Analysis of the flow distribution in the Back Supporting Structure manifolds of the HCPB Breeding Blanket for the EU DEMO fusion reactor

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Abstract

The European Demonstration Fusion Power Reactor (EU DEMO) is facing its pre-conceptual design phase. In this phase, the research and development activities make extensive use of computational tools, to e.g. verify the design calculations or to perform parametric analyses aimed at optimization. The design of the Breeding Blanket, which will be a first-of-a-kind component in EU DEMO, is supported from the thermal-hydraulic point of view by local 3D CFD analyses, mainly aimed at verifying the heat removal capabilities of the system, and by analyses at the system level, using 1D codes.

This work presents the development and application of a detailed 1D model of the coolant manifolds for the Helium-Cooled Pebble Bed Breeding Blanket concept for the EU DEMO; this model, implemented in the GEneral Tokamak THErmal-hydraulic Model (GETTHEM), allows performing fast analyses at the global level, but still maintaining a good level of detail concerning the coolant distribution. The first results obtained with the model prove that 3D CFD analyses of the manifolds may provide misleading results due to non-representative Boundary Conditions, which must be used to avoid having a too complex domain. The application of a global model, which is indeed characterized exploiting local analyses, can in turn provide better Boundary Conditions to the detailed 3D CFD analyses.

Keywords: EU DEMO, Breeding Blanket, HCPB, Back Supporting Structure, GETTHEM

I. Introduction

The European Roadmap to the Realization of Fusion Electricity[1] foresees that the EU DEMO reactor produces net electricity from fusion by the 2050s. One of its missions is to prove the feasibility of a closed fuel cycle, and, to this aim, it will be the first European machine to include a Breeding Blanket (BB). Among the BB concepts under development in the EUROfusion Consortium, the Helium-Cooled Pebble Bed (HCPB)[2] foresees in its 2015 version the use of helium (300 °C – 500 °C) as coolant, Li_4SiO_4 as breeder material in the form of a pebble bed, and Be as neutron multiplier material, again in the form of a pebble bed. The development and design of the HCPB concept is led by the Karlsruhe Institute of Technology (KIT) through for instance detailed analyses, including 3D Computational Fluid Dynamics (CFD) studies for the thermal-hydraulic calculations. Such kind of analyses, however, are limited by the computational cost, which may become significant if the domain of interest becomes large. Therefore, they are typically limited to the analyses of sub-domains of the blanket, as, e.g., a single "elementary unit", assumed representative of one entire segment. In the case at hand, CFD models, targeted to the verification of the cooling design, are limited to such elementary unit, and need boundary conditions (pressure, mass flow rate) to be assumed. To overcome that limitation, CFD models could be used in conjunction with and supported by analyses performed with system-level tools. In this framework, some analyses have been performed with the MELCOR code[3] for the ITER HCPB Test Blanket Module (TBM), with RELAP5-3D for the First Wall Mock-up[4] or with RELAP5-mod3.2 for the ITER HCSB TBM[5]; DEMO-relevant analyses have been carried out for K-DEMO with the MARS-KS code[6] while, within the EU, MELCOR has been used for safety analyses[7], and, for normal operation, the GEneral Tokamak THErmal-hydraulic Model (GETTHEM)[8-10], under development, validation and application at Politecnico di Torino since 2015, has been employed. On the other hand, system-level codes exploit simplifications in the modelling of the physics underlying the involved phenomena (from 3D to 1D, for instance), and, as a consequence, the accuracy of the results must be carefully checked.

As far as the manifolds feeding the Blanket Modules (BMs) are concerned, they have been typically modeled so far through a simple 0D approach[8], which, however, does not account for the fact that the manifolds are very long (~ 10 m), with a dominant direction of the flow, so that the resulting mass flow rate entering each module can suffer from large approximations.

In this work, a 1D model of the HCPB manifolds is developed and implemented in the GETTHEM code. The 1D manifold model, connected to the already-available 1D model of the BMs, is then applied to compute the pressure and mass flow rate distribution among the different BMs of an outboard segment of the HCPB in nominal operation, and the differences with respect to the available 3D analysis are presented and discussed.

II. 1D model of the Helium-Cooled Pebble Bed Back Supporting Structure

A view of the HCPB Back Supporting Structure (BSS), which contains the coolant manifolds, is reported in Fig. 1, whereas the corresponding design of the BM is shown in Fig. 2, where the detail of the coolant flow path is also reported. This work is based on the 2015 revision of the HCPB design, but the model development and the results obtained are fully applicable to newer revisions, as the design of the BSS manifold has maintained the same approach.

The detailed thermal-hydraulic analyses of such complex systems are carried out using detailed 3D CFD models. In particular, the cooling performances inside the Blanket Modules are studied with analyses focused on one “elementary unit” (i.e. a portion of the BM which is identically repeated along the poloidal direction), usually located at the equatorial outboard region[2], as shown in Fig. 3a. On the other hand, the coolant distribution among the different BMs, which should match the mass flow rate requirements computed according to the power distribution, is driven by the geometry and pressure drop in the BSS manifold. This is computed performing 3D CFD analyses of the inlet and outlet manifolds separately, as shown in Fig. 3b.

