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Thermal-hydraulic scaling of the prototypical mock-up for European DEMO HCPB breeding blanket

Gaurav Verma *, Guangming Zhou, Francisco A. Hernández

Institute for Neutron Physics and Reactor Technology (INR), Karlsruhe Institute of Technology (KIT), Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany

A R T I C L E I N F O

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A B S T R A C T

The Helium-Cooled Pebble Bed (HCPB) blanket concept is a leading candidate for the driver blanket in the European Fusion Demonstration Power Plant (DEMO), developed within the EUROfusion framework's Work Package Breeding Blanket (WPBB). A crucial component of the HCPB blanket is the First Wall (FW), which must withstand high heat fluxes from the plasma while maintaining a uniform temperature distribution as much as possible. This uniformity is achieved through an alternating coolant flow design. The present study focuses on the thermal-hydraulic scaling methodology for the First Wall-Prototype Mock-Up (FW-PMU) to replicate the HCPB blanket's thermal and hydraulic performance. The FW-PMU is designed to emulate the flow distribution and thermal behavior of the HCPB Breeding Blanket (BB) First Wall, including flow patterns from the Breeder Zone Manifold to the fuel-breeder pins. In the present work, a power-to-volume scaling approach is employed to maintain the characteristic time ratio by analyzing non-dimensional parameters, while scaling of component dimensions in the breeder zone manifold ensures a consistent velocity field. The FW-PMU is set for testing in HELOKA, a high-pressure, high-temperature helium facility at the Karlsruhe Institute of Technology to validate the HCPB First Wall design under realistic operating conditions, advancing its potential deployment in fusion energy systems.

1. Introduction

The Helium-Cooled Pebble Bed (HCPB) blanket concept [1] is one of the driver blanket candidates for the European Fusion Demonstration Power Plant (DEMO) within the EUROfusion framework of the Work Package Breeding Blanket (WPBB). The First Wall (FW) is a key component in the breeder blanket dealing with the high heat load from the plasma. The FW is a U-shaped plate made out of Eurofer (see Fig. 1). It has internal cooling channels allowing the coolant to enter through an inlet manifold in an alternating flow direction to ensure a homogeneous temperature distribution. The coolant exits from the FW and is collected at the breeder zone inlet manifold. In the HCPB blanket, the Breeder Zone (BZ) is formed by the so-called fuel-breeder pins, which are located between the FW and backplate. There are many fuel-breeder pins; homogenous temperature distribution in the breeder zone is desired, and therefore the flow distribution from the breeder zone manifold into the fuel-breeder pins needs investigation.

In the present work, the thermal-hydraulic scaling methodology of the First Wall-Prototype Mock-Up (FW-PMU) for the DEMO HCPB BB is described. This is done in order to realize the design of PMU such that it reproduces the thermal-hydraulic behavior of the HCPB BB FW, and the flow distribution pattern from the BZ Manifold to the fuel-breeder pins. With this, it is intended that the test results obtained in the mock-up emulate those of the HCPB BB. For the FW, a power-to-volume scaling approach is used to preserve the characteristic time ratio by evaluating the non-dimensional grouping parameters, whereas for the breeder zone manifold, an approach involving the scaling of component dimensions is utilized in order to obtain a consistent velocity field. This mock-up is planned to be tested in the high-pressure, high-temperature HElium LOop KArlsruhe facility (HELOKA) at the Karlsruhe Institute of Technology (KIT).

2. Design description and significance

2.1. Design description of the HCPB BB

The HCPB breeding blanket consists of a U-shaped FW (Eurofer97 steel) with a Tungsten-coated armor which directly faces the plasma and endures extreme thermal loads, fatigue-creep, and radiation damage

* Corresponding author.
E-mail address: gaurav91verma@gmail.com (G. Verma).

