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Design of a cooling system for the ITER Ion Source and Neutral Beam test facilities

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ABSTRACT

This paper deals with the requirements, operational modes and design of the cooling system for the ITER Neutral Beam test experiments. Different operating conditions of the experiments have been considered in order to identify the maximum heat loads that constitute, with the inlet temperature and pressure at each component, the design requirements for the cooling system.

The test facility components will be actively cooled by ultrapure water realizing a closed cooling loop for each group of components. Electrochemical corrosion issues have been taken into account for the design of the primary cooling loops and of the chemical and volume control system that will produce water with controlled resistivity and pH. Draining and drying systems have been designed to evacuate water from the components and primary loops in case of leakage, and to carry out leak detection.

Tritium concentration, water resistivity and pH will be measured and monitored at each primary loop for safety reasons and high voltage holding reliability. The measured water flow rates and temperatures will be used to calculate the exchanged heat fluxes and powers. Flow regulating valves and speed of variable driven pumps will be adjusted to control the component temperatures in order to fulfil the functional and thermohydraulic requirements.

1. Introduction

Two test facilities are planned to be built in Padua for testing the ITER Neutral Beam Injectors: a low energy 60/100 keV full size Ion Source (IS) and the 1 MeV Heating Neutral Beam (HNB). The total power to be removed from both the experiments (up to 70 MW) and the power produced by the auxiliary systems will be exhausted by the cooling system (CS).

The design of the CS has been developed considering the specifications of the ITER Neutral Beam Heating and Current Drive Injector subsequently revised in order to fulfil the updated component requirements [1,2]. Furthermore, modifications of the ITER cooling water system [3] have been considered to reproduce the ITER working conditions in the 1 MeV HNB.

The CS will be composed of three main heat transfer systems that exchange thermal power between them, the experiment test facilities and the environment. The primary heat transfer system (PHTS) will be directly connected to the test facilities for cooling and thermal control of the in-vessel components. The secondary heat transfer system (SHTS) will act as a confinement barrier for tritium generated by the interaction of the HNB deuterium with copper alloy and for corrosion contaminants produced in the primary loops; furthermore it will transfer the thermal power from the PHTS to the tertiary heat transfer system (THTS). The latter will be an open circuit that will transfer the thermal power from SHTS to the heat rejection system that will consist of cooling towers and dry coolers for heat rejection in the environment. Water basins with large stored energy will be interfaced to the THTS in order to reduce the installed power of heat rejection machines.

2. Design requirements

The cooling system will remove the experiments thermal power by feeding primary water at temperature, flow rate, pressure and resistivity required by components. Different phases of the experimental campaigns have been considered in order to determine the CS requirements corresponding to the worst operating scenario: conditioning, full power, shut down.

2.1. Thermohydraulic requirements

The CS requirements are shown in Tables 1 and 2 and below explained in detail.

During conditioning, components initial temperature will be the inlet water temperature that has to be Controlled Before and during Operation (CBO) within ±20 °C range, ±2 °C tolerance in order to satisfy functional requirements; temperature of other components can Reach the nominal value During experiments Operation (RDO).

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Table 1
IS thermohydraulic requirements.

Component	Water type	Thermal power (kW)	T_{inlet} (°C)	T_{outlet} (°C)	Secondary loop temp. range	Conditioning
RF coils	II	25	34	46	MT	RDO
RF source	II	817	40	56	MT	CBO
Plasma grid and bias plate	II	40	150	160	MT	CBO
Extraction grid	II	1000	34	56	MT	CBO
Grounded grid	II	700	34	57	MT	CBO
Calorimeter	II	5300	34	72	MT	RDO
Power supply	II	1400	34	45	MT	RDO

Table 2
HNB thermohydraulic requirements.

Component	Water type	Thermal power (kW)	T_{inlet} (°C)	T_{outlet} (°C)	Secondary loop temp. range	Conditioning
RF coils	I	25	15	27	LT	RDO
Faraday shields	I	930	40	61	MT	CBO
Source case	I	590	40	54	MT	CBO
Plasma grid and bias plate	I	40	150	160	MT	CBO
Extraction grid	I	1000	15	37	LT-MT	CBO
Grid 1	I	1000	15	29	LT-MT	CBO
Grid 2	I	2000	15	43	LT-MT	CBO
Grid 3	I	2170	15	46	LT-MT	CBO
Grid 4	I	2000	15	43	LT-MT	CBO
Grounded grid	II	2500	15	35	LT-MT	CBO
Electron dump	II	2000	80	90	HT	RBO
Neutralizer	II	5700	80	120	HT	RDO
Residual ion dump	II	19000	80	129	HT	RDO
Calorimeter	II	21000	80	106	HT	RDO
Power supply	II	3200	34	45	MT	RDO

Calorimeter inlet pressure (3 MPa) will be higher than that one of the other components (2 MPa) owing to the higher pressure drops in the panels.