These analyses if consistent may provide detailed and reliable information about the coolant distribution, however, they are computationally expensive, and require to be run again if major design changes occur. Moreover, the combined analysis of the BSS and BM is prohibitive from the point of view of the dimension of the computational problem, and consequently in the BM analysis a fixed mass flow rate is used at the inlet of the elementary unit, whereas in the BSS analysis all the channels downstream the Inlet Manifold (IM) or upstream the Outlet Manifold (OM) are assumed to be at the same pressure. For this reason, the GETTHEM code has been used in the past to perform analyses that included in the same simulation both the BSS and the BMs[10]. Nevertheless, in the referenced analysis the BSS was modelled using a 0D approach, which does not allow computing the pressure distribution inside the manifolds, and consequently causes an approximation in the resulting mass flow rate distribution to the BMs.

To overcome this limitation, in 2016 the development of a 1D model of the BSS manifolds has started, supported by CFD analyses, aiming also at the sizing of a scaled-down mock-up for the model qualification against experimental data[12]. In view of the derivations, which imply a change of the mass flow rate (and consequently velocity), the model computes the major and minor pressure losses in the form of total pressure $p_0 = p + \frac{1}{2}\rho v^2 + \rho g L$ (gravitational head is however negligible in view of the low helium density). Concerning the mass flow rate distribution at the derivation, it is assumed to be proportional to the pressure difference between the main branch of the manifold and the derivation outlet[12]. The model, built, calibrated and verified for the equatorial outboard region of the BSS[12], has been extended to cover the entire manifold, allowing now the modelling of the entire HCPB in-vessel cooling system with the details of the coolant distribution in the manifolds, according to the scheme in Fig. 4. The entire BSS is split in sub-models, each representing a set of inlet/outlet derivations: for the OM, each derivation object (OMD) models the manifold portion in between two derivations, whereas, in view of the large number of IM derivations (see Fig. 1), each IM derivation object (IMD) accounts for 10 or 11 derivations, for a total of 34 IMDs. More details about the rationale behind the model development and a description of its modular nature are reported in Ref. #7.

The simulation is set up according to the right part of Fig. 4, using in input and output the same boundary conditions (BCs) as used in the mentioned CFD analysis[11], but connecting the IM and OM models through the BM models, already implemented and available in GETTHEM. In the CFD analysis, instead, the IM and OM were analyzed in standalone, substituting the BMs with a fixed pressure BC in the IM model (equal to the reference pressure value of 80 bar) and with a fixed mass flow rate BC in the OM model; for consistency, in the CFD study the distribution of the mass flow rate entering the OM model was set equal to that computed with the IM model.

III. Results

The distribution of the pressure in the IM, as computed by GETTHEM, is reported in Fig. 5 in terms of static pressure p (the pressure distribution in the OM is almost uniform at 78 bar). The pressure slightly decreases along the BSS axis; due to the reduction of the mass flow rate, inducing a reduction of the velocity, inside each BM a very small increase of the static pressure is visible.

The consequent distributions of the coolant mass flow rate among the different Blanket Modules, as computed by CFD and GETTHEM models, are reported in Fig. 6, where also the target coolant distribution is shown (i.e. the mass flow rate distribution computed to achieve the desired temperature increase in each BM according to the different power deposited). Both CFD and GETTHEM models compute a more uniform mass flow rate distribution among the BMs, if compared to the target value, highlighting that the design of the BSS should be updated accordingly, introducing for instance orifices in the BMs which get more mass flow rate than the required value (which are then overcooled, i.e. BM1, BM2 and BM7, far from the equatorial region), at the expenses of a larger pressure drop, or modifying the geometry of the BSS manifolds. However, the two distributions computed by CFD and GETTHEM show sensible differences, in particular concerning the top and bottom BMs mentioned above, with a 4.9 % discrepancy on average and 15 % as maximum (computed in BM7). The effect of the different Blanket Module hydraulic impedances is indeed making the coolant distribution more uniform, and, consequently, even further from the target mass flow rate values. The only exception is represented by BM1, for which GETTHEM computes a mass flow rate closer to the required value with respect to CFD, but still 25 % larger. To understand this different behavior of the BM1, the hydraulic characteristics of the BMs is investigated, applying the GETTHEM model varying the inlet mass flow rate from -95 % to +30 % of the nominal value, and computing the pressure drop inside the different BMs. This result is reported in Fig. 7, where all the BMs behave with similar characteristics but the BM1, showing a larger pressure drop. As a consequence, the mass flow rate to BM1 is reduced with respect to the CFD-computed value, which cannot take this different hydraulic characteristic into account. This results proves that the use of a uniform pressure as Boundary Condition for the CFD analysis of the IM provides for most of the modules non-conservative results (lower discrepancy between computed and required mass flow rates values than actually predicted by GETTHEM): for instance, an orifice dimensioned looking at the CFD results, would result under-dimensioned.

