, (iii) Maximum pressure head at 110 % speed, (iv) Different speeds at 80 %, 60% and 20%, (v) Cold Circulator inlet at 10 bar, (vi) Cold Circulator inlet at 6 K and (vii) cold circulator OFF. Heat balance equation as shown below demonstrates the operation methodology.

$$Q_{Total} = Q_{TACB} + Q_{Cryolines} + Q_{LHe\,Tank} = \begin{cases} Q_{Refrigeration}, ; & Q_{Total} \leq 5\,kW \\ Q_{Refrigeration} + Q_{Liquefaction}, ; & Q_{Total} > 5\,kW \end{cases}$$

Where, $Q_{TACB} = Q_{CC} + Q_{Heater} + Q_{Static}$= Operational Heat Load from TACB
$Q_{Cryolines}$= Static heat load from interfacing cryolines
$Q_{LHe\,Tank}$= Static heat load from Liquid Helium Storage Tank

2.3. Instrumentation & Control Methodology and Associated Interfaces

Both the cold circulators have been equipped with programmable logic controllers (PLC), with stand-alone and remote operating capabilities as MASTER-SLAVE configurations. Figure 2 shows the control architecture in which two PLCs of cold circulators have been interfaced using profibus with master PLC of TACB.

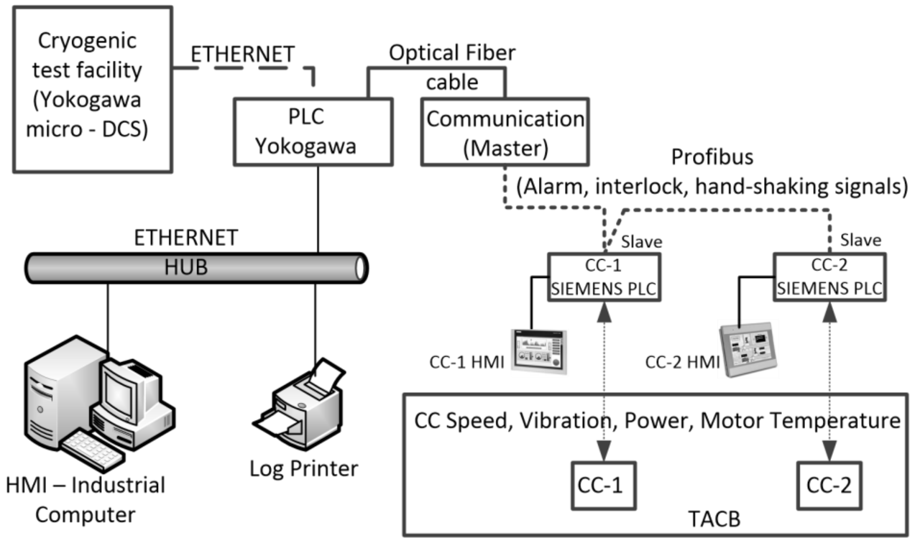

Figure 2. Control architecture of TACB with CC-1 and CC-2.

3. Results and Discussion

3.1. Physical Interface Analysis Results

Table 2. Interface loads for cold circulators.

	Description		Values for nozzle loads from TACB to CC-1		CC-1	Values for nozzle loads from TACB to CC-2		CC-2
		Unit	Inlet	Outlet		Inlet	Outlet	
Design conditions [2.0 MPa & 4.15 K]	Forces-X direction	[N]	-196.75	-377.53	Passed	-116.67	-28.99	Passed
	Forces-Y direction	[N]	202.79	325.9		289.21	61.52	
	Forces-Z direction	[N]	189	-7		-385	153	
	Moment-X direction	[Nm]	316.12	315.68		357.8	57.98	
	Moment-Y direction	[Nm]	204.45	361.23		231.93	29.7	
	Moment-Z direction	[Nm]	73	4		47	-5	
Test condition [2.5 MPa & 300 K]	Forces-X direction	[N]	-183.79	-351.5	Passed	-116.67	-28.99	Passed
	Forces-Y direction	[N]	188.34	302.82		289.21	61.52	
	Forces-Z direction	[N]	166	-19		-385	153	
	Moment-X direction	[Nm]	292.74	293.1		357.8	57.98	
	Moment-Y direction	[Nm]	190.95	334.34		231.93	29.7	
	Moment-Z direction	[Nm]	68	4		47	-5	

