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Thermal-hydraulic assessment of the ITER IBED PHTS

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ABSTRACT

One of the key elements for the success of ITER is the efficient removal of the thermal power generated by the deuterium-tritium fusion reaction within the confined plasma. The Integrated Blanket ELM/VS Coils and Divertor (IBED) Primary Heat Transport System (PHTS) is a pressurized, closed-loop cooling system designed to supply cooling water to the in-Vessel components. To support process design of the IBED PHTS, a thermal-hydraulic research campaign has been conducted to analyse the proper operation of the system during selected operational scenarios. The work has been carried out using the commercially available thermal-hydraulic software AFT Fathom, performing steady-state hydraulic and heat transfer analyses of complex hydraulic systems. The present paper summarizes the research activity, describing the computational model used and the scenarios investigated, as well as the results obtained and their critical discussion.

1. Introduction

The ITER reactor is called upon to bridge the gap between the current small-scale experimental fusion devices and the demonstration fusion power plants of the future. Scientists will be able to study plasmas under conditions similar to those expected in a future power plant and test technologies such as heating, control, diagnostics, cryogenics and remote maintenance.

In particular, the main objective of ITER is to demonstrate the feasibility of a burning plasma and test the availability and integration of key technologies for a fusion reactor, such as superconducting magnets, remote maintenance and plasma energy exhaust systems, and the viability of tritium breeding module concepts that would lead to tritium self-sufficiency in a future reactor.

ITER is designed to produce ten times more power ($Q = 10$) under nominal operating conditions than that delivered to the plasma, i.e. 500 MW of fusion power from 50 MW of input heating power. Therefore, although ITER is not designed to convert the thermal energy produced into electricity, it needs to be equipped with an adequate cooling system to control the temperatures of the main in-vessel and ex-vessel components effectively and efficiently.

In this respect, ITER is provided with a Cooling Water System (CWS) which consists of four sub-systems: the Tokamak Cooling Water System (TCWS), the Component Cooling Water System (CCWS), the CHilled Water System (CHWS) and the Heat Rejection System (HRS) [1].

The TCWS consists of a set of cooling loops designed to transfer thermal power from tokamak client systems to the CCWS and then to the environment through the HRS. The Integrated Blanket ELM/VS Coils and Divertor Primary Heat Transport System (IBED PHTS) is part of the TCWS and is a pressurized closed-loop cooling water system whose main function is to supply cooling water to in-Vessel components [2,3], i.e. the Blanket Modules (BMs) and Divertor Cassettes (DIV) as well as the Edge Localized Modes (ELM) and Vertical Stabilization (VS) coils and other clients located in the Upper Ports (UPs), Equatorial Ports (EPs) and Lower Ports (LPs) of the machine. In addition, the piping and components of the IBED PHTS provide the primary confinement for the radioactive material and must maintain watertight integrity during all modes of operation [2].

In this context, the University of Palermo has carried out a research campaign aiming at assessing the main thermal-hydraulic parameters of the IBED PHTS under selected operational scenarios. The activity has been based on the use of the AFT Fathom 9 lumped-parameters code [4].

Specifically, the first phase has been mainly devoted to updating the geometry of the current IBED PHTS Fathom model provided by IO to make it consistent with the latest plant layout developments. In addition, the pressure drops, required flow rates, and powers associated with each of the in-vessel components as well as the set-points of each client control valves, flow coefficients, and inherent characteristics of each valve in the model have been updated. Then, in a second step, the

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Abbreviations

BM	blanket module
CCWS	component cooling water system
CDL	connect duct liner
CHWS	CHilled water system
CVCS	chemical and volume control system
CWS	cooling water system
DIV	divertor
DL	duct liner
ECH&CD	electron cyclotron heating and current drive
ELM	edge localized modes
EP	equatorial port
FW/BLK	first wall/blanket
GDC	glow discharge cleaning
HRS	heat rejection system
HX	heat eXchanger
IBED	integrated blanket ELM/VS coils and divertor
ICH&CD	ion cyclotron heating
IO	ITER organization
IS	interface sheet
IVC	in-vessel coils
LP	lower port
NBI	neutral beam injector
NPSHA	net positive suction head available
PBS	plant breakdown structure
PHTS	primary heat transport system
PRZ	pressurizer
TBM	test blanket modules
TCWS	tokamak cooling water system
UP	upper port
UPC	upper pipe chase
VFD	variable frequency drive
VS	vertical stabilization
VV	vacuum vessel

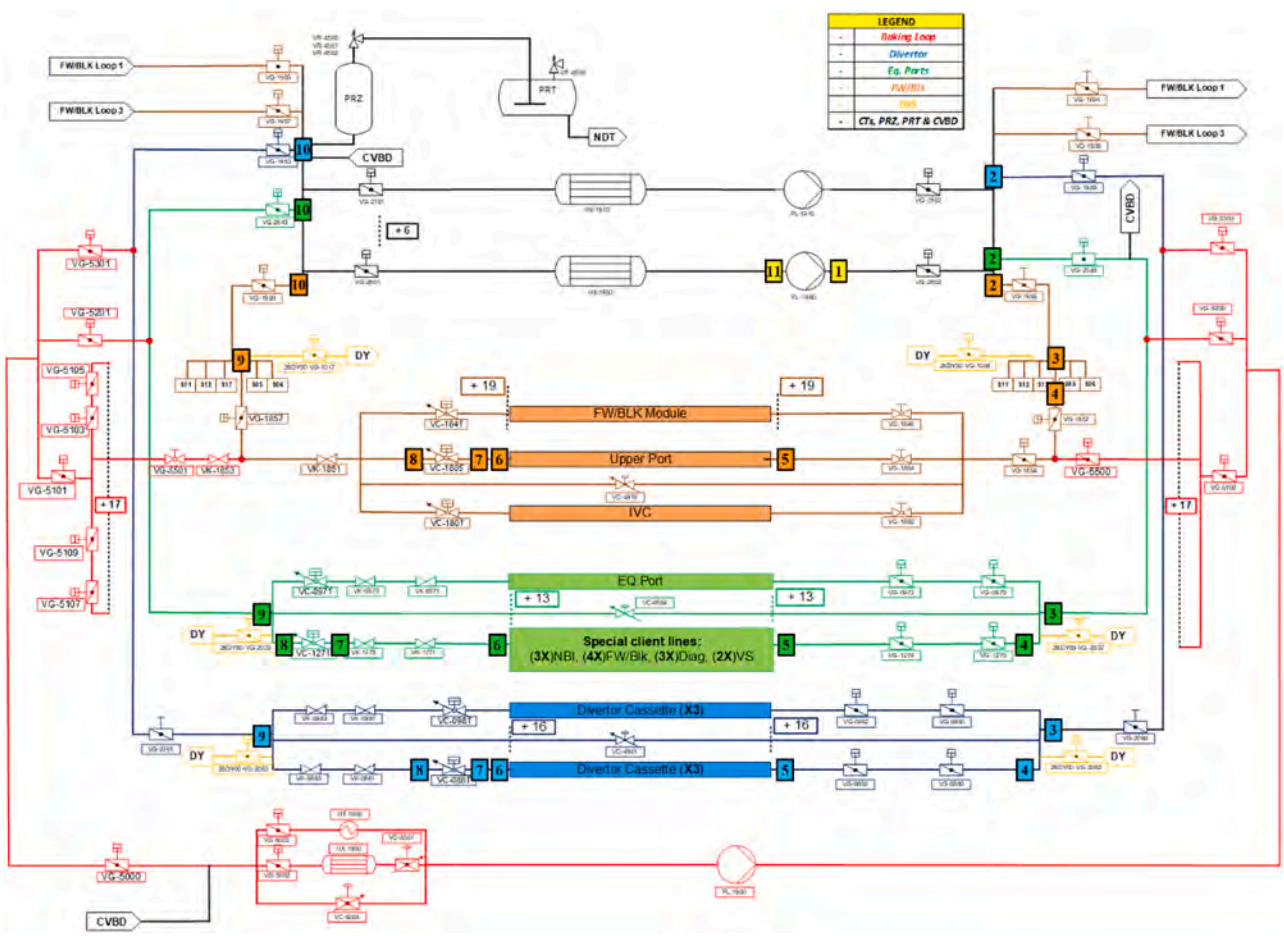

Fig. 2.1. IBED PHTS simplified diagram [2].

selected operational scenarios have been defined in agreement with the IBED PHTS designers and have been investigated.