The application of a system-level code like GETTHEM, with a 1D description of the manifolds, can instead provide a better idea of the pressure distribution at the inlet of the Blanket Modules, with a level of detail driven by the number of IMDs used; this result is reported in Fig. 8. This kind of detailed pressure distribution can be used e.g. to better characterize the BMs from the hydraulic point of view, or may be used as BC for CFD analyses of the BSS manifold, which would be more representative of the BM hydraulic resistance.

IV. Conclusions

A 1D model of the HCPB Back Supporting Structure manifolds has been developed and integrated in the GETTHEM model of the HCPB Breeding Blanket cooling system. This 1D model, connected to the 1D models of the HCPB Blanket Modules, has been used to analyze the mass flow rate and pressure distribution in one entire HCPB segment, allowing for the first time to estimate the coolant distribution in the segment with a self-consistent model. The analysis showed that the uniform pressure Boundary Conditions used for detailed 3D CFD analyses of the BSS manifolds cannot be considered a good representation of the phenomenon, yielding misleading and non-conservative results. The 1D model can instead provide a more accurate value of the pressure at the inlet of the BMs, which e.g. may be used as improved BCs in the 3D modelling.

In perspective, the 1D BSS model as implemented in GETTHEM should be validated through an experimental campaign planned at KIT. The validated tool could then be used to compute more realistic flow repartition among the BMs, and perform parametric thermal-hydraulic investigations of the HCPB cooling performances during foreseen operational and accidental transients.

Acknowledgements

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References

[1] A. J. H. Donné, W. Morris, X. Lituadon, C. Hidalgo, D. McDonald, H. Zohm, E. Diegele, A. Möslang, K. Norlund, G. Federici, P. Sonato, C. Waldon, D. Borba and P. Helander, European research roadmap to the realisation of fusion energy, EUROfusion Consortium, 2018. [Online] Available: https://www.euro-fusion.org/eurofusion/roadmap/.

[2] F. A. Hernández, F. Arbeiter, L. V. Boccaccini, E. Bubelis, V. P. Chakin, I. Cristescu, B.-E. Ghidersa, M. González, W. Hering, T. Hernàandez, X. Z. Jin, M. Kamlah, B. Kiss, R. Knitter, M. H. H. Kolb, P. Kurinskiy, O. Leys, I. A. Maione, M. Moscardini, G. Nàdasi, H. Neuberger, P. Pereslavtev, S. Pupeschi, R. Rolli, S. Ruck, G. A. Spagnuolo, P. V. Vladimirov, C. Zeile and G. Zhou, Overview of the HCPB Research Activities in EUROfusion, IEEE Transactions on Plasma Science 46 (6) (2018) 2247-2261.

[3] X. Z. Jin and B.-E. Ghidersa, Thermal-hydraulic system study of a high pressure, high temperature helium loop using RELAP5-3D code, Nuclear Engineering and Design 249 (2012) 57-62.

[4] V. Di Marcello, B.-E. Ghidersa, X. Z. Jin, A. Abou-Sena and R. Stieglitz, Development and validation of the blanket First Wall mock-up model in RELAP5-3D, Fusion Engineering and Design 136 (B) (2018) 1534-1539.

[5] M.-Y. Ahn, S. Cho, D. H. Kim, E.-S. Lee, H.-S. Kim, J.-S. Suh, S. Yun and N. Zin Cho, Preliminary safety analysis of Korea Helium Cooled Solid Breeder Test Blanket Module, Fusion Engineering and Design 83 (10-12) (2008) 1753-1758.

[6] G.-W. Kim, J.-H. Lee, H.-K. Cho, G.-C. Park, K. Im, Development of thermal-hydraulic analysis methodology for multiple modules of water-cooled breeder blanket in fusion DEMO reactor, Fusion Engineering and Design 103 (2016) 98-109.

[7] X. Z. Jin, BB LOCA analysis for the reference design of the EU DEMO HCPB blanket concept, Fusion Engineering and Design 136 (B) (2018) 958-963.

[8] A. Froio, C. Bachmann, F. Cismondi, L. Savoldi and R. Zanino, Dynamic thermal-hydraulic modelling of the EU DEMO HCPB breeding blanket cooling loops, Progress in Nuclear Energy 93 (2016) 116-132.

[9] A. Froio, F. Casella, A. Del Nevo, L. Savoldi and R. Zanino, Dynamic thermal-hydraulic modelling of the EU DEMO WCLL breeding blanket cooling loops, Fusion Engineering and Design 124 (2017) 887-891.

[10] A. Froio, F. Cismondi, L. Savoldi and R. Zanino, Thermal-hydraulic analysis of the EU DEMO helium-cooled pebble bed breeding blanket using the GETTHEM code, IEEE Transactions on Plasma Science 45 (5) (2018) 1436-1445.

[11] F. A. Hernández, P. Pereslavtev, Q. Kang, P. Norajitra, B. Kiss, G. Nàadasi and O. Bitz, A new HCPB breeding blanket for the EU DEMO: Evolution, rationale and preliminary performances, Fusion Engineering and Design 124 (2017) 882-886.