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Nomenclature

L	Length of the section of interest
u	Mean velocity of the fluid
T	Average coolant temperature
ρ	Density of the fluid for T
H	Fluid enthalpy per unit mass
P	Power
q"	Heat flux through transfer area
h	Heat transfer coefficient
c_p	Specific heat at constant pressure for T
Q"	Incident heat flux
ΔT	Temperature difference
ω	Specific frequency of the transfer
t	Time of interest
V	Volume
A_h	Transfer area
φ	Spatial scale
Π	Non-dimensional grouping parameter
R/LOB	Right/Left Out-Board Segment of HCPB
R/LIB	Right/Left In-Board Segment of HCPB
COB	Central Out-Board of HCPB
A_t	Incident area

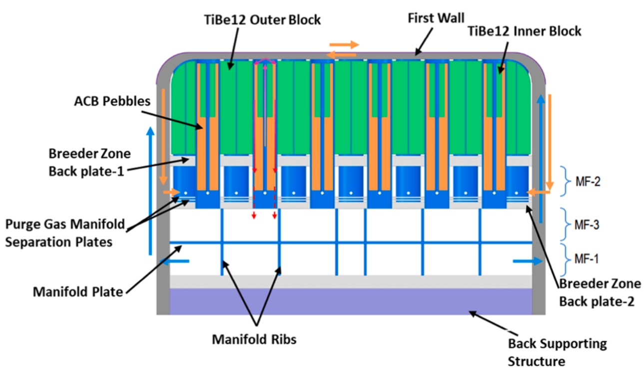

Fig. 1. Schematic of the HCPB BB.

(primarily due to high energy fusion neutrons). The heat flux seen by the First Wall depends on the location in the tokamak. Without limiters, the EU DEMO First Wall will see a peak flux up to 1.25 MW/m^2 [2]. With the help of limiters to take the particle heat fluxes, the EU DEMO would see a heat flux in the range of 0.1 to 0.75 MW/m^2 at normal conditions. Behind this lies the Breeder Zone consisting of fuel breeder pin architecture. These breeder pins are composed of tritium breeding materials (Advanced Ceramic Bed Pebbles) and neutron multipliers ($TiBe_{12}$) in the form of triangular prism blocks. The cladding of the fuel-breeder pin houses the ACB pebbles and to limit temperature in the ACB pebbles, an inner block of $TiBe_{12}$ is placed into the fuel-breeder pin. The tritium generated in this zone is then extracted and removed via a purge gas (He + 200 Pa H_2 at 80 bar). The total nuclear heating estimated in the BB is approx. 1892 MW. Fig. 1 shows the schematic of HCPB BB section and Table 1 shows some of the major dimensions of HCPB BB section.

The coolant flow scheme of the HCPB BB is shown in Fig. 2. The helium coolant enters the segment at a temperature of 300 °C with an operating pressure of 8 MPa. Firstly, it flows from the First Wall manifold inlet (MF-1) to the FW cooling channels (12 mm x 12 mm), which are cooled in a counter flow arrangement to homogenize the temperature distribution. The coolant is then collected and mixed in the Breeder Zone inlet manifold (MF-2). After that, the coolant is distributed into the fuel-breeder pins in the BZ. The coolant is thereafter collected from the pins in the outlet plenum and redirected to the BZ outlet (MF-3), which is the outlet piping, at an expected mixed temperature of 520 °C.

Table 1
Major dimensions of HCPB BB (for COB).

No.	Parameter	Size
1	poloidal height	0.75m
2	toroidal width	1.48m
3	First Wall sidewall length	0.51m

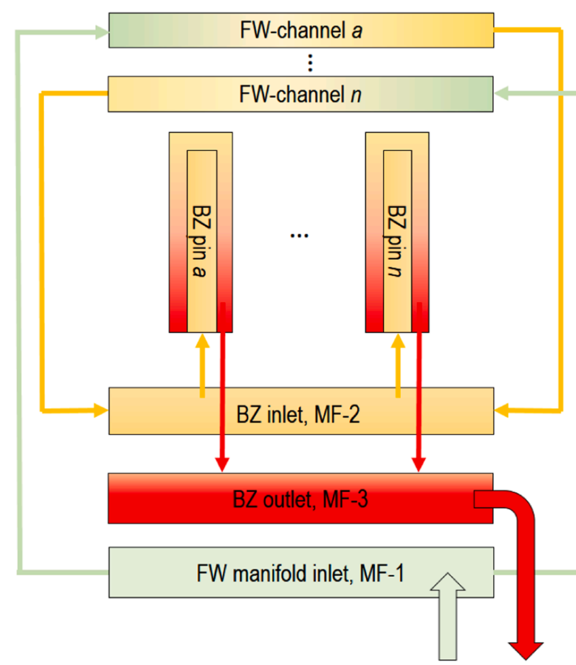

Fig. 2. Schematic flow scheme of the HCPB BB [1].