The present paper summarizes the research activity, describing the computational model used and the scenarios investigated, as well as the results obtained and their critical discussion.

2. The ITER IBED PHTS

The key functional requirement of the IBED PHTS is to provide cooling water to the in-vessel components and to bake the in-vessel components at 240 °C [3,5,6]. The main components of the IBED PHTS, shown in Fig. 2.1, are the pumps, the heat exchangers, the baking

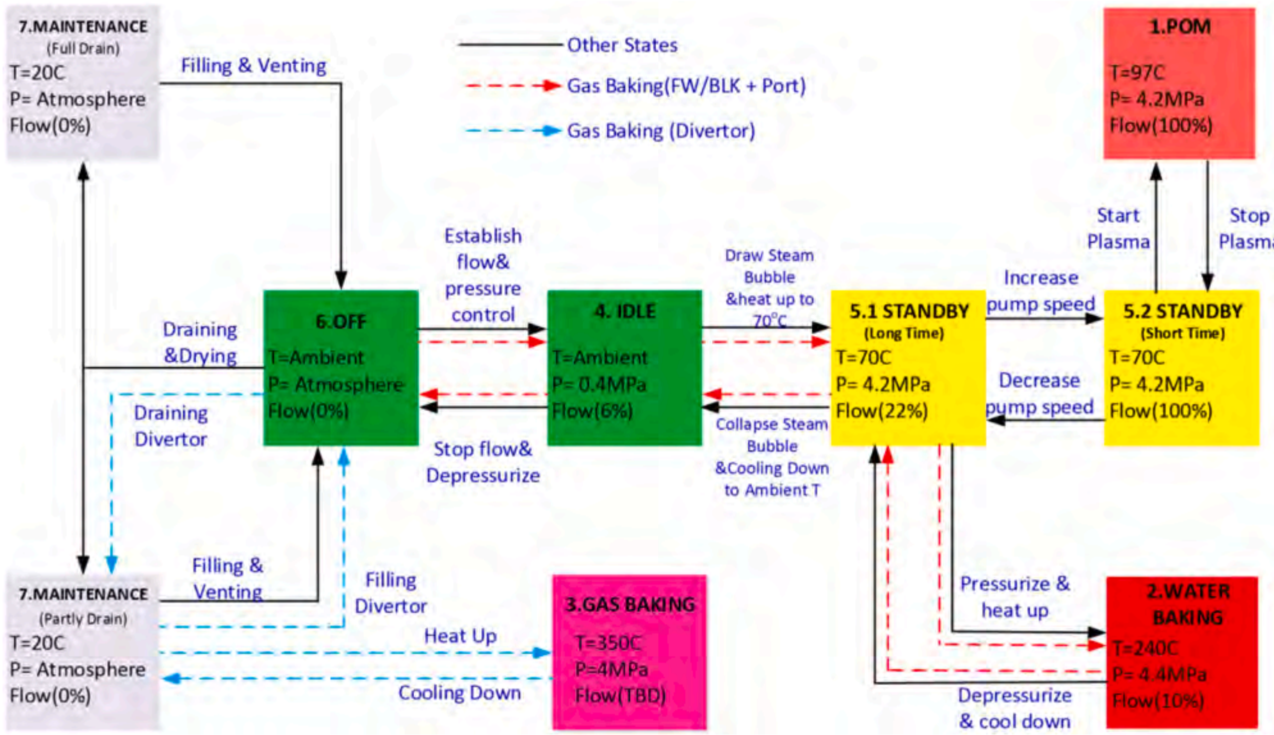

Fig. 2.2. IBED PHTS transitions between operation modes.

heater, and the pressurizer (PRZ).

The client systems having interfaces with IBED PHTS are divided into four types: FW/BLK, DIV, In-Vessel Coils (IVCs) and Port Plug Components [2]. There are 18 ports at the upper level of the machine, 14 regular and 3 Neutral Beam Injector (NBI) ports at the equatorial level, and 9 ports and 18 local penetrations at the lower level [7]. The IBED PHTS supplies cooling water to in-Vessel components via five loops; three of them deliver water to the First Wall/Blanket (FW/BLK), Upper Ports and ELM/VS coils while the other two cooling circuit are devoted to feed the DIV cassettes and the EP components. In addition, the loop for EPs cools the duct liner and connecting duct liner of NBIs, the lower diagnostics and VS coils and some FW/BLK modules served thorough the Lower Ports.

They are all connected to a common set of eight parallel cooling trains [2] through a common supply and return header. Each primary train contains a heat exchanger and a main pump. The heat extracted from the IBED PHTS is rejected to the HRS through the CCWS-1 cooling loop. In addition to the eight primary cooling trains, there is a separate baking train containing a baking heater, a baking heat exchanger, a baking pump and the associated piping and valves [2]. The baking pump is intended also to provide freeze protection flow for the IBED PHTS systems, circulating water at a low flow rate to prevent water from stagnating and thus freezing. The baking train is connected to a separate baking loop header, which serves the IBED PHTS clients connected to the three FW/BLK loops and to the same Equatorial loop and DIV loop also used for plasma operation. Fig. 2.1 shows a simplified schematic of IBED PHTS in which the pressure probing sections that will be referred to in section 4 are also indicated.

The IBED PHTS is equipped with a PRZ which, in combination with a Chemical and Volume Control System (CVCS), controls system pressure and water volume during operations [2]. The PRZ of the IBED PHTS is connected to the hot section of the system, upstream of the main heat exchangers and pumps. Connections to the CVCS are provided to control the water chemistry within the system. Connections are also provided to allow emptying, filling, drying and gas baking.

The IBED PHTS is expected to operate in seven different modes [2]:

1. *Plasma Operation Mode (POM)*: a constant flow rate is maintained through the main pumps, in-vessel components, and main heat exchangers. A supply temperature of 70 °C is maintained for the in-vessel components [3]. This operation mode presents three variants: inductive, hybrid and non-inductive. Each mode has different requirements in terms of heat removal and pulse length. The inductive mode of operation represents the maximum plasma power scenario among the three basic plasma scenarios [5] and, therefore, the resulting steady-state thermal-hydraulic conditions should be used to establish the maximum heat removal requirements.
2. *Water Baking Operation Mode*: the system provides water at 240 °C for baking the FW/BLK modules, DIV cassettes, In-Port components, and ELM/VS coils [3]. The baking pump circulates fluid through the system and the baking heater is used to heat the system. During the water baking operation, the total system is in water solid condition, i.e. the system is filled with liquid water and the pressure control function is performed by the CVCS. System pressure is increased above the saturation pressure to maintain a sub-cooling margin. When the system is under heating up, the temperature control is done by tuning the electric power of the baking heater. Heat up to baking temperature must be accomplished within 48 hrs and the temperature rise during heat up is limited to 5 °C per hour. When the system is under cooling down conditions, the temperature control is performed by a bypass line to change the flow to the baking heat exchanger. The system is cooled from baking temperature to operating temperature within 24 hrs at a maximum rate of 7 °C per hour, by circulating water through the baking heat exchanger.
3. *Gas Baking Operation Mode*: the DIV loop is isolated, drained, and filled with nitrogen gas. During gas baking operations in the DIV loop, the rest of the IBED PHTS is under water baking mode to keep thermal stresses and heat losses at minimum levels.
4. *Idle Mode*: the system is removing a small amount of decay heat or is circulating flow to prevent freezing that would occur due to the heat loss to the cryostat. There is no plasma heat to be removed during this operation mode. Water for freezing protection will be circulated using the baking pump. The system is water-solid in this mode of

Table 2.1
Thermal-hydraulic requirement for IBED PHTS [2,3].