[12] A. Bertinetti, A. Froio, B.-E. Ghidersa, F. A. Hernández, L. Savoldi and R. Zanino, Hydraulic modeling of a segment of the EU DEMO HCPB breeding blanket back supporting structure, Fusion Engineering and Design 136 (B) (2018) 1186-1190.

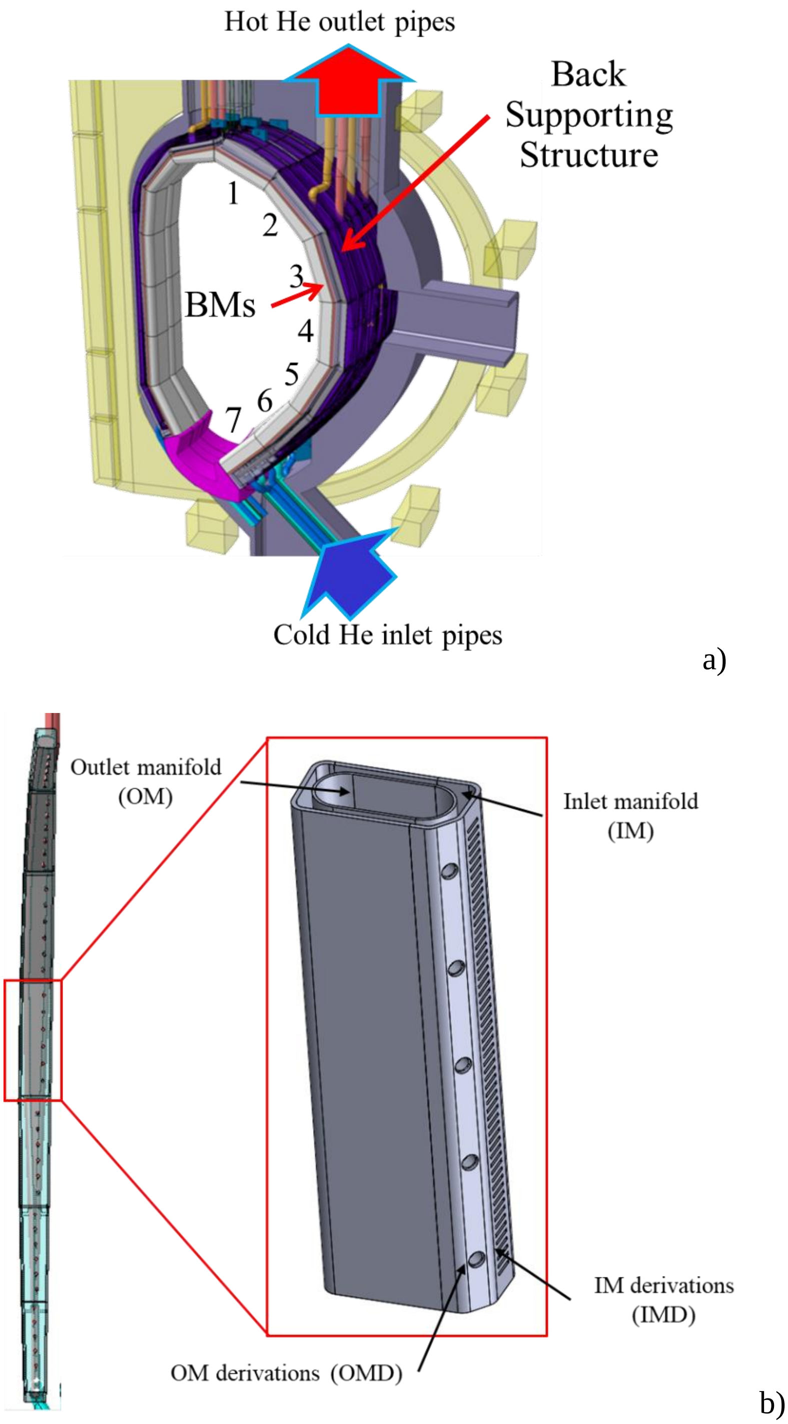

Fig. 1. a) CAD of one EU DEMO sector, showing the 2015 HCPB Blanket Modules and Back Supporting Structure, including the coolant flow path and BM numbering[11]; b) View of half of the 2015 HCPB Back Supporting Structure, showing a detail of the Inlet and Outlet Manifolds[11-12].