In order to further enhance the heat transfer, use of V-ribs for enhanced heat transfer in the HCPB FW channels is also being explored.

2.2. Significance of FW-PMU for DEMO HCPB FW

The schematic of the FW-PMU is shown in Fig. 3. The U-shaped part of the FW is proposed to be manufactured with parts of a previous project at KIT, using the so-called fail-safe sandwich FW manufacturing procedure [3,4]. Also, the design of the mock-up is more focused towards the inlet and outlet manifolds and its installation within the HELOKA facility. As planned, some of the main objectives of the FW-PMU with similar operating pressure conditions as the HCPB BB First Wall:

a) to exhibit the capability of the V-ribs in First Wall channels of handling high heat flux (~0.75 MW/m^2);
b) to estimate the flow distribution into Breeder Zone channels and manifold;
c) to estimate the pressure-drop across the FW and the manifold section when flow rate is varied.

Based on the results of the mock-up experiments, use of V-ribs for

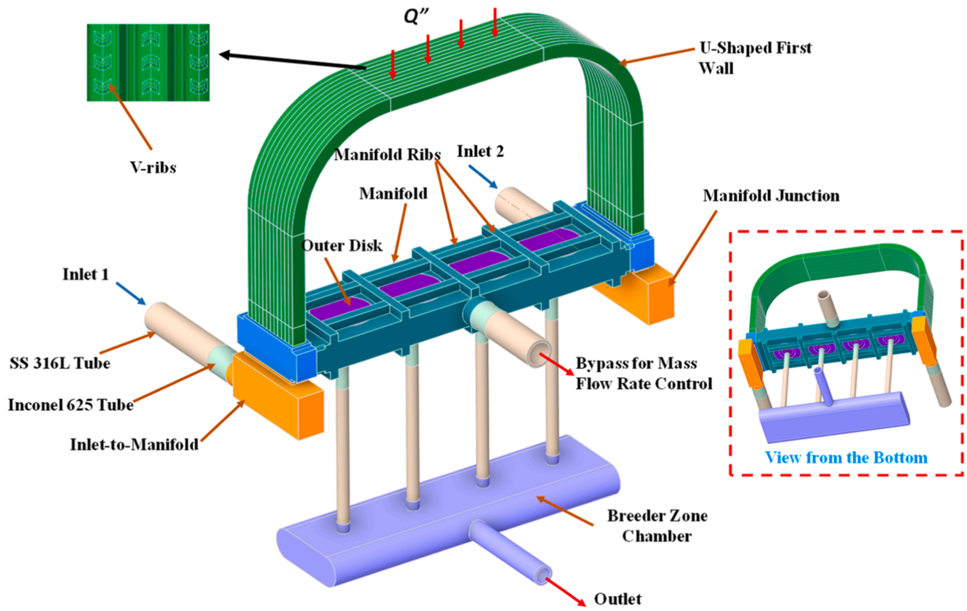

Fig. 3. Component nomenclature of First Wall-Prototype Mock-up.

enhanced heat transfer in the HCPB BB First Wall channels will also be explored.

3. Scaling methodology for FW-PMU and its manifold section

3.1. Thermo-hydraulic scaling of PMU FW

The scaling methodology adopted is such that the physical design and operating conditions obtained ensure relevant thermal-hydraulic phenomena are preserved in the prototype mock-up. Also, the data obtained from the tests on the prototype mock-up are also applicable to the DEMO HCPB FW. The general scaling methodology adopted in order to develop the design of the FW-PMU is Power-to-Volume scaling approach within the Hierarchical Two-Tiered Scaling methodology (H2TS) which is deduced by preserving the Characteristic Time Ratio for the prototype FW mock-up and the DEMO FW as discussed by Zuber et al. [5] and Levy [6]. This preservation of Characteristic Time Ratio considers the spatial and temporal (rate) scales of the process and the system, as well as the effect of the volume concentrations that are present in the system, hence, all the measures of mass, volume, space and time for the process and for the system are combined in a single dimensionless group.