The full power that has to be removed from the IS will be 9.3 MW considering the power produced by the experiment (7.9 MW) and the requirements of the power supply and vacuum system. The HNB full power will be 63 MW considering the power produced by the experiment (60 MW) and the requirements of the power supply and cryo system.

Maximum pulse length of the experiments will be 3600 s, but simultaneous operation is foreseen with reduced pulse duration that is expressed by a duty cycle of 1/4: the thermal energy will be produced during the pulse operation (beam on) with duration of one time unit, whereas it will be removed during the entire period with duration of four time units.

2.2. Primary water requirements

The PHTS will be directly connected to the test facility components that operate at different electrical potentials. High voltage components (down to −1 MV potential) require insulating breaks and voltage insulation also along the water columns. The required primary water grades are type I for HNB high voltage components and type II [4] for other components [3] as shown in Tables 1 and 2. Continuous water resistivity degradation will occur in the primary cooling loops for dissolved piping and component contaminants. Then, the primary water will be chemically treated and controlled in a chemical and volume control system (CVCS) to restore the required purification level. For HNB high voltage components, initial water resistivity shall be 18 MΩ cm and it will diminish during the HNB experimental operation; the minimum allowable value will be identified on the basis of experimental measurements during operations.

For all the other primary loops, the water resistivity shall be always greater than 1.0 MΩ cm [1].

2.3. Drying requirements

In case of small leak events, the leaking primary circuit will be identified and water shall be evacuated completely from the component and primary loop. For this aim a draining and refilling system (DRS) and a drying system (DS) shall be provided.

3. System design and capabilities

The main concept, basis for the design of the CS, is to use different cooling machine types depending on the temperature ranges of the produced powers; this will be the cheaper solution considering the large amount of power to be rejected and the related operational costs of energy for rejection systems.

The designed cooling loops and machines have been arranged in the plans of the experiments and services buildings considering operational requirements, overall dimensions, installation, maintenance and possible replacement.

3.1. Primary heat transfer system

Each experiment component or group of components is thermally controlled by a primary cooling loop that has the configuration represented in Fig. 1.

Table 3
Padua climate conditions.

Season	Dry bulb temperature (°C)	Wet bulb temperature (°C)	Relative humidity	Condition
Summer	31.5 (max.)	24	55%	Extreme
Winter	−5 (min.)	−6	75%	
	15	12		Average