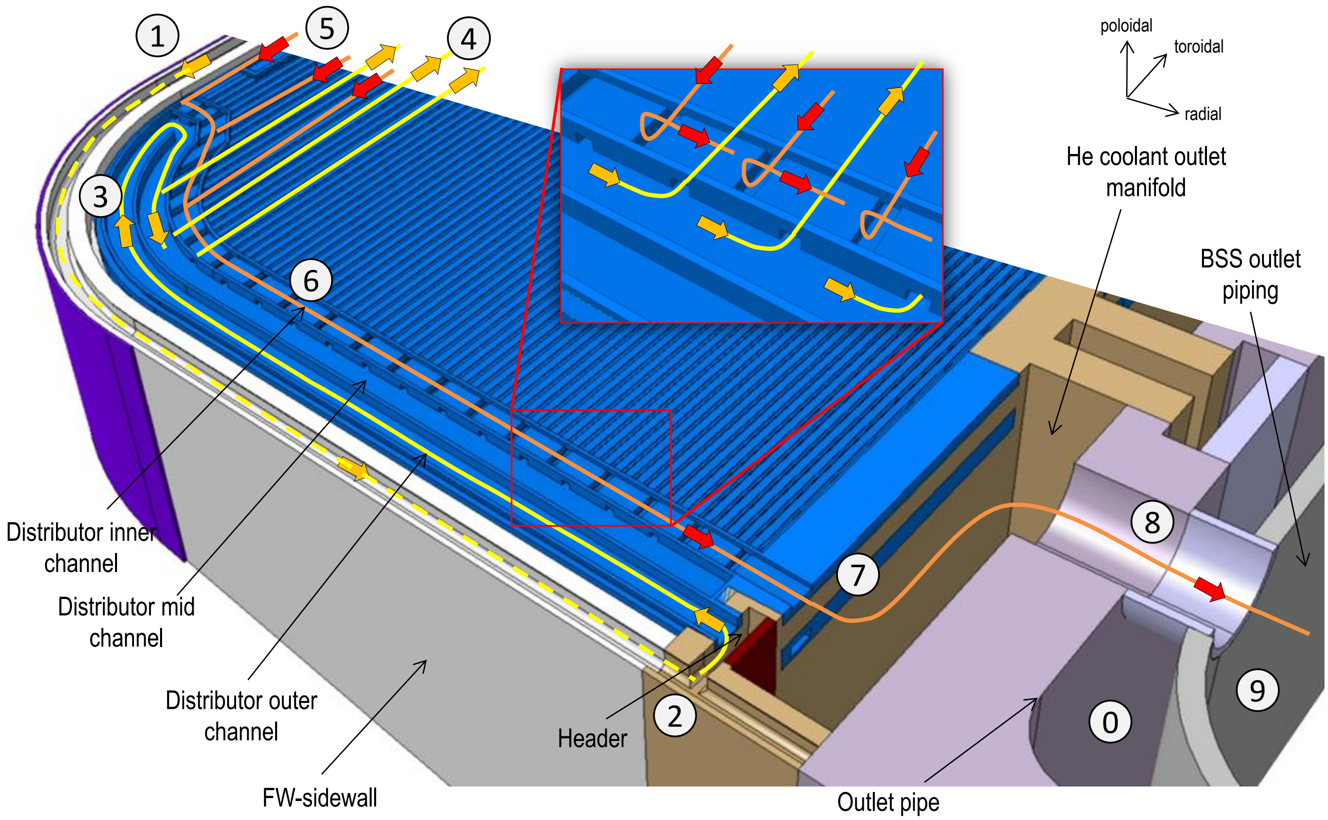

Fig. 2. Detailed view of the coolant flow path inside a 2015 HCPB Blanket Module[11].

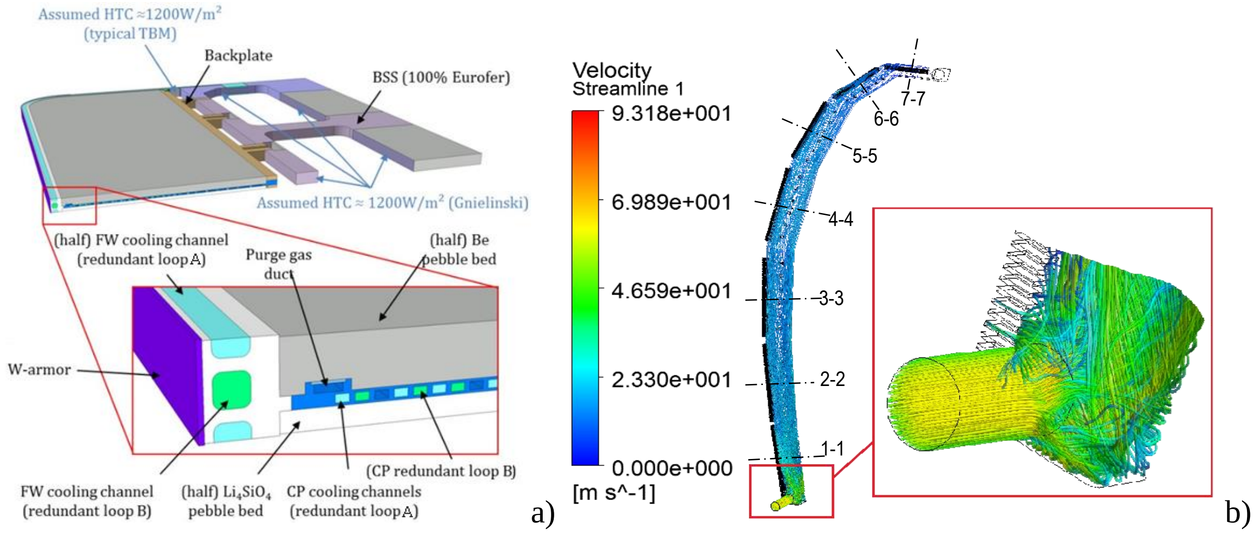

Fig. 3. Example of the domains used in 3D CFD analyses of the blanket: a) elementary unit used for the thermal-hydraulic analysis of the HCPB BM; b) hydraulic analysis of the outboard BSS Inlet Manifold, focused on the domain as reported in Fig. 1b above[2,11].