In order to develop a hierarchical volume scaling, for a control volume V_{cv}, the volume occupied by a particular constituent *C* with fraction α_c is V_c and are related as

$$V_c = \alpha_c V_{cv} \tag{1}$$

If the constituent *C* has different phases, for phase *P*, the total volume occupied is V_{cp} with fraction α_{cp} of the volume V_c is related as

$$V_{cp} = \alpha_{cp} V_c \tag{2}$$

For a particular geometry G of phase P, the volume occupied is Vcpg which is a fraction of Vcp given by

$$V_{cpg} = \alpha_{cpg} V_{cp} \tag{3}$$

Thus, the volume occupied in the control volume by a specific geometry of a phase constituent is given as

$$V_{cpg} = \alpha_c \alpha_{cp} \alpha_{cpg} V_{cv} \tag{4}$$

For each process, the spatial scale φ associated is obtained by dividing the transfer area Ah by the volume V which is given as

$$\varphi = \frac{A_h}{V} \tag{5}$$

For each heat transfer process, the temporal scale τ is defined by the transfer process rate, by an incident area A_t and the property ψ (per unit volume) being transferred. Therefore, the temporal scale can be expressed as,

$$\tau = \frac{\psi V}{Q'' A_t} = \frac{1}{\omega} \tag{6}$$

where *Q”* is the incident flux of the property and ω is the specific frequency of the transfer. The time of interest *t* for the process is the transit time and can be described as

$$t = \frac{L}{u} \tag{7}$$

where L is the length of the section of interest and u is the mean flow velocity of the fluid. To ensure the applicability of the mock-up tests data on the same time scale as the DEMO FW, the fluid properties and initial conditions are preserved from the DEMO FW to the prototype mock-up. Thus, the non-dimensional grouping Π is expressed in Eq. (8) as

$$\Pi = \frac{Q'' A_t L}{\rho u H V} = \frac{t}{\omega} = \frac{PL}{\rho u H V} = \frac{q'' A_h L}{\rho u H V} = \frac{h A_h L}{\rho u c_p V} \tag{8}$$

$$Q'' A_t = q'' A_h \tag{9}$$

where ρ is the density of the fluid for average coolant temperature *T, H* is the fluid enthalpy per unit mass, *P* is the power, *q”* is the flux through the transfer area, h is the heat transfer coefficient and c_p are the specific heat at constant pressure for average coolant temperature *T*. Now, this non-dimensional grouping is preserved for both the DEMO FW and the prototype mock-up.

3.2. Evaluation of non-dimensional grouping parameter

For evaluation of the non-dimensional grouping parameter, the values of $\alpha_c = \alpha_{cp} = \alpha_{cpg} = 1$ as the complete control volume is filled with only one constituent and in only one phase (He gas). Tables 2-4 describes the various components for evaluating the non-dimensional grouping parameter for various sections and segments of the DEMO HCPB BB First

Table 2
Non-dimensional grouping parameter estimation for R/LOB as per Gnielinski correlation for heat transfer coefficient.

Segment	T (°C)	ρ (kg/m^3)	c_p (J/kg.s)	U (m/s)	H (W/m^2.s)	L (m)	A_h (m^2)	V (m^3)	Π^R
R/LOB 1	312.0	6.4732	5197	38.68	4983.8	0.947	0.010551	0.000133	0.3151
R/LOB 2	316.2	6.42797	5197	35.42	4984.6	1.046	0.011654	0.000147	0.3482
R/LOB 3	319.0	6.39817	5197	35.58	4985.2	1.17	0.013036	0.000165	0.3896
R/LOB 4	321.8	6.36865	5197	35.75	4985.8	1.27	0.01415	0.000179	0.4229
R/LOB 5	323.8	6.34772	5197	35.86	4986.2	1.355	0.015097	0.000191	0.4512
R/LOB 6	324.5	6.34043	5197	35.90	4986.4	1.331	0.014829	0.000188	0.4433
R/LOB 7	327.6	6.30834	5197	36.09	4987	1.494	0.016646	0.000211	0.4976
R/LOB 8	329.1	6.29293	5197	36.18	4987.3	1.547	0.017236	0.000218	0.5153
R/LOB 9	330.2	6.28168	5197	36.24	4987.5	1.585	0.017659	0.000223	0.5280
R/LOB 10	331.0	6.27352	5197	36.29	4987.7	1.611	0.017949	0.000227	0.5367
R/LOB 11	331.6	6.26741	5197	36.32	4987.8	1.624	0.018094	0.000229	0.5410
R/LOB 12	332.0	6.26335	5197	36.35	4987.9	1.624	0.018094	0.000229	0.5410
R/LOB 13	331.8	6.26538	5197	36.33	4987.9	1.612	0.01796	0.000227	0.5370
R/LOB 14	330.9	6.27454	5197	36.28	4987.7	1.578	0.017581	0.000222	0.5257
R/LOB 15	330.2	6.28168	5197	36.24	4987.5	1.552	0.017292	0.000219	0.5170
R/LOB 16	329.2	6.29191	5197	36.18	4987.3	1.507	0.01679	0.000212	0.5020
R/LOB 17.1	328.2	6.30217	5197	36.12	4987.1	1.406	0.015665	0.000198	0.4683
R/LOB 17.2	322.4	6.36235	5197	35.78	4985.9	1.204	0.013414	0.00017	0.4009
R/LOB 17.3	318.8	6.40029	5197	35.57	4985.2	1.018	0.011342	0.000144	0.3389

