Thermal-hydraulic Scaling of the Prototypical Mock-Up for European DEMO HCPB Breeding Blanket First Wall

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Significance of FW-PMU

- Thermal-hydraulic scaling methodology of First Wall (FW)-Prototype Mock-Up (PMU) for DEMO Helium Cooled Pebble Bed (HCPB) Breeding Blanket [1], which reproduces thermal-hydraulic behaviour of HCPB Breeding Blanket FW, is presented.
- Primary objectives of FW-PMU:

a) Demonstration of manufacturing procedure of V-ripped FW using P92 steel
b) Exhibition of capability of V-ripped FW for handling high heat flux (tests)
c) Estimation of flow distribution into each breeder zone channels and manifold (tests)
d) Estimation of pressure-drop across FW and manifold section with flow rate (tests)

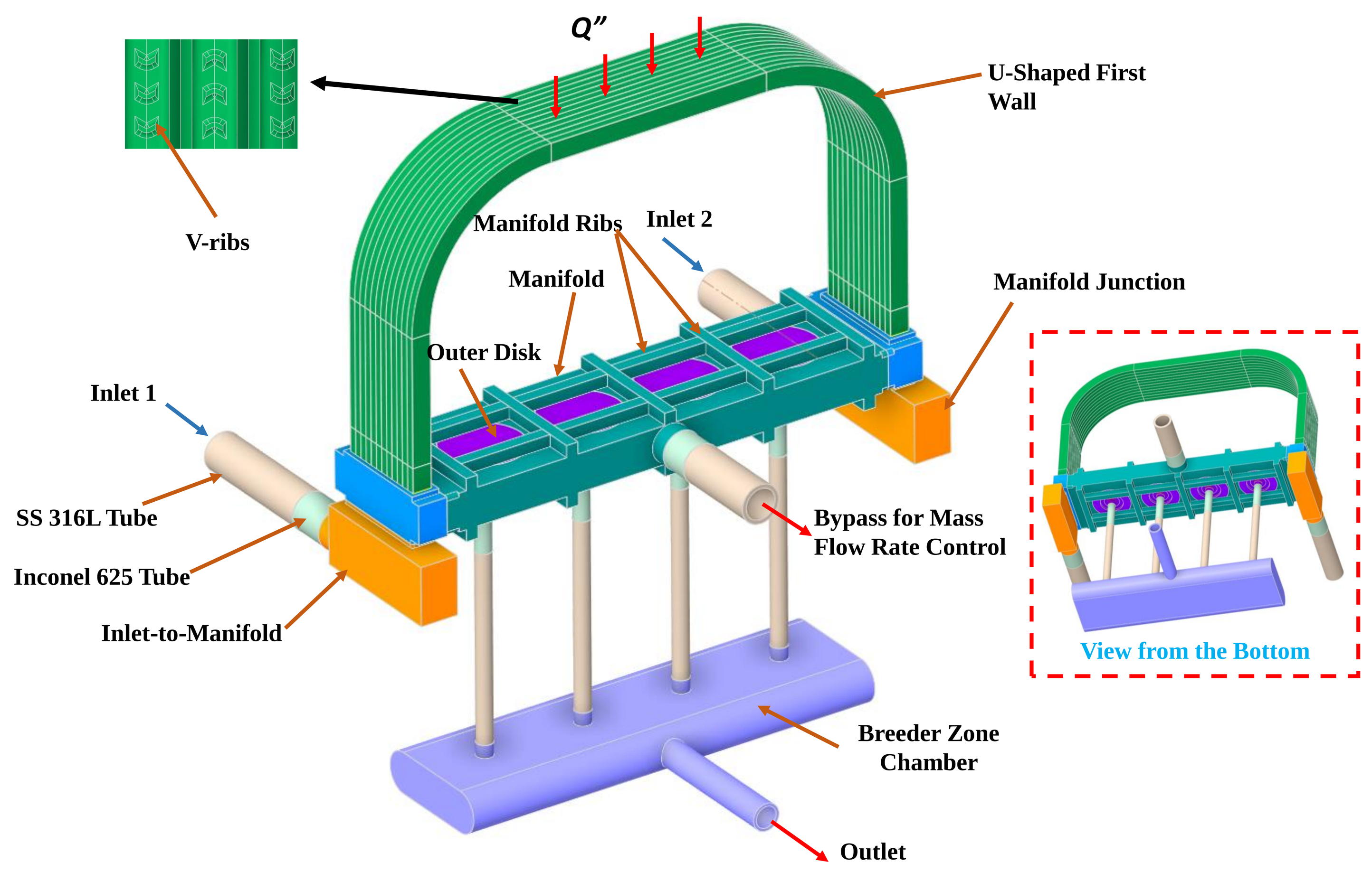

Fig. 1: Component nomenclature of FW – PMU

Scaling Methodology for FW-PMU

- Scaling methodology of **Power-to-Volume scaling** is adopted within Hierarchical Two-Tiered Scaling methodology (H2TS) deduced by preserving Characteristic Time Ratio for FW Channels of PMU and DEMO FW [2].
- For hydraulic scaling of manifold section, methodology of scaling component dimensions is adopted such that consistent velocity field, mass flow distribution and cross-section area variation along the manifold is achieved.

For control volume V_{cv}, volume occupied by a particular constituent C with fraction α_c is V_c

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

→ If constituent C has many phases, for phase P, total volume occupied is V_{cp} with fraction α_{cp} of volume V_c, $V_{cp} = \alpha_{cp} V_c$

↓ For a geometry G of phase P, volume occupied is V_{cpg} is fraction of V_{cp} given by, $V_{cpg} = \alpha_{cpg} V_{cp}$

↓ Volume occupied in control volume by specific geometry of a phase constituent is given as,

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

↓ For each process, spatial scale φ associated is obtained by dividing transfer area A_h by volume V given as, $\varphi = \frac{A_h}{V}$