Design and analysis of the pressure containing wall of the cold circulators, which were performed by the individual industrial partners as components, have been verified with the same boundary conditions and as an integrated system fulfilling the requirements. In-cryostat cold casing of the cold circulator is very specially designed thin wall with responsible to (i) sustain all the interfacing piping loads from the TACB and (ii) reduce the conductive heat-in-leak to the cold process line. Hence, In-cryostat cold casing of the cold circulator has been selected for the prime area of investigation as the interfacing point. Several design iterations have been performed in order to achieve the safe design condition for all the interfacing load cases. The portion between warm part to cold part of the in-cryostat casing is designed by keeping balance between the static heat in-leak and imposed loading from the internal piping of the TACB. This balance is critically evaluated with several design checks and analysis of the combined cold circulator system and TACB. The forces and moments on the cold circulator nozzles from the internal piping of TACB are imposed in the CC analysis and confirmed that the stresses on CC are still within allowable limits. The forces and moments values are summarized in table 2 for CC-1 and CC-2.
Figure 3 and 4 show the thermomechanical design results performed under the condition of the interfacing piping forces and moments from TACB as per table 2. Maximum stresses of 119.33 MPa and 162 MPa have been obtained in CC-1 and CC-2 respectively.

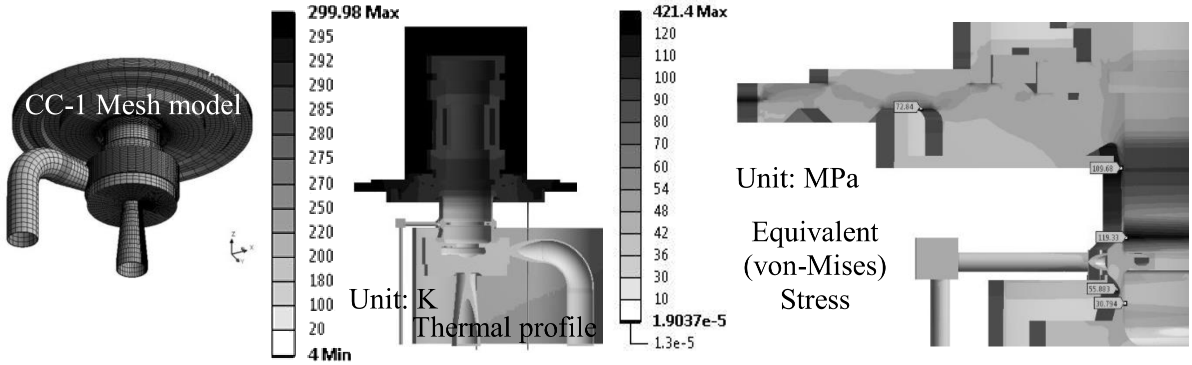

Figure 3. Thermo-mechanical analysis for Cold circulator-1.

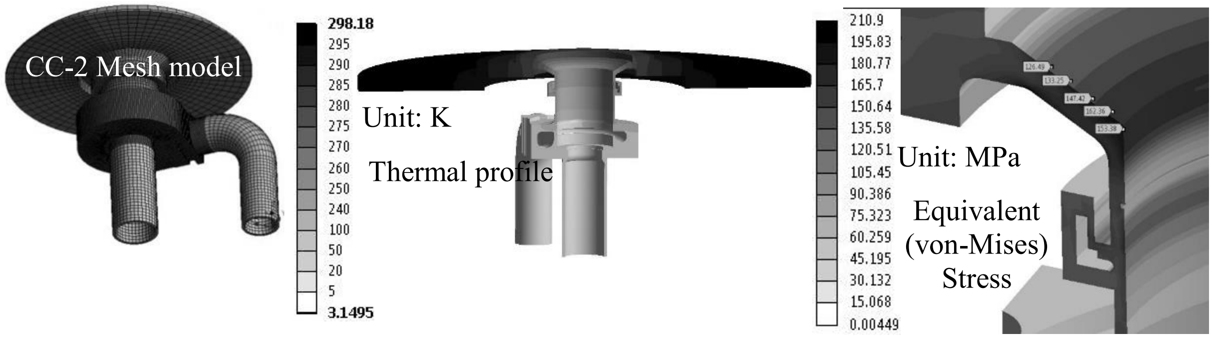

Figure 4. Thermo-mechanical analysis for Cold circulator-2.