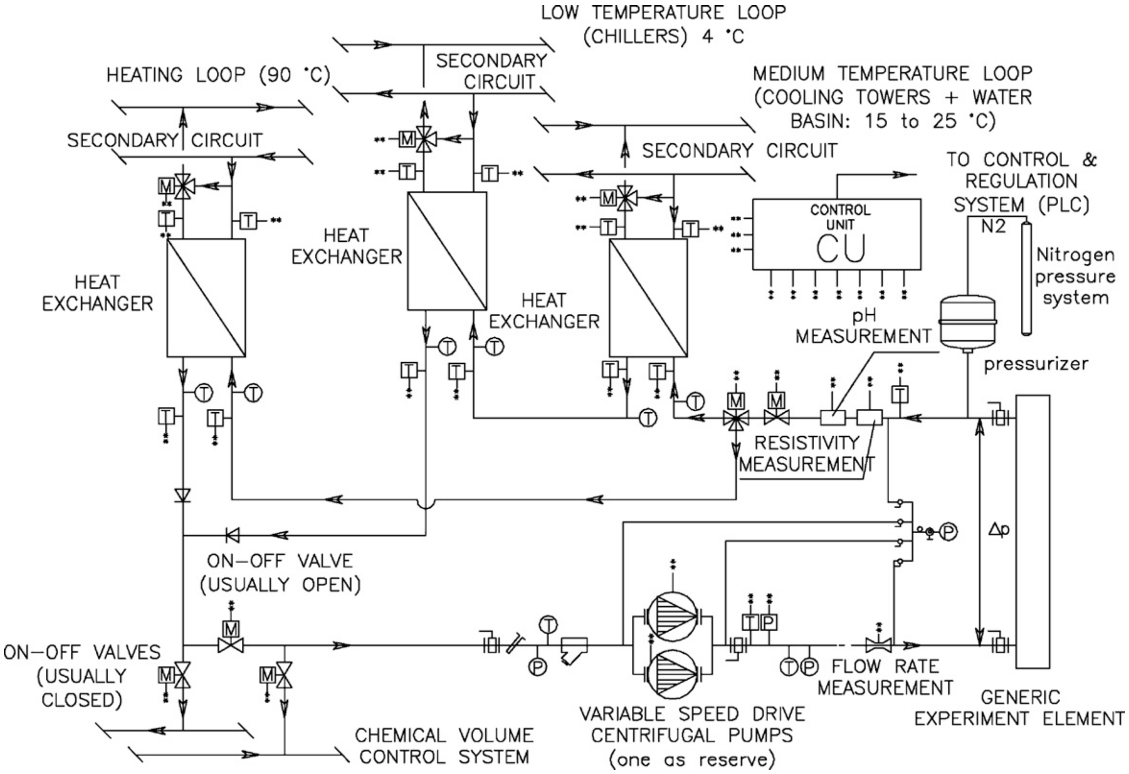

Fig. 1. Primary loop of the HNB generic component.

Water absolute pressure is controlled at the hot branch of the primary loop by a pneumatic pressuriser fed with nitrogen, while the pump head balances the pressure loss. Three ways valves will divert the water flow in the heating heat exchangers (if request during conditioning operation) or in the cooling heat exchangers (pulse operation). The variable thermal power produced by the experiments will be removed by changing the flow rates with variable speed driven pumps in order to maintain almost constant the water temperature rises in the components. The primary inlet water temperature will be adjusted using three ways valves at secondary to bypass the flow rate at the heat exchangers or using two ways valves with variable speed driven pumps.

Primary water resistivity and pH will be continuously measured and monitored; water will be replaced when limit values will be reached (estimated 4 weeks operation). A CVCS with total $5\,m^3/h$ treatment capacity is foreseen to demineralise waste water drained in $60\,m^3$ tanks and to supply ultrapure water to $60\,m^3$ tanks interfaced to all the primary loops (see Fig. 2). The CVCS will consist of two parallel units with UltraFiltration and double stage Reverse Osmosis plus ElectroDeIonization to produce $18\,M\Omega\,cm$ water resistivity at 25 °C.

A DRS and a DS have been designed to carry out the leak detection; a schematic of the system is shown in Fig. 3. The drying procedure consists in the following five phases:

- blowing-out most of the residual water using nitrogen at 20 bar;
- heating-up the primary loops and the in-vessel components with hot nitrogen (up to 150 °C) at 20 bar;

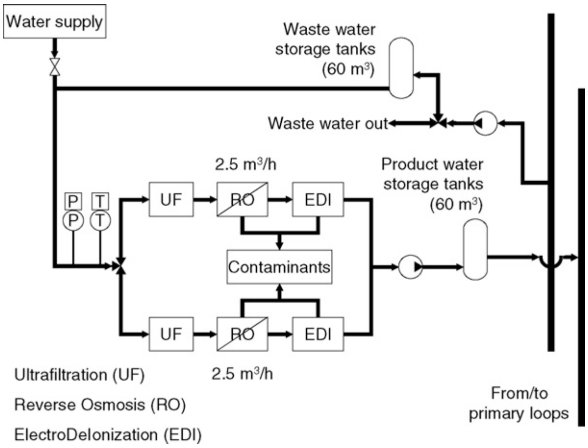

Fig. 2. Schematic of the CVCS interfaced with the PHTS.

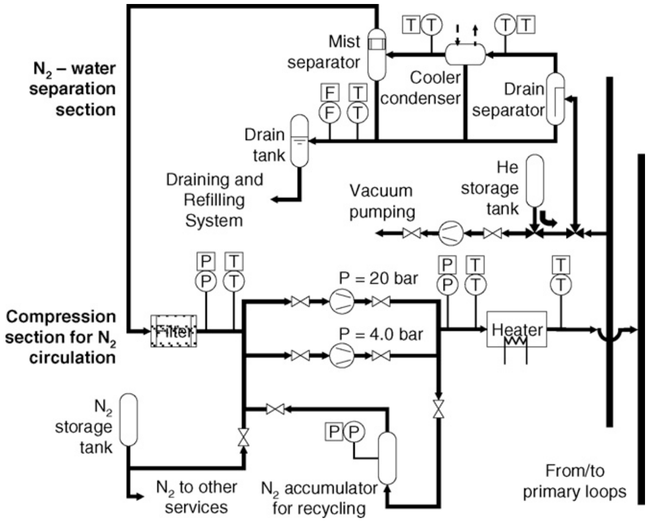

Fig. 3. Schematic of the DS interfaced with the PHTS.