Thermal-hydraulic parameters	Plasma operation	Baking
Max thermal power requirement [MW]	~880	0
Coolant inlet temperature [°C]	70(+/−5)	240(−5/+0)
Coolant outlet temperature [°C]	≤126(+10)	
Coolant inlet pressure [MPa]	4.0(−0.2/+0.6)	4.4(+/−0.4)
Max allowable client pressure drop [MPa]	1.29	–
Mass flow rate [Kg/s]	>4764	~476
Max. cool-down time [h]	–	24
Max. heat-up time [h]	–	48

Table 2.2
IBED PHTS thermal power breakdown under inductive plasma operation.

Source	Power [MW]
FW/BLK, in-port components, and DIV	847
In-vessel coils (ELM/VS)	12.5
Pumps power to coolant	~20
Total	~880

operation since the pressurizer is not available. The CVCS provides both pressure and volume control during this mode and can process coolant at its reduced capacity.

5. *Stand-by Mode*: it is initiated just prior to entering a POM. The stand-by mode of operation is for intervals between periods of plasma operation. This mode includes long interval standby and short interval standby. For short standby intervals, the 8 main pumps will be operated to provide the nominal flow rate to the in-vessel components. For long standby intervals, to save electrical power, all 8 main pumps will run at their minimum speed to ensure freeze protection. If necessary, the pump speed can be increased via the Variable Frequency Drive (VFD) to cope with the increased decay heat load. The system pressure will be controlled by means of the IBED PHTS PRZ set to the normal plasma operating pressure set point. The fluid temperature will be kept at 70 °C to allow for a quick transition into plasma operating mode.
6. *Off Mode*: is activated when the active management of decay heat is no longer required and freeze protection is no longer needed, or in off-normal events where the flow of cooling water is stopped or unavailable.
7. *Maintenance Mode*: all or part of the IBED PHTS is drained, dried if necessary and secured as required for maintenance. The TCWS provides the capability to drain and dry client systems so that leak localization and maintenance can be performed. The system is depressurized at ambient conditions, including the PRZ, and cooling water is isolated to the heat exchangers. The PRZ which is not water solid is used to control the pressure. Alternatively, the CVCS can be applied for pressure control when the PRZ is under maintenance. Therefore, the PRZ and CVCS cannot perform the maintenance at the same time. Upon completion of the maintenance activity, the system integrity is restored, checked and the system filled during the transition to the Off Mode.

In Fig. 2.2 the transitions between the operation modes of IBED PHTS are shown.

The main thermal-hydraulic requirements for IBED PHTS are listed in Table 2.1 [2,3].

During long time standby and idle mode, a minimum flow for the freeze protection is required [2].

The total thermal load that needs to be removed by the IBED PHTS is 880 MW [3,5], and it is distributed according to the breakdown given in Table 2.2 under inductive plasma operation.

The total heat load for the FW/BLK, DIV, and In-Port Components is 847 MW under inductive plasma operation, but the distribution of heat load during plasma operation will depend upon the experiment being performed. In this respect, IO has identified two limiting operating scenarios. Such scenarios denoted as A and B assume that the power deposited on the Divertor and the power deposited on the FW/BKT, respectively, are maximized [8]. The thermal load breakdown under the two nominal cases is given in Table 2.3.

Table 2.3
Thermal load distribution under inductive plasma operation.

Scenario	FW/BLK	Port-Plug	DIV	Total
A (Max DIV)	639 MW	54 MW	154 MW	847 MW
B (Max FW/BLK)	678 MW	58 MW	111 MW	847 MW

3. Fathom model of the IBED PHTS

The present activity has been carried out adopting the thermal-hydraulic model of the IBED PHTS developed by the IO to simulate its behaviour under steady-state conditions using the AFT Fathom 9 lumped-parameters code.

As already mentioned, the main focus has been initially on verifying and updating the current Fathom model, especially with regard to the pressure drops, target mass flow rates and thermal powers associated with each of the in-vessel clients, as well as the setpoints of the corresponding flow control valves together with the valve flow coefficients (Cvs) and characteristic curves of the latter and of all the other valves belonging to IBED PHTS. In addition, the geometry of the region dedicated to feeding NBIs within the EP loop of the model provided by the IO has been updated to make it consistent with the latest Piping & Instrumentation Diagrams (P&IDs) [9] and isometric drawings.

In IBED PHTS, almost all pipes are sized to maintain velocities below 9 m/s. However, some pipelines can be sized for lower velocities to reduce pressure losses in certain parts of the system. The pipe routing in the Fathom model is consistent with the latest isometric drawings. The equivalent hydraulic roughness of the pipelines has been assumed to be 15 μm [10].

The key bend and elbow details (i.e. number of bends, radius of curvature and angle of curvature) have been included in the Fathom model in accordance with the latest design developments of IBED PHTS in order to accurately predict pressure losses within the circuit. Detailed tee components are used in the Fathom model to provide a more accurate estimate of pressure losses through these joints. Cross-sectional variations are always simulated as conical transitions.

Each in-vessel client has been simulated by means of the heat exchanger component within the Fathom model of IBED PHTS.

The mass flow rates required by the clients have been taken from the relevant interface sheets (ISs) [11,12,13,14,15,16,17,18,19,20,21] or from other documents made available by the clients when available or required. The same mass flow rate has been assigned as setpoint to the corresponding control valve.

On the other hand, the pressure drop at the required mass flow rate has been derived from the results of steady-state 3D CFD analyses made available by the clients themselves. In those cases where such results were not yet available, the pressure drop at the required mass flow rate has been assumed to be equal to the maximum pressure drop made available by IBED PHTS and typically reported in the relevant interface sheets. These data are entered as points in Fathom and are extrapolated according to a quadratic characteristic curve. In this way, the dependency of the pressure drop across the client on the mass flow rate can be simulated.

As far as the adopted thermal loads are concerned, the distribution of heat loads in the in-vessel clients for each of the two above-mentioned scenarios has been drawn from documents made available by the clients themselves. In cases no information on this was available, these values have been conveniently inferred from the data available.

The FW/BKT loops feed 359 out of the 363 circuits of the ITER Blanket. The FW/BKT loops also feed the UPs and IVCs. Due to the