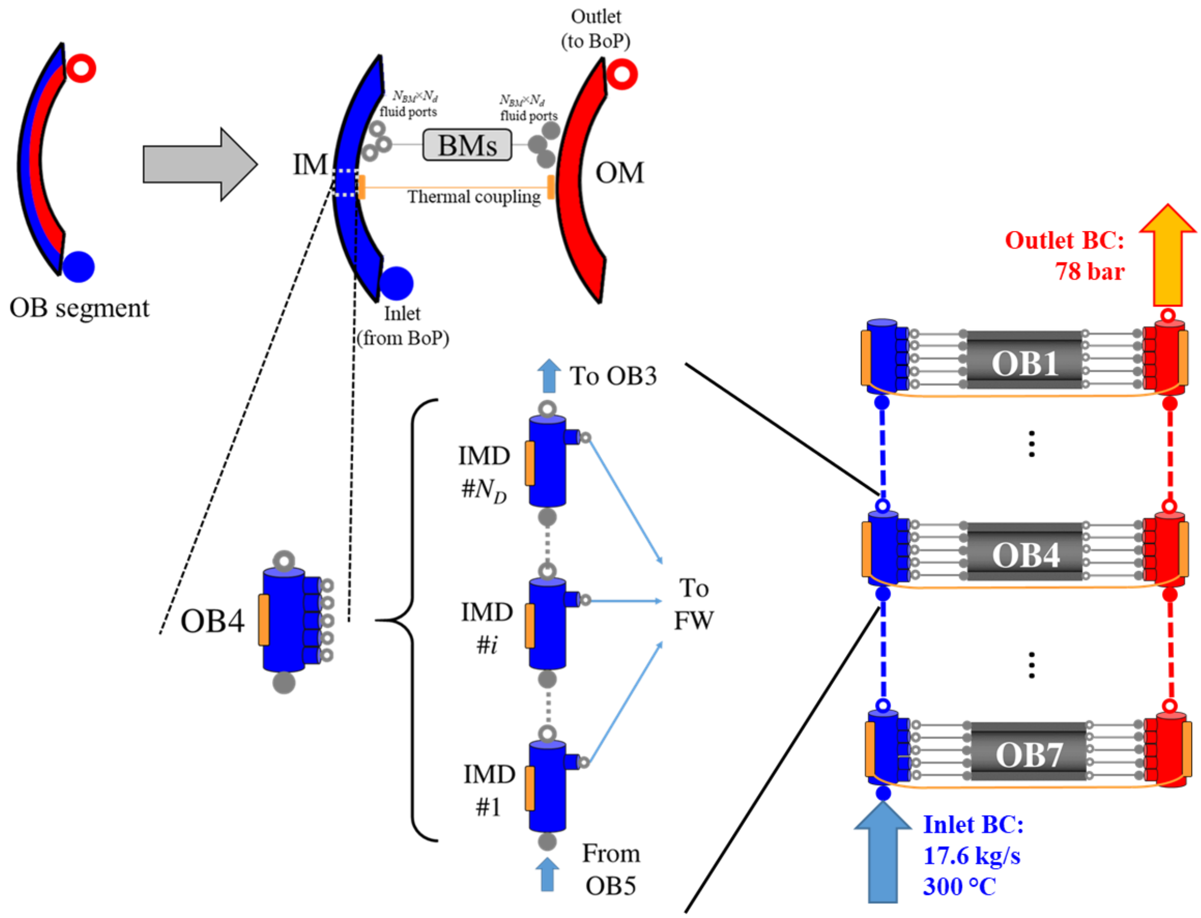

Fig. 4. Scheme of the 1D model of the BSS manifolds, highlighting its modular structure. This model refers to one outboard segment.