Table 3
Non-dimensional grouping parameter estimation for COB as per Gnielinski correlation for heat transfer coefficient.

Segment	T (°C)	P (kg/m^3)	c_p (J/kg.s)	U (m/s)	H (W/m^2.s)	L (m)	A_h (m^2)	V (m^3)	Π^R
COB 1	321.7	6.473198	5197	39.09	5436.124	1.480	0.01649	0.000209	0.4928
COB 2	322.0	6.427973	5197	39.11	5436.187	1.480	0.01649	0.000209	0.4928
COB 3	322.9	6.398172	5197	39.17	5436.375	1.480	0.01649	0.000209	0.4928
COB 4	323.8	6.368646	5197	39.23	5436.564	1.480	0.01649	0.000209	0.4928
COB 5	311.3	6.347721	5197	38.42	5433.936	1.480	0.01649	0.000209	0.4926
COB 6	324.9	6.34043	5197	39.30	5436.794	1.480	0.01649	0.000209	0.4929
COB 7	325.3	6.308341	5197	39.32	5436.878	1.480	0.01649	0.000209	0.4929
COB 8	325.8	6.29293	5197	39.35	5436.982	1.480	0.01649	0.000209	0.4929
COB 9	326.1	6.281676	5197	39.37	5437.045	1.480	0.01649	0.000209	0.4929
COB 10	326.5	6.273517	5197	39.40	5437.129	1.480	0.01649	0.000209	0.4929
COB 11	328.8	6.267411	5197	39.55	5437.609	1.480	0.01649	0.000209	0.4929
COB 12	326.8	6.263347	5197	39.42	5437.191	1.480	0.01649	0.000209	0.4929
COB 13	326.9	6.265378	5197	39.43	5437.212	1.480	0.01649	0.000209	0.4929
COB 14	326.7	6.274535	5197	39.41	5437.17	1.480	0.01649	0.000209	0.4929
COB 15	326.7	6.281676	5197	39.41	5437.17	1.480	0.01649	0.000209	0.4929
COB 16	326.6	6.291905	5197	39.41	5437.149	1.480	0.01649	0.000209	0.4929
COB 17.1	328.1	6.302167	5197	39.50	5437.463	1.480	0.01649	0.000209	0.4929
COB 17.2	326.2	6.362354	5197	39.38	5437.066	1.480	0.01649	0.000209	0.4929
COB 17.3	325.5	6.400292	5197	39.34	5436.919	1.480	0.01649	0.000209	0.4929

Wall. From Tables 2 and 4, it is observed that the lower and upper bounding non-dimensional grouping parameter are for L/ROB 1 and L/RIB 12 respectively. The lower bound value of Π^R_{Low} is 0.3142 for the L/ROB 1 whereas the upper bound value of Π^R_{Hi} is 0.6061 for the L/RIB 12.

In order to preserve the value of $\Pi^R = \Pi^M$, for the prototype mock-up also, lower bound value of Π^M_{Low} is 0.3142 and upper bound value of Π^M_{Hi} is 0.6061 is considered for scaling. As the geometry of the Prototype Mock-Up First Wall channels is already fixed (shown in Table 5 and

Table 4
Non-dimensional grouping parameter estimation for R/LOB as per Gnielinski correlation for heat transfer coefficient.