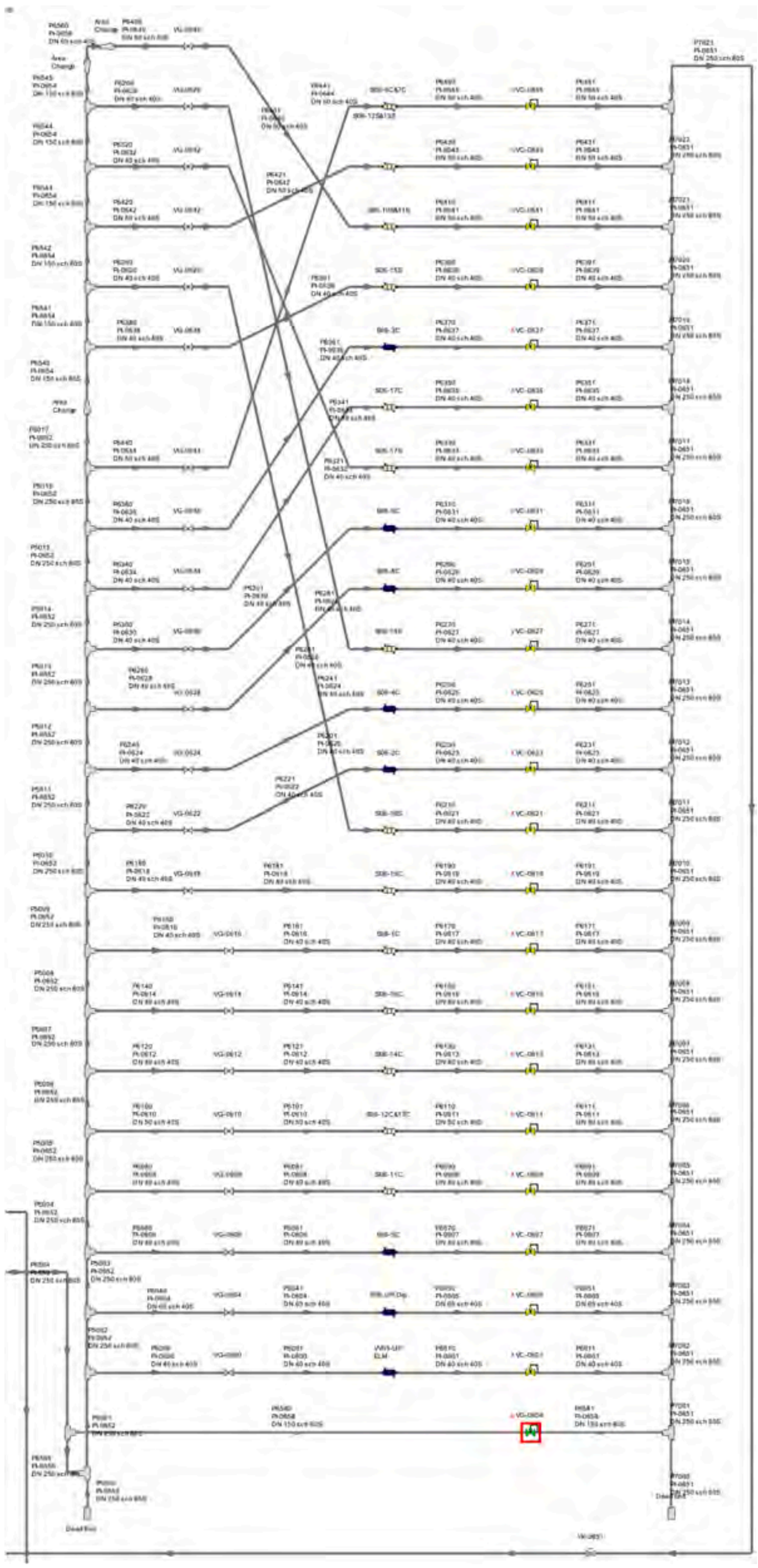

Fig. 3.1. Fathom model of Blanket sector #6.

enormous complexity of these systems, only two out of eighteen Blanket sectors have been simulated in detail, namely sector #6 and #10, while the others have been collapsed into equivalent components. The Fathom model of Blanket sector #6 is reported in Fig. 3.1.

Since the 3D thermal-hydraulic analyses of the BMs are still in progress, only a limited number of pressure drop values under nominal conditions are available [22]. Details on the methodology adopted for the 3D thermal-hydraulic analyses of the BMs may be retrieved from [23,24]. For modules whose pressure drops at nominal conditions are not available, this has been assumed to be equal to the maximum

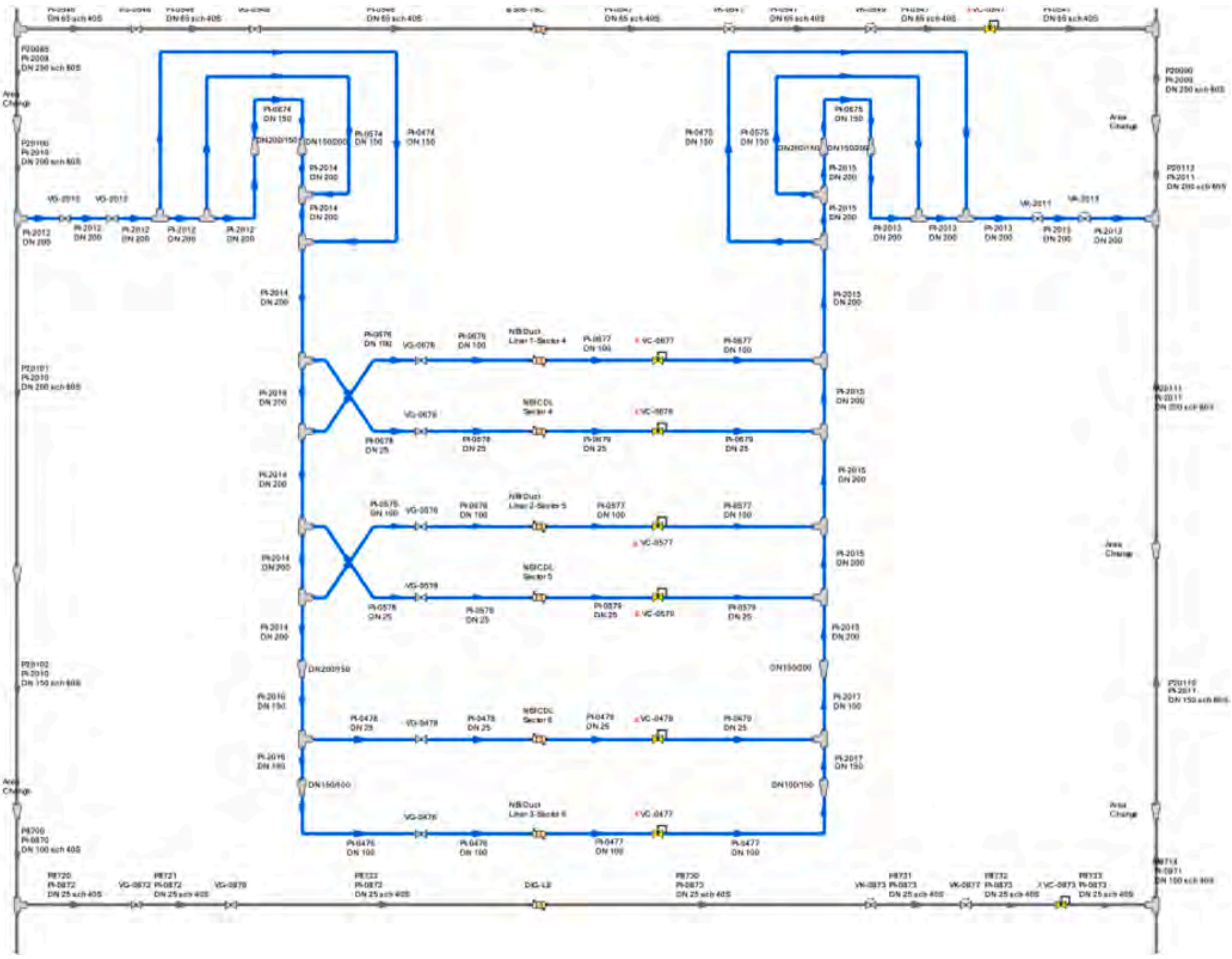

Fig. 3.2. Detail of the Fathom model of the EP loop.

pressure drop available as reported in [15], i.e. 1.29 MPa. Conversely, for the equivalent collapsed sectors, the pressure drop at nominal conditions has been assumed to be equal to 1.35 MPa [2].

As far as the thermal loads on the port plugs (W_{Ports}) are concerned, it is worth highlighting that they have been distributed among all the components located in the ports using as scaling factors the maximum heat loads reported in the corresponding interface sheets (W^i_{IS}) according to the formula $W^i = W_{Ports} W^i_{IS} / \sum W^i_{IS}$, since there so far were no documents indicating the actual heat loads deposited in these components during the considered scenarios.

The EP loop feeds besides the EPs also the Lower Port Diagnostics, the Lower VS Coils and the so-called “special clients”, i.e. four Blanket circuits and the NBIs. The mass flow rates required by each client have been taken from the relevant interface sheets. In the case of components fed in parallel, the sum of the mass flow rates of the components served by the same flow control valve has been assigned as setpoint to this latter. The pressure drop at the mass flow rate required by each client has been mostly derived from the corresponding interface sheets. Fig. 3.2 shows a detail of the Fathom model of the EP loop including the section devoted to feeding the NBIs which is highlighted in light blue.