← For each process, temporal scale τ is defined by the transfer process rate, by incident area A_t and property ψ (per unit volume) being transferred. Temporal scale is expressed as, $\tau = \frac{\psi V}{Q'' A_t} = \frac{1}{\omega}$

↑ Time of interest t for process is transit time and can be described as, $t = \frac{L}{u}$

↑ Thus, non-dimensional grouping Π is expressed as

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

$$Q'' A_t = q'' A_h$$

Fig. 2: Power-to-Volume scaling approach within the Hierarchical Two-Tiered scaling methodology (H2TS) for FW Channels

Thermo-hydraulic Scaling For FW Channels

Table-1: Π estimation for R/LOB of DEMO HCPB FW for h

Segment	T (°C)	ρ (kg/m³)	c_p (J/kg.s)	u (m/s)	h (W/m².s)	L (m)	A_h (m²)	V (m³)	Π^R
R/LOB 1	312.0	6.4732	5197	38.68	4983.8	0.947	0.01055	0.00013	0.3151
R/LOB 2	316.2	6.4279	5197	35.42	4984.6	1.046	0.01165	0.00014	0.3482

Table-2: Π estimation for COB of DEMO HCPB FW for h

Segment	T (°C)	ρ (kg/m³)	c_p (J/kg.s)	u (m/s)	h (W/m².s)	L (m)	A_h (m²)	V (m³)	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

Table-3: Π estimation for R/LIB of DEMO HCPB FW for h

Segment	T (°C)	ρ (kg/m³)	c_p (J/kg.s)	u (m/s)	h (W/m².s)	L (m)	A_h (m²)	V (m³)	Π^R
R/LIB 12	339.89	6.18422	5197	26.41	3678.338	1.614	0.01798	0.000207	0.6059
R/LIB 11	360.77	5.98426	5197	27.30	3682.369	1.536	0.01711	0.000216	0.5265

Table-4: 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	V-ribs per Channel
0.02m x 0.02m	0.015m	0.015m	0.004m	0.285m	6	0.02m	28

- Values of $\alpha_c = \alpha_{cp} = \alpha_{cpg} = 1$ as full control volume is filled with only one constituent in one phase (He gas).
- Lower bound value of Π^R_{Low} = 0.3142 for L/ROB 1 and upper bound value of Π^R_{Hi} = 0.6061 for L/RIB 12.
- To preserve $\Pi^R = \Pi^M$ for FW-PMU, lower bound value of Π^M_{Low} and upper bound value of Π^M_{Hi} is considered.

Table-5: Controlling parameters of FW-PMU channel having V-ribs

Fixed Parameters					Controlling Parameters	
Π^M	Transfer Area, A_h(m²)	Coolant Vol., V (m³)	Coolant, ρ (kg/m³)