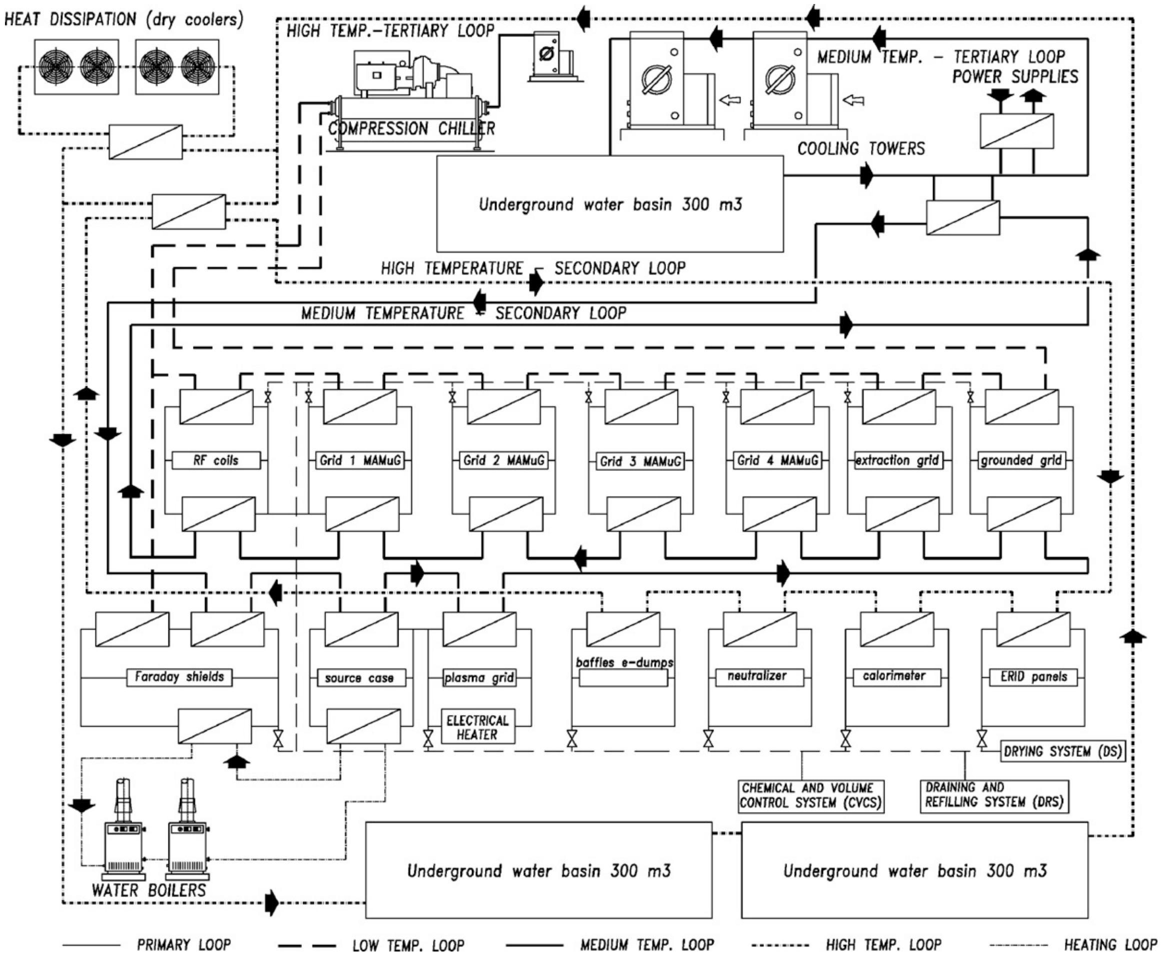

Fig. 4. SHTS and THTS for the HNB.

- drying-out the piping by evaporation of the remaining water with hot nitrogen at reduced pressure (4 bar);
- pumping-out the nitrogen from the piping (down to 10 mbar);
- pressurising the primary cooling loop with He at 3 bar to carry out the leak detection with a spectrometer.