The Divertor loop feeds the 54 Divertor cassettes through the Lower Pipe Chase. The mass flow rates required by the different Divertor cassettes are the same and their value has been derived from the relevant interface sheet [16]. The pressure drop at the required mass flow rate has been extracted from the interface sheet, which prescribes a value of 1.35 MPa [16].

Each flow control valve in the Divertor loop serves a group of three cassettes. Therefore, the setpoints of these valves have been set so that each of the 54 Divertor cassettes can be fed the minimum required flow rate at least [16]. Fig. 3.3 shows a detail of the Fathom model of the Divertor loop including three groups of cassettes.

Regarding the thermal loads on the Divertor, the thermal power deposited in the individual cassette has been calculated by dividing by the number of cassettes the values given in Table 2.3 for each of the two load scenarios considered, having assumed that all 54 cassettes are identical to each other.

Valve flow coefficients have been verified and updated based on the list of fully open Cvs provided by IO [25]. Specifically, isolation valves and check valves are modelled with a constant “User-specified” Cv while control valves are modelled as valves that adjust their Cv based on a target mass flow rate between zero and a user-specified maximum value associated to the fully open valve. For each scenario investigated, the degree of opening of each control valve was derived from the flow coefficient resulting from the Fathom calculation by interpolation of the data provided by IO [26] when available, while for all other cases an equal-percentage characteristic curve was assumed. Figs. 3.4 and 3.5 show as an example the comparison between the data agreed with IO and their interpolation for the DN25 and DN100 control valves, respectively.

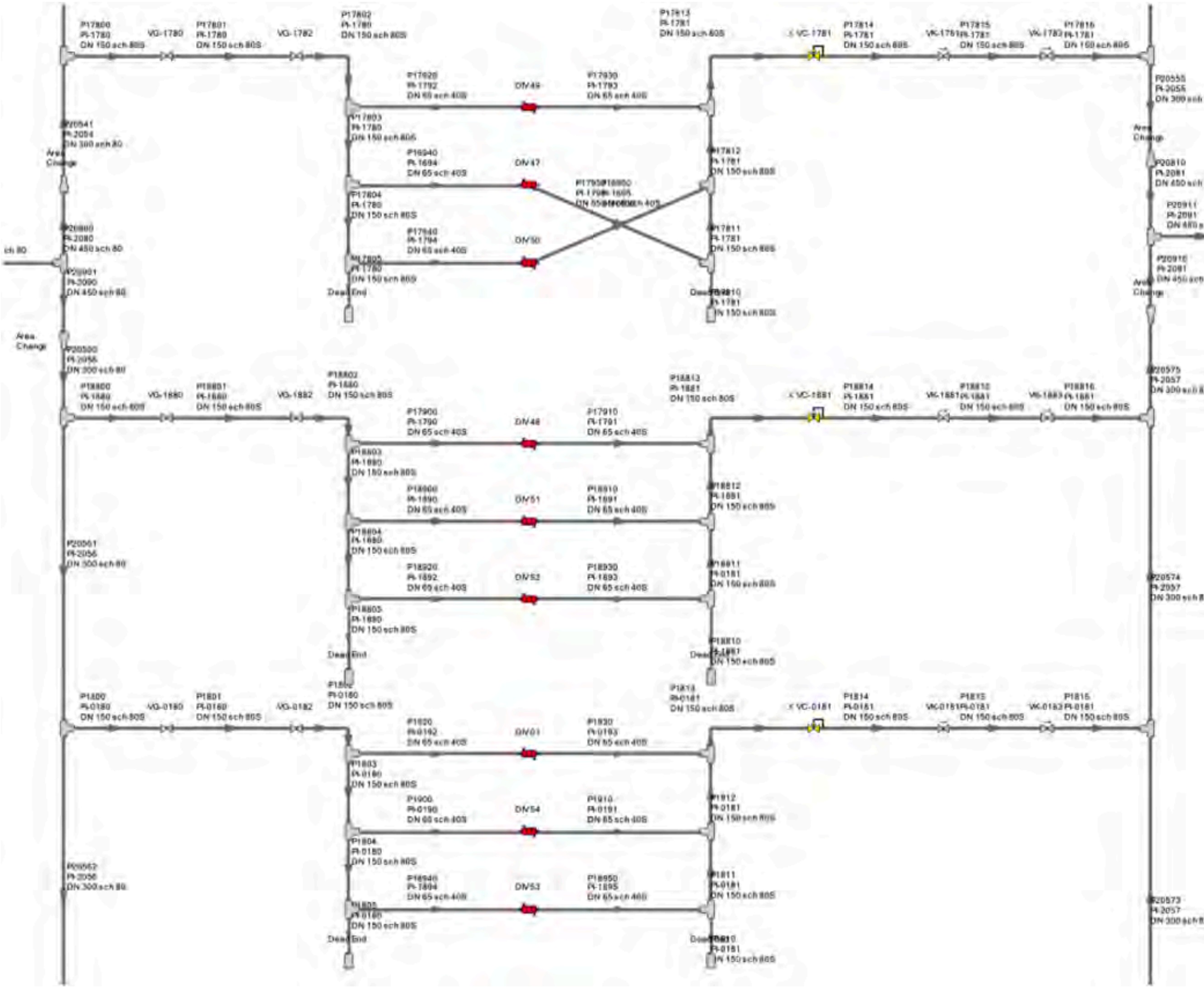

Fig. 3.3. Detail of the Fathom model of the Divertor loop.

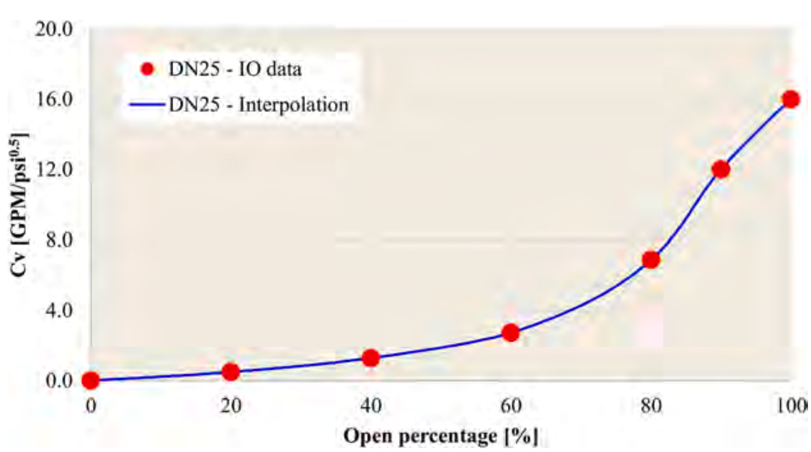

Fig. 3.4. Characteristic curve of DN25 control valves.

4. Thermal-hydraulic analysis campaign

In order to assess the system behaviour under steady-state conditions, three main scenarios have been selected in consultation with the IBED PHTS design team: one simulating the standby mode and the other two simulating the limiting operating conditions assumed in [8]. The fluid properties used for the various cases have been obtained from the Fathom database, which is based on the ASME steam tables. The present

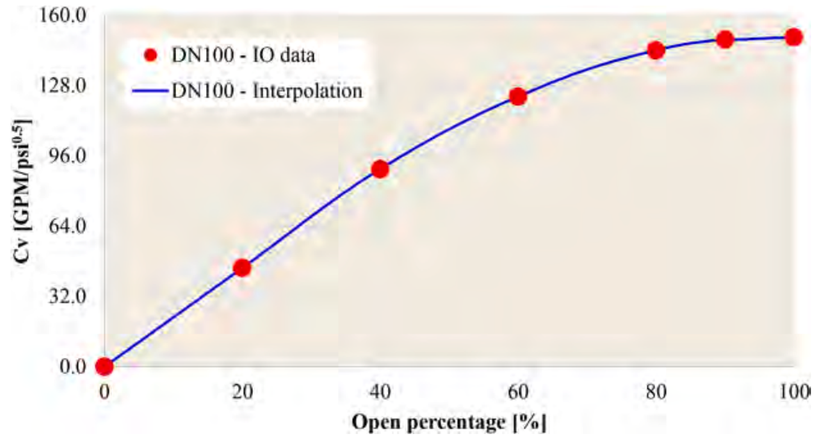

Fig. 3.5. Characteristic curve of DN100 control valves.