Segment	T (°C)	P (kg/m^3)	c_p (J/kg.s)	U (m/s)	H (W/m^2.s)	L (m)	A_h (m^2)	V (m^3)	Π^R
R/LIB 12	339.8902	6.184247	5197	26.41	3678.338	1.614	0.017983	0.0002075	0.6059
R/LIB 11	360.77	5.984236	5197	27.30	3682.369	1.536	0.017113	0.0002166	0.5265
R/LIB 10	365.5996	5.939797	5197	28.39	3746.773	1.475	0.016434	0.000208	0.4984
R/LIB 9	345.853	6.12578	5197	27.52	3742.959	1.414	0.015754	0.0001994	0.4773
R/LIB 8	341.5494	6.167867	5197	27.34	3742.121	1.335	0.014874	0.0001882	0.4505
R/LIB 7	345.0022	6.134055	5197	29.12	4057.981	1.263	0.012809	0.0001781	0.3971
R/LIB 6	335.2098	6.230926	5197	28.67	4056.043	1.210	0.012271	0.0001706	0.3803
R/LIB 5	323.8771	6.346917	5197	28.14	4053.782	1.172	0.011886	0.0001653	0.3681
R/LIB 4	316.8434	6.421101	5197	27.82	4052.37	1.150	0.011663	0.0001622	0.3611
R/LIB 3.3	315.6662	6.433686	5197	27.76	4052.133	1.117	0.011328	0.0001575	0.3507
R/LIB 3.2	316.3224	6.426664	5197	27.79	4052.265	1.117	0.011328	0.0001575	0.3507
R/LIB 3.1	316.979	6.419654	5197	27.82	4052.397	1.117	0.011328	0.0001575	0.3507
R/LIB 2.2	316.7784	6.421795	5197	27.82	4052.357	1.095	0.011105	0.0001544	0.3438
R/LIB 2.1	317.1784	6.417529	5197	27.83	4052.437	1.095	0.011105	0.0001544	0.3438
R/LIB 1.3	321.6893	6.369807	5197	28.04	4053.344	1.140	0.011561	0.0001607	0.3580
R/LIB 1.2	321.5065	6.371728	5197	28.03	4053.307	1.140	0.011561	0.0001607	0.3580
R/LIB 1.1	323.3585	6.352329	5197	28.12	4053.678	1.140	0.011561	0.0001607	0.3581

Table 5
Fixed geometrical parameters of FW-PMU channel having V-ribs.

Outer Dim. of Channel (L x B)	Channel Height	Channel Width	Internal Radius	Length	No. of Channels	Pitch	No. of V-ribs per Channel
0.02 m x 0.02 m	0.015m	0.015m	0.004m	0.285m	6	0.02m	28

Table 6
Fixed geometrical parameters of HCPB FW channels (for COB).

Channel Height	Channel Width	Internal Radius	Length	Pitch
0.012m	0.012m	0.002m	1.48m	0.0165m

Table 6) due to the reason specified in Section 2.2, the parameters that are left to control in order to achieve the appropriate scaling based on the lower bound and upper bound values of the Π^M are described in Table 7. Fig. 4 shows the variation of controlling parameters i.e., incident heat flux, Q'' and the temperature difference ΔT for varying mass flow rate of the coolant for testing in the Prototype Mock-Up based on the preservation of the non-dimensional grouping parameter.

3.3. Hydraulic scaling methodology for FW-PMU manifold section

For the hydraulic scaling of the manifold section, the methodology of scaling the component dimensions is adopted such that consistent velocity field, mass flow distribution and cross-section area variation along the manifold is achieved, the same method proposed by the researchers in [7]. Figs. 5a and 5b shows the schematic geometrical representation of the DEMO Breeder Zone inlet manifold and the manifold section of the mock-up. From the schematic of PMU manifold section (Fig. 5b), it can be seen that the coolant exits the FW channels from both the sides into the flat manifold section. A part of the coolant flow is distributed among the four fuel-breeder pins through two-diametrical opposite holes present in the Outlet Disc (emulating the flow into the Fuel-Breeder Pins of the HCPB shown in Fig. 5a). Remaining flow exits the manifold section through the bypass flow tube. Table 5 describes the various geometrical parameters for hydraulic scaling of the manifold section.

From Table 8, it can be seen that the coolant mass flow rate required to demonstrate the consistent velocity field in the manifold section at cross-section X-X is 98 g/s whereas for cross-section Y-Y, the required mass flowrate is approx. 169 g/s. Thus, average coolant mass flow rate at cross-section X-X is 16.33 g/s per channel and at cross-section Y-Y is 28.21 g/s per channel.