Integrated analysis have been performed considering the two cold circulators along with TACB for 'test pressure condition' as per 'Pressure Equipment Directive', which has been found more stringent than that of Japanese regulations as per JHPGSA. Figure 5 shows the results of integrated structural analysis and obtained profile of stress. In order to fine tune the obtained results, linearization has been performed and maximum stress of 100.9 MPa and 191.3 MPa have been obtained at the CC-1 and CC-2 respectively. Maximum integrated deformation obtained as 1.368 mm from the integrated analysis.

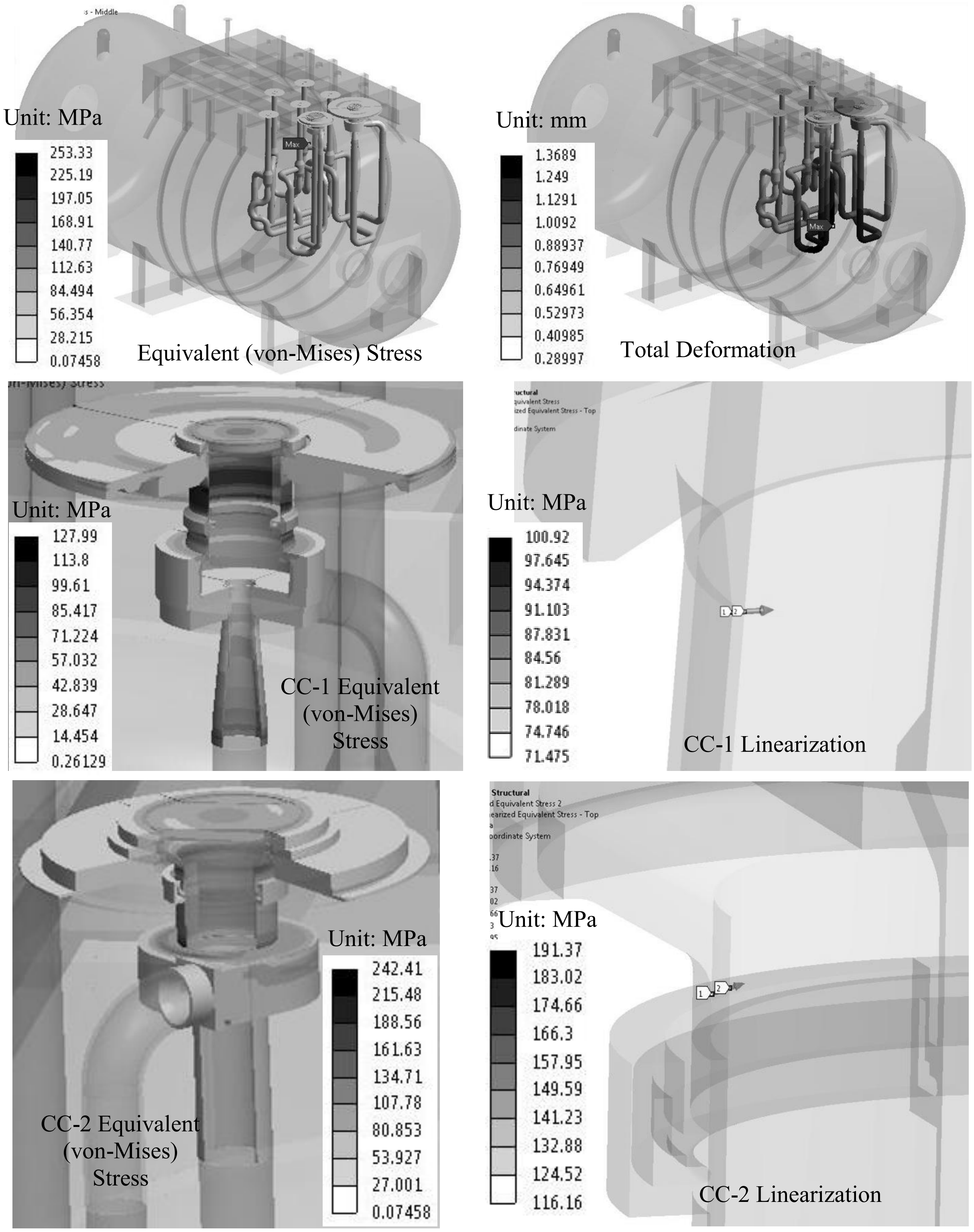

Figure 5. Integrated structural analysis for TACB, CC-1 and CC-2.