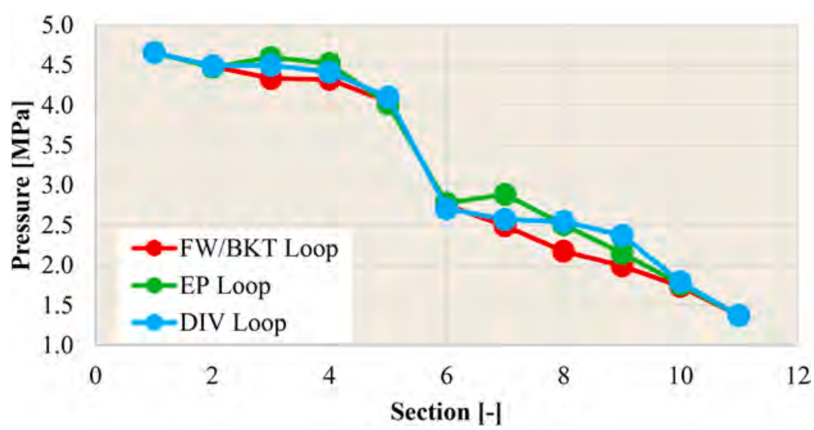

Fig. 4.1. Case 1 pressure profiles.

paragraph reports a detailed description of the investigated scenarios as well as a selection of the obtained results. Furthermore, a comparison of the two nominal scenarios considered is reported as well as a preliminary calculation of the margins to be applied to the design of the main pumps of IBED PHTS.

4.1. Case 1: standby mode

The case has been conceived to provide the sizing requirements for the flow control valves of the clients based on the mass flow rate needed by each client under nominal operating conditions.

All main pumps are set at a constant mass flow rate equal to the sum of all mass flow rates required by the clients plus the mass flow rate that under nominal conditions should go to the CVCS divided by the number of main pumps. The mass flow rate that would flow through each main pump is equal to 596.0 kg/s. It was also assumed that each main pump delivers a thermal power of 2.5 MW to the fluid. In the scenario under investigation, the client flow control valves are modelled in Fathom. The junctions simulating the client flow control valves in the model are set to provide the flow distribution required in each line under nominal operating conditions. For Fathom to operate with a fixed pump flow, a flow path must have a set pressure drop without control, i.e. the valve must remain fully open (100 %). In this case, this flow path belongs to the DIV loop. From this case, the Cvs of the flow control valves for the clients are determined, which is then used in the other two cases.

Table 4.1
Main pump results summary for Case 1.

Name	Q [m^3/h]	H [m]	NPSHa [m]
PL-1910	2190	336.7	164.8
PL-1920	2190	339.6	162.5
PL-1930	2190	342.0	162.7
PL-1940	2190	336.6	164.9
PL-1950	2190	342.1	163.5
PL-1960	2190	337.3	163.3
PL-1970	2190	345.7	157.9
PL-1980	2190	343.6	155.5

Fig. 2.1 shows the pressure profile reference points in the system, while Fig. 4.1 gives the comparison of pressure profiles within the system under the conditions envisaged for Case 1. Specifically, pressure profiles are shown for three flow paths, namely, one flowing through the FW/BKT loop, one flowing through the EPs loop, and one flowing through the DIV loop.

In particular, as far as the flow path flowing through the FW/BKT loop is concerned, the section between points 1 and 2 is from the pump outlet to the linear header (linear header included). The supply header is between points 2 and 3. The section between points 3 and 4 is from the ring header to the jungle gym sub-header. Points 5 and 6 are upstream and downstream of the client. The pressure difference between 7 and 8 gives indications of the pressure drop of the flow control valve located at the outlet of the client. The section bounded by points 9 and 10 contains the return header while the section between points 10 and 11 accounts for the pressure drop from the linear return header to the pump inlet. Similar points have been selected for the EP loop and the DIV loop.

With reference to Fig. 4.1, it should be emphasised that the profiles shown are static pressure profiles and, as such, are closely related to the significant elevation changes that occur within the IBED PHTS loops, as can be seen, for example, in the pressure profile of the EP loop, which

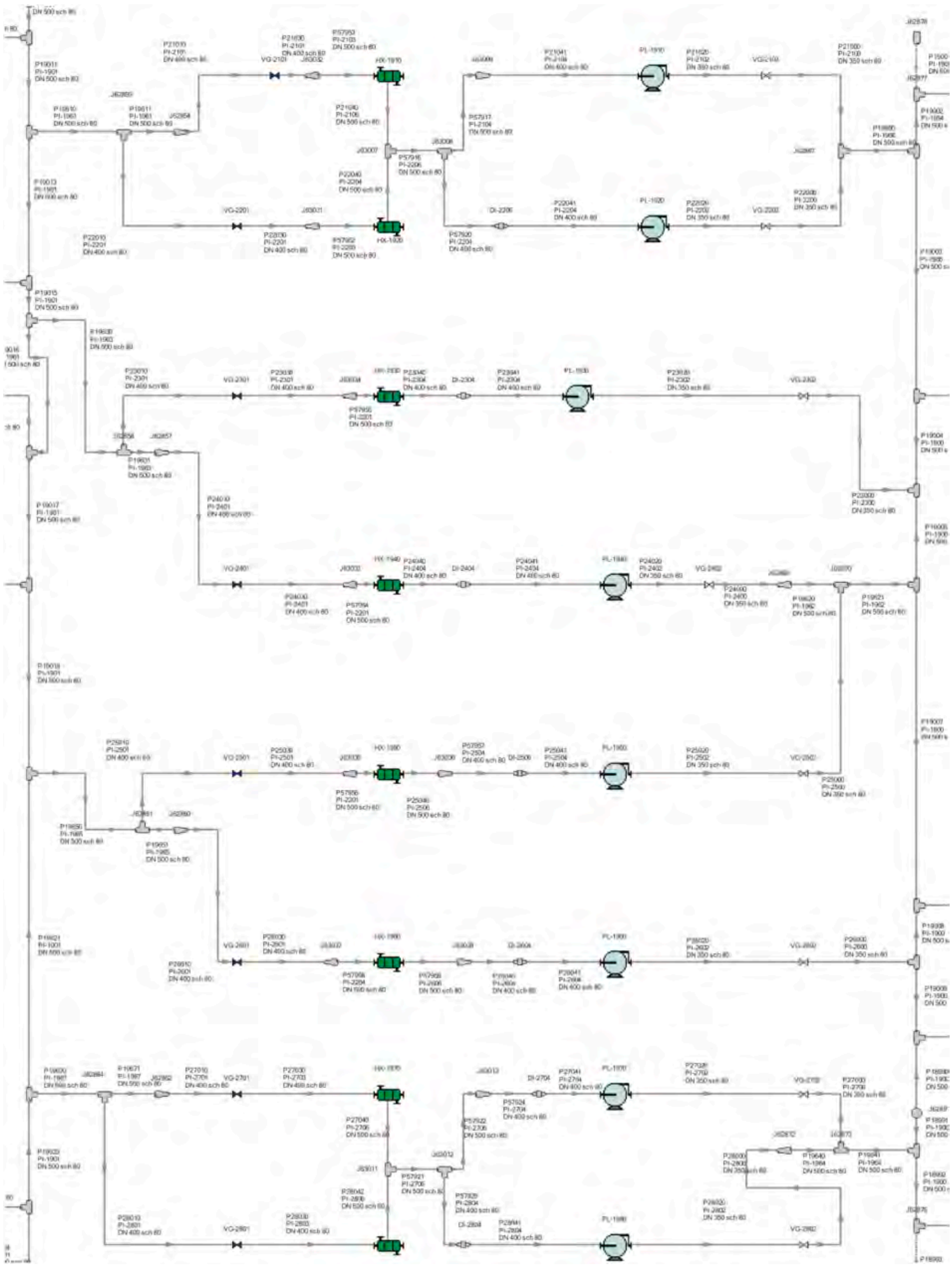

Fig. 4.2. Fathom model of the IBED PHTS cooling trains.

shows an increasing trend between points 2 and 3 and between points 6 and 7, primarily related to the relative elevation change that the fluid experiences between the respective sections.