Test parameters for the PMU can be obtained by coupling the thermal-hydraulic scaling of the FW channels and the manifold section. Fig. 6 displays the variation of the controlling test parameters for the FW channels i.e., incident heat flux, Q" and the temperature difference ΔT, for the mass flow rate of the coolant obtained through hydraulic scaling of the manifold section based on the preservation of the non-dimensional grouping parameter.

Table 7
Controlling parameters of FW-PMU channel having V-ribs.

Fixed parameters					Controlling parameters	
Π^M	Transfer Area, A_h (m^2)	Coolant Volume (m^3)	Coolant ρ (kg/m^3)	Coolant c_p (J/kg.s)	$\frac{q''}{(\Delta T)u}$ (W.s/m^3 °C)	$\frac{Q''}{(\Delta T)u}$ (W.s/m^3 °C)
0.3142 0.6061	0.006027	5.98×10^{-5}	6.47	5197	367.98 709.85	389.1 750.58

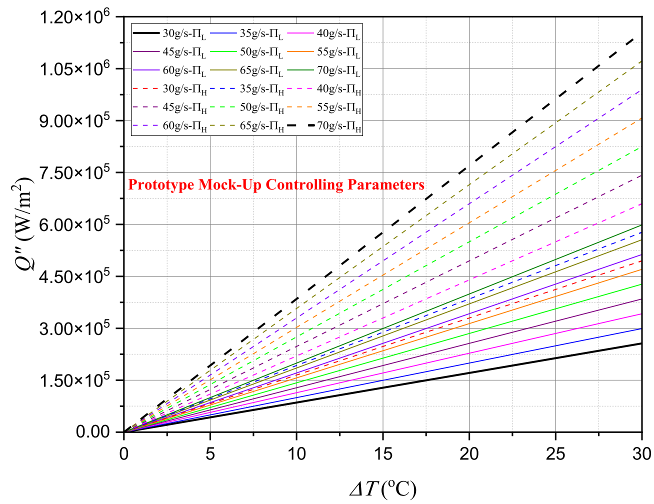

Fig. 4. Controlling parameters for testing in FW-PMU based on scaling analysis.

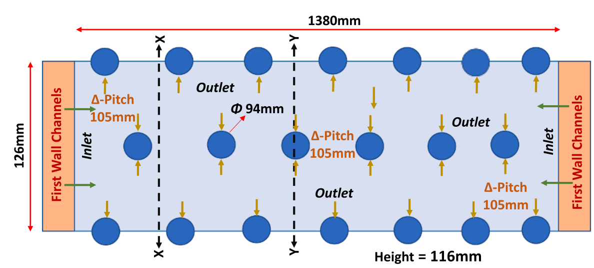

Fig. 5a. Schematic geometry of the DEMO HCPB Manifold.

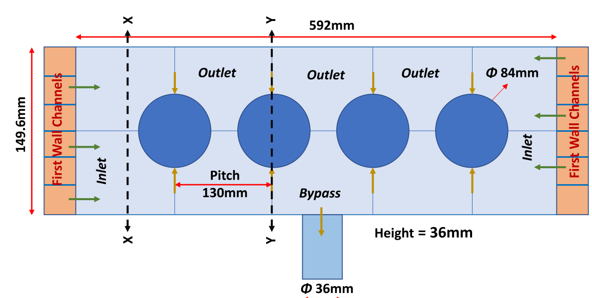

Fig. 5b. Schematic geometry of the PMU Manifold Section.

4. Conclusion

In the present work, significance of the FW-PMU in regards to the DEMO HCPB FW is discussed. In addition, the thermal-hydraulic scaling methodology adopted for designing the prototype mock-up is presented. The scaling methodology adopted for PMU FW channels is Power-to-Volume scaling within the Hierarchical Two-Tiered Scaling methodology (H2TS) deduced by preserving the Characteristic Time Ratio for the FW mock-up and the DEMO FW. For PMU manifold section, the methodology involving scaling of the component dimensions is adopted in order to obtain consistent velocity field and mass flow distribution. Subsequently, test parameters for the mock-up are obtained by coupling

Table 8
Hydraulic scaling parameters for the PMU Manifold Section.