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3.2. Functional Interface Analysis Results

Figure 6 shows the total heat load to the cryoplant with respect to the operating condition. During the ‘maximum mass flow operation’ and the ‘Cold Circulator inlet at 6 K’, it has been observed that 'Q_Total' exceeds the cryoplant capacity limit. In order to suit the additional operating demands, liquid helium (LHe) will be transferred having mass flow rate as 20 g/s from the LHe Tank to the TACB LHe bath.

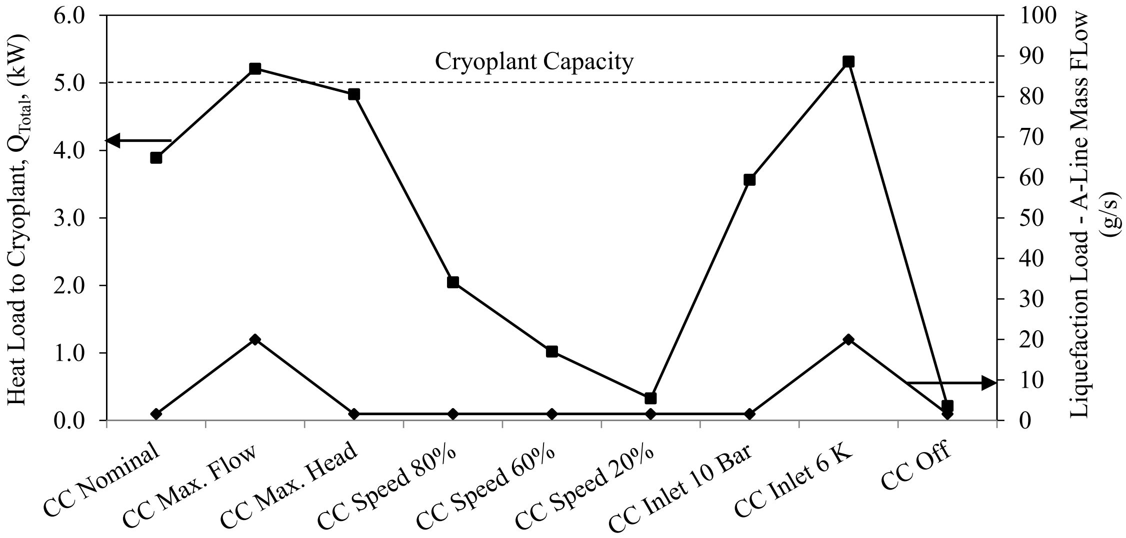

Figure 6. Total heat load to the cryoplant with respect to the operating condition.

4. Factory Acceptance Test

Factory acceptance test (FAT) of cold circulators from both suppliers has been completed successfully. Verification of all the interfaces has been performed satisfactorily. The test results are summarized in table 3, which have been performed under no-load condition.

Table 3. Summary of Factory Acceptance Test.

	CC-1		CC-2	
	Design	Test Result	Design	Test Result
Speed at Design Point (rpm)	12000	12000	8000	8000
Mock-up Cartridge Replacement time (mm:ss)	< 120:00	60:00	<120:00	55:35
Electrical input power to motor at 100% speed (kW)	-	0.33	-	2.06
Electrical input power to motor at 110% speed (kW)	-	0.43	-	2.15
Vibration Upper bearing at 100% speed (Resultant)	35 µm	1.0 µm	< 2.54 mm/s	1.36 mm/s
Vibration Lower bearing at 100% speed (Resultant)		1.0 µm		0.77 mm/s
Vibration Upper bearing at 110% speed (Resultant)		1.0 µm		1.19 mm/s
Vibration Lower bearing at 110% speed (Resultant)		1.0 µm		0.54 mm/s
Acoustic Noise at 1 m distance, 100% speed (dB)	< 85	62.5	< 85	64.2
Acoustic Noise at 1 m distance, 110% speed (dB)		62.5		65.6

5. Conclusion

Designs of two cold circulators along with TACB have been completed with supporting analysis. Integrated analysis has been performed in order to obtain a safe interfacing design condition for physical interfacing points. Results show that stresses and deflections are within the allowable limit as per the selected material and construction codes and standards. Functional interface has been evaluated considering all modes of operation for the cold circulators suitable to the cryogenic test facility. Factory acceptance tests for both the cold circulators have been successfully completed and ready for the final qualification test.

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Disclaimer

The views and the opinion expressed herein do not necessarily express those of the ITER organization and the ITER partners.

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