As already mentioned, the main pumps have been modelled as having a fixed flow rate. In this case, the Fathom code allows the pump head required for that flow rate to be determined. Due to small differences in client loops, each pump requires a slightly different head to meet the flow requirements. The key characteristic quantities, such as

Table 4.2
Heat exchanger results summary for Case 1.

Name	G [kg/s]	p_{in} [MPa]	Δp [MPa]	T_{in} [°C]	ΔT [°C]	W [MW]
HX-1910	630.20	1.686	0.084	71.0	1.0	2.625
HX-1920	561.70	1.670	0.067	71.0	1.0	2.340
HX-1930	596.00	1.627	0.075	71.0	1.0	2.389
HX-1940	596.00	1.653	0.075	71.0	1.0	2.389
HX-1950	596.00	1.622	0.075	71.0	1.0	2.483
HX-1960	596.00	1.633	0.075	71.0	1.0	2.483
HX-1970	635.60	1.605	0.085	71.0	1.0	2.648
HX-1980	556.40	1.585	0.065	71.0	1.0	2.318

the pump head (denoted as "H") and the Net Positive Suction Head Available (NPSHa), are shown in Table 4.1. For the component nomenclature please refer to Fig. 4.2. In this respect, Fig. 4.2 shows the detailed layout of the IBED PHTS cooling trains, i.e. those shown in the diagram in Fig. 2.1 in an extremely simplified form as parallel branches, each equipped with a heat exchanger and a pump. In fact, the diagram in Fig. 4.2 shows a much more complex layout developed by the IBED PHTS designers to facilitate the mixing of the coolant and thus supply the different loops of the IBED PHTS with coolant at a uniform temperature.

From the present case, it is possible to derive the requirements for the sizing of the client flow control valves. The results obtained from the simulation of Case 1 in terms of the Cv of the client flow control valves are used as input for the other two selected cases in which these valves are simulated by adopting constant Cvs. It is worth mentioning that the mass flow rates flowing through most of the clients match exactly the nominal mass flow rates required by them because the flow control valves actively act to ensure the required mass flow rate. On the other hand, as far as the DIV cassettes and some other clients within the EP loop are concerned, the flow control valves are placed on the lines feeding two or three components in parallel and it is for this reason that slight deviations of the mass flow rate from its nominal value have been detected for each of them.

The main heat exchangers have been modelled so that they could ensure a fixed outlet temperature of 70 °C. In this case, the Fathom code enables the mass flow through each exchanger and thus its heat duty to be calculated. Similarly to what has been observed for the main pumps, as a result of the differences in the client loops, each heat exchanger will have to cope with a different heat duty from the others in order to meet the imposed output temperature requirement. The calculated quantities for the main heat exchangers are shown in Table 4.2. For the component nomenclature please refer to Fig. 4.2.

Table 4.3
Main pump results summary for Case 2A.

Name	Q [m^3/h]	H [m]	NPSHa [m]
PL-1910	2190	340.5	164.2
PL-1920	2190	343.5	162.0
PL-1930	2190	346.0	162.0
PL-1940	2190	340.5	164.4
PL-1950	2190	346.1	162.8
PL-1960	2190	341.2	162.6
PL-1970	2190	349.6	157.2
PL-1980	2190	347.6	154.9

Table 4.4
Main pump results summary for Case 2B

Name	Q [m^3/h]	H [m]	NPSHa [m]
PL-1910	2190	340.6	164.3
PL-1920	2190	343.6	162.0
PL-1930	2190	346.1	162.0
PL-1940	2190	340.6	164.4
PL-1950	2190	346.2	162.8
PL-1960	2190	341.3	162.6
PL-1970	2190	349.8	157.2
PL-1980	2190	347.7	154.8

4.2. Case 2A and 2B: plasma operation mode heat load in scenario A and scenario B

Case 2A and 2B have been conceived to derive pump sizing requirements and simulate a realistic plasma operating condition, maximizing respectively the power channelled to the DIV (2A) and to the FW/BLK (2B). However, these cases cannot yet be considered fully realistic because the pumps are simulated as ideal pumps operating at constant flow rate. Nevertheless, cases 2A and 2B can still provide useful hints for the sizing of IBED PHTS main pumps.

It is worth highlighting that, in order to take into account that the flow control valves of the clients should be set under standby conditions, these valves are simulated as valves with constant Cv equal to the value previously calculated for Case 1. Therefore, the mass flow rate that actually flows through each client may exhibit slight deviations from its nominal value because the circuit is at a higher average temperature than in Case 1 due to the power deposited within the clients. Fig. 4.3 reports the pressure profiles within the system under the conditions envisaged for Case 2A. The pressure profiles under Case 2B are almost identical and, therefore, they have not been reported.

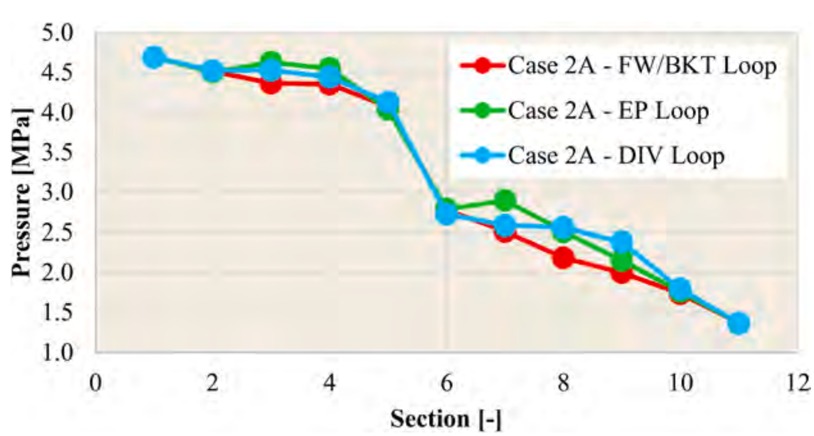

Fig. 4.3. Case 2A pressure profiles.

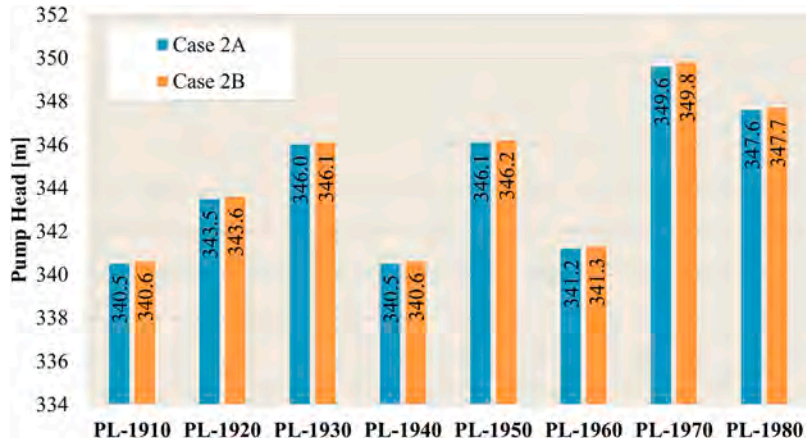

Fig. 4.4. Comparison of pump head distributions between cases 2A and 2B.