CVCS, DS and DRS are common supporting systems in the PHTS. The material selected for construction of the PHTS and supporting systems is AISI316L to reduce the release of contaminants in demineralised water.

3.2. Secondary and tertiary heat transfer systems

Each group of experiment components will be cooled by common secondary loops depending on the primary water inlet and outlet temperatures. Only one secondary loop at medium temperature (MT) is necessary for IS (see Table 1); it will transfer thermal power to a tertiary loop that will be connected to a water basin coupled to cooling towers in open circuit. In this way, it is possible to guarantee 35 °C as maximum inlet temperature at each component, taking account of worst-case climate conditions at the construction site in Padua as shown in Table 3.

Three secondary loops covering different temperatures ranges are foreseen for HNB heat rejection system (see Fig. 4): low temperature (LT) chillers loop with 8–25 °C range, MT cooling towers loop with 25–45 °C range, high temperature (HT) dry coolers loop with 45–120 °C range. The thermal range required for each component is guaranteed by heat exchangers that will be disposed in series at the primary and connected to different loops at the secondary.

Main hypotheses on the pulse length during daily experimental campaigns are:

1. 400 s is the maximum length of a pulse for IS or HNB in any weather conditions and with repeatable 1/4 duty cycle, named short pulse operation mode;
2. 3600 s is the maximum length of a pulse for HNB during winter, named long pulse operation mode; the pulse operation can start again after the initial temperature of basins water will be reached.

The thermal powers that have to be rejected by the CS considering the experiments operation modes and temperature ranges are shown in Table 4. The cooling power requested by the experiments power supply will be removed by MT cooling loops.

The pulsed thermal power generated by the experiments will be transferred from the primary to the secondary and tertiary loops.

Table 4
Rejected thermal powers by temperature range.

Operation mode	Rejected thermal power			
	P_{LT} (MW)	P_{MT} (MW)	$P_{MT_{\text{power supplies}}}$ (MW)	P_{HT} (MW)
Short pulse IS	–	8.0	1.4	–
Long pulse HNB	5.8	6.4	3.2	45.7

Table 5
Cooling machines installed powers.

Cooling machine	Installed power (MW)	Operative conditions
Chillers	6.0	$T_{wb} = 12\,°C$, $T_{inlet} = 10\,°C$, $T_{outlet} = 4\,°C$
Cooling towers	6.5	$T_{wb} = 12\,°C$, $T_{inlet} = 27\,°C$, $T_{outlet} = 21\,°C$
Dry coolers	9.0	$T_{db} = 15\,°C$ (max.)

Then it will be stored in water basins and finally rejected in the environment by cooling machines.

Using storage basins at the THTS and limiting the HNB pulse length during summer, the installed power of heat rejection machines will be reduced with respect to the peak pulse power. In fact, the performance of cooling towers depends on the external climate conditions, especially on the wet bulb air temperature. The capacity of storage basins results by minimising the total costs of heat rejection machines (chillers, cooling towers and dry coolers) and buildings and considering the operating costs of the CS. The total basins capacity will be 900 m^3 in order to satisfy the HNB cooling requirements of long pulse operation mode; the tertiary MT cooling towers loop will be connected to 300 m^3 water basin and the tertiary HT dry coolers loop will be connected to 600 m^3 water basin. Only a 300 m^3 basin capacity will satisfy IS operation, whereas the whole capacity will be used for both the facilities during short pulse operation. The cooling machines installed powers have been determined in order to utilise the above basin capacities and to satisfy the HNB long pulse operation mode (see Table 5).

It has been verified that short pulse operation mode is guaranteed in any weather conditions, in particular during summer, and with repeatable 1/4 duty cycle.

4. Conclusions

The conceptual design and plant configuration of the cooling system (CS) for the Neutral Beam test facilities have been carried out the environmental conditions of the construction site in Padua.

The necessity of a secondary heat transfer system as confinement barrier is presently under revision considering the estimated release of tritium and corrosion contaminants diluted in the primary water of the components. The SHTS removal will simplify the CS and will significantly reduce costs and overall dimensions. Safety requirements can be satisfied using double plate heat exchangers for the calorimeters. Other simplifications (e.g. common heat exchangers) are under consideration producing cheaper solutions.

Thermohydraulic simulations of the CS in steady state and transient conditions will be carried out for performance and safety analyses. Different operative conditions for water basins are expected and assumptions about temperature ranges will be verified with further numerical simulations.

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