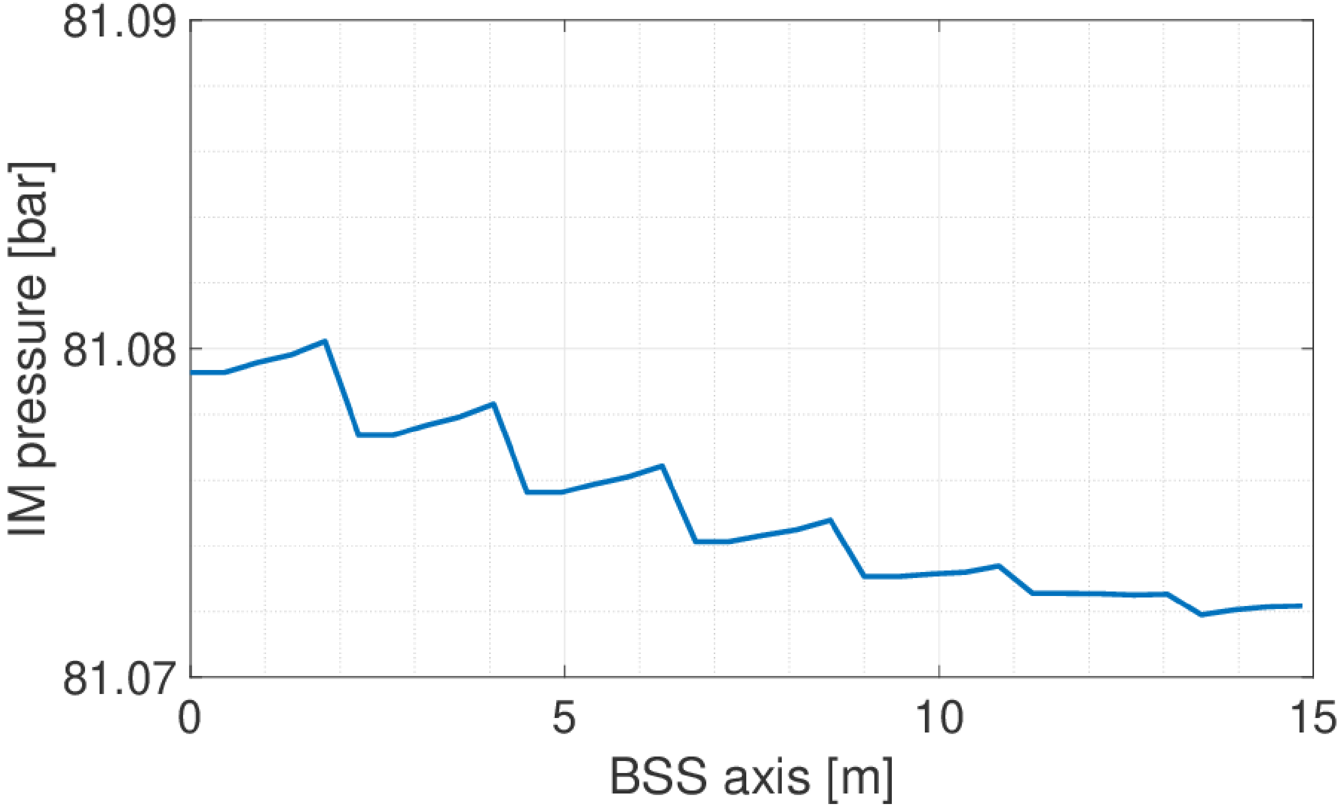

Fig. 5. 1D distribution of the pressure along the Inlet Manifold.

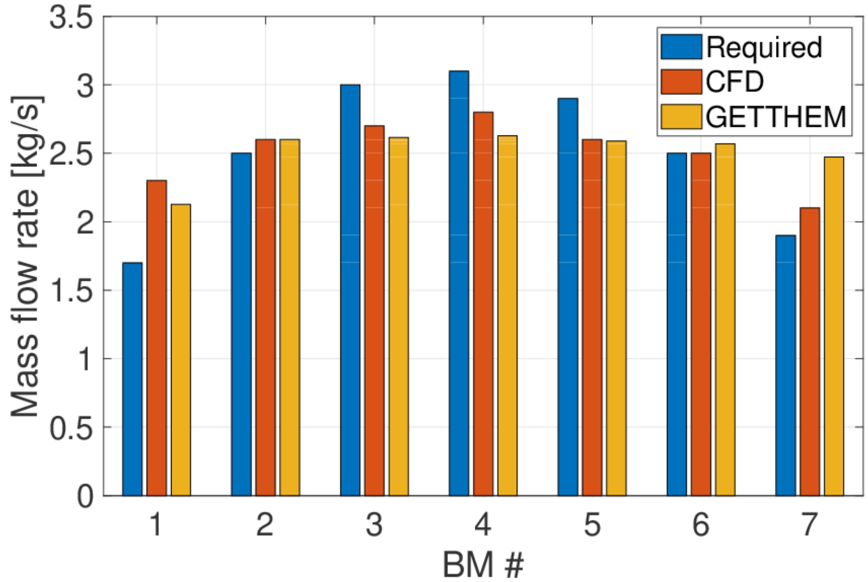

Fig. 6. Distribution of the mass flow rate among the BMs: required value (blue), computed by 3D CFD manifold model (red), computed by 1D GETTHEM BSS+BM model (yellow).

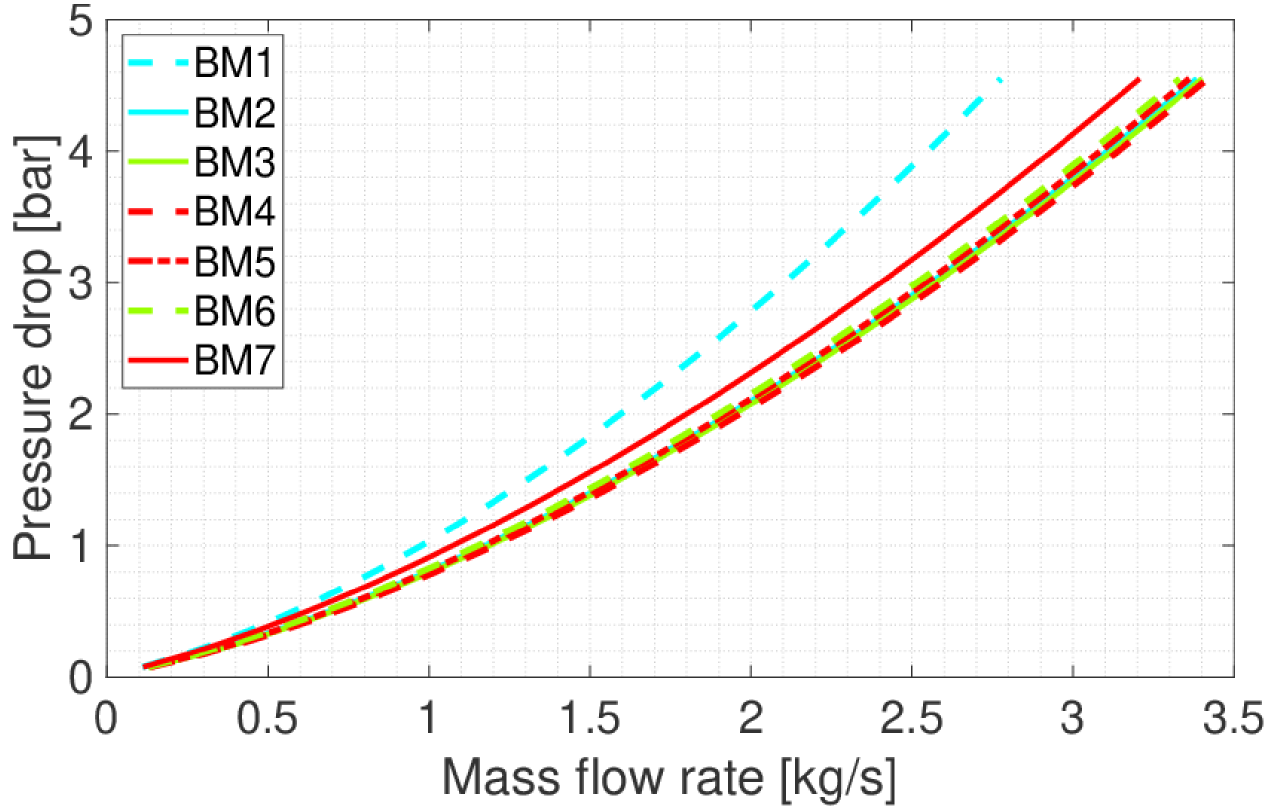

Fig. 7. Computed hydraulic characteristic of the seven Outboard Blanket Modules.

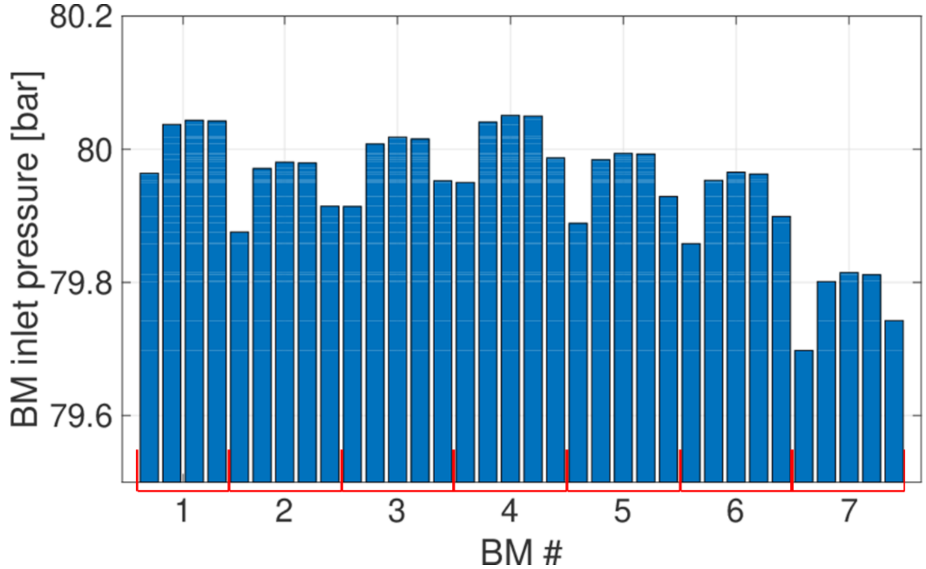

Fig. 8. Distribution of the pressure at inlet of the BMs, as computed by GETTHEM.