Table 4.5
Main parameters of pump head distributions of cases 2A and 2B

Parameter	Case 2A	Case 2B
Maximum value [m]	349.6	349.8
Minimum value [m]	340.5	340.6
Relative maximum variation [−]	2.6 %	2.6 %
Average value [m]	344.4	344.5
Standard deviation [m]	3.5	3.5
Coefficient of variation [−]	1.0 %	1.0 %

Tables 4.3 and 4.4 reports a summary of the results obtained for the main pumps under case 2A and 2B, respectively, while Fig. 4.4 shows the comparison of the pump head distribution among the IBED PHTS main pumps and Table 4.5 reports the main parameters describing the two distributions. For the component nomenclature please refer to Fig. 4.2.

From the analysis of the results, it can be deduced that Cases 2A and 2B are almost identical with the second one appearing to be slightly more demanding in terms of pump head.

The cases considered could provide useful indications also for the sizing of the main heat exchangers. In this regard, Tables 4.6 and 4.7 reports a summary of the results obtained for the main pumps under case 2A and 2B, respectively, while Fig. 4.5 shows the comparison of the heat load distributions among the IBED PHTS main heat exchangers while Table 4.8 shows the main parameters describing the two distributions. For the component nomenclature please refer to Fig. 4.2.

From the analysis of the results, it can be seen that cases 2A and 2B provide deeply dissimilar distributions due to the different distribution of heat loads between the various IBED PHTS loops. Both distributions are strongly asymmetrical with deviations between the minimum and maximum values close to and even greater than 20 %.

5. Conclusions

Within the framework of activities promoted by the IO, the University of Palermo has performed a research campaign aiming at assessing the main thermal-hydraulic parameters of the IBED PHTS under selected operational scenarios. The activity has been carried out at the University of Palermo, adopting the IBED PHTS thermal-hydraulic model already set-up at IO to simulate its steady-state behaviour by means of the AFT Fathom 9 thermal-hydraulic lumped parameter code.

Specifically, the work has been articulated in two consecutive phases. The first phase has been mainly devoted to verifying and updating the current Fathom model, particularly with regard to the pressure drops, target mass flow rates, and thermal powers associated with each of the in-vessel clients, as well as the setpoints of the corresponding flow control valves along with the Cvs and characteristic curves of all the

Table 4.6
Heat exchanger results summary for Case 2A.

Name	G [kg/s]	p_{in} [MPa]	Δp [MPa]	T_{in} [°C]	ΔT [°C]	W [MW]
HX-1910	630.80	1.681	0.084	115.7	45.7	120.9
HX-1920	561.20	1.664	0.067	115.7	45.7	107.6
HX-1930	596.00	1.620	0.075	114.7	44.7	111.7
HX-1940	596.00	1.647	0.075	114.7	44.7	111.7
HX-1950	596.00	1.615	0.075	115.0	45.0	112.5
HX-1960	596.00	1.626	0.075	115.0	45.0	112.5
HX-1970	636.20	1.598	0.086	110.5	40.5	108.0
HX-1980	555.80	1.579	0.065	110.5	40.5	94.4

Table 4.7
Heat exchanger results summary for Case 2B.

Name	G [kg/s]	p_{in} [MPa]	Δp [MPa]	T_{in} [°C]	ΔT [°C]	W [MW]
HX-1910	630.70	1.681	0.084	112.1	42.1	111.4
HX-1920	561.20	1.665	0.067	112.1	42.1	99.1
HX-1930	596.00	1.620	0.075	113.2	43.2	108.0
HX-1940	596.00	1.647	0.075	113.2	43.2	108.0
HX-1950	596.00	1.615	0.075	117.7	47.7	119.3
HX-1960	596.00	1.626	0.075	117.7	47.7	119.3
HX-1970	636.20	1.598	0.086	112.9	42.9	114.5
HX-1980	555.80	1.578	0.065	112.9	42.9	100.1

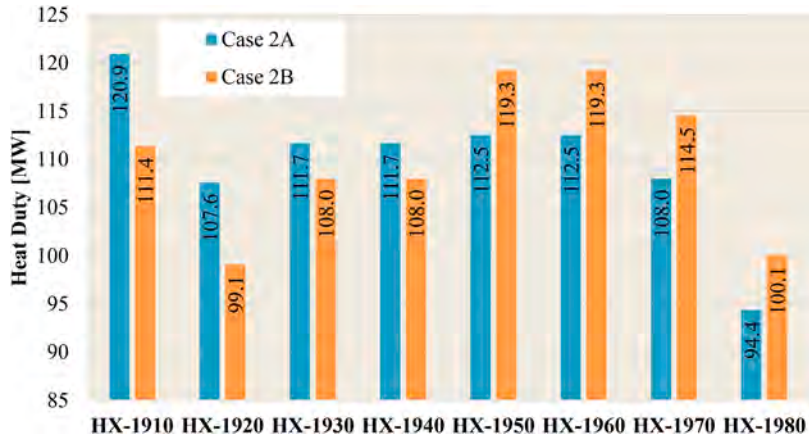

Fig. 4.5. Comparison of HX heat duty distributions between cases 2A and 2B.

Table 4.8
Main parameters of HX heat duty distributions of cases 2A and 2B.

Parameter	Case 2A	Case 2B
Maximum value [MW]	120.9	119.3
Minimum value [MW]	94.4	99.1
Relative maximum variation [−]	22.0 %	16.9 %
Average value [MW]	109.9	109.9
Standard deviation [MW]	7.5	7.7
Coefficient of variation [−]	6.8 %	7.0 %

valves in IBED PHTS.

Moreover, the geometry of an entire region of the model provided by ITER Organization has also been checked and updated in order to make it consistent with the latest plant layout developments.

Then, in a second step, three main scenarios have been selected, i.e. one that simulates hot standby conditions and is used to derive a rough sizing of the client flow control valves, while the other two simulate the limiting operating conditions reported in [8] and should provide indications on the sizing of the main pumps and heat exchangers.

Case 1 has been set up to reproduce conditions similar to those that would be attained within the IBED PHTS under hot standby conditions and it has been conceived to provide the sizing requirements for the flow control valves of the clients based on the mass flow rate needed by each client under nominal operating conditions. The results obtained from the simulation of Case 1 in terms of the Cv of the client flow control valves are used as input for the other two selected cases in which these valves are simulated by means of constant Cv valves.

As far as cases 2A and 2B are concerned, they have been conceived to derive pump sizing requirements and simulate a realistic plasma operating condition.

With regard to the distribution of the pump head, the analyses have shown that cases 2A and 2B are almost identical, with the latter appearing slightly more demanding. On the other hand, as far as the heat load distribution among the heat exchangers is concerned, the analyses have indicated that cases 2A and 2B provide deeply dissimilar distributions due to the different distribution of heat loads between the various IBED PHTS loops. Both distributions are strongly asymmetrical, with deviations between the minimum and maximum values close to and even exceeding 20 %.

However, it must be emphasised that the investigated cases cannot yet be considered fully realistic because the pumps have been simulated as ideal pumps operating at a constant flow rate, so it may be worthwhile to study the distribution of flow rates within the pump train when considering real pumps.

Disclaimer

The views and opinions expressed herein do not necessary reflect those of the ITER Organization.

CRediT authorship contribution statement

E. Vallone: Writing – review & editing, Writing – original draft, Methodology, Investigation. **G. Agnello:** Writing – original draft, Investigation. **L. Basili:** Writing – review & editing, Validation, Supervision, Methodology. **A. Ciampichetti:** Writing – review & editing, Supervision, Methodology. **P.A. Di Maio:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Investigation. **D. Lioce:** Writing – review & editing, Supervision. **A. Quartararo:** Writing – original draft, Software, Investigation. **F.L. Venturi:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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