Parameter	DEMO BZ Inlet Manifold (For COB)	PMU Manifold Section
No. of Inlet Channels	$N_D = 7.6$	$N_M = 6$
Cross-section Area at X-X	$A_D^O = 1.46 \times 10^{-2}\ \mathrm{m}^2$	$A_M^O = 5.38 \times 10^{-3}\ \mathrm{m}^2$
Cross-section Area at Y-Y	$A_D^C = 3.7\ \mathrm{m}^2$	$A_M^C = 0.0023616\ \mathrm{m}^2$
Coolant Velocity at X-X	$U_D^O = \frac{\dot{m}_D}{\rho A_D^O} = U_M^O = \frac{\dot{m}_M}{\rho A_M^O}$	
Coolant Velocity at Y-Y	$U_D^C = \frac{\dot{m}_D}{\rho A_D^C} = U_M^C = \frac{\dot{m}_M}{\rho A_M^C}$	
Total Mass Flow Rate at X-X	$\dot{m}_D = 7.6 \times 35g/s = 266g/s$	$\dot{m}_D^O = 98g/s$
Total Mass Flow Rate at Y-Y		$\dot{m}_D^C = 169g/s$

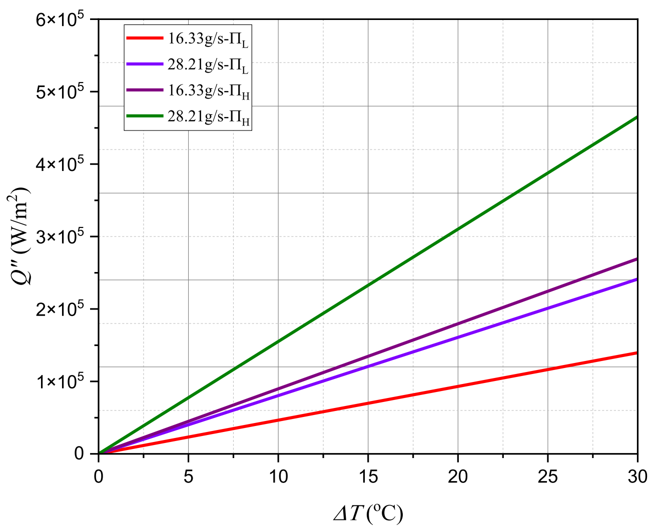

Fig. 6. Controlling parameters for testing in PMU based on coupled thermal-hydraulic scaling.

the thermal-hydraulic scaling parameters of the FW channels and the manifold section. Using the obtained controlling parameters for tests, the data obtained from the tests on the prototype mock-up are applicable to the DEMO HCPB FW.

CRediT authorship contribution statement

Gaurav Verma: Writing – review & editing, Writing – original draft, Methodology, Investigation, Conceptualization. **Guangming Zhou:** Supervision, Resources, Data curation, Conceptualization. **Francisco A. Hernández:** Supervision, Resources, Project administration.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Gaurav Verma reports financial support was provided by EU Framework Programme for Research and Innovation Euratom. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

References

[1] G. Zhou, et al., The European DEMO helium cooled pebble bed breeding blanket: design status at the conclusion of the pre-concept design phase, Energies 16 (14) (2023) 5377, https://doi.org/10.3390/en16145377.
[2] G. Zhou, et al., Thermal hydraulics activities for consolidating HCPB breeding blanket of the European DEMO, Nucl. Fusion 60 (2020) 096008, https://doi.org/10.1088/1741-4326/ab96f2.
[3] M. Rieth, et al., Cost effective fabrication of a fail-safe first wall, in: proceedings of the 1st Joint ITER-IAEA Technical Meeting of Analysis of ITER Materials and Technologies, Monte Carlo, Monaco, 2010, https://doi.org/10.5445/IR/230081118.
[4] L. Commin, et al., A fail-safe and cost-effective fabrication route for blanket first walls, J. Nucl. Mater. 442 (2013) 538–541, https://doi.org/10.1016/j.jnucmat.2013.07.043.
[5] N. Zuber, et al., An integrated structure and scaling methodology for severe accident technical issue resolution: development of methodology, Nucl. Eng. Des. 186 (1998) 1–21, https://doi.org/10.1016/S0029-5493(98)00215-5.
[6] S. Levy, Two-Phase Flows in Complex Systems, John Wiley & Sons, 1999.
[7] A. Collaku, et al., Design of test section for the experimental investigation of the WCLL Manifold hydraulic features, Energies 16 (5) (2023) 2246, https://doi.org/10.3390/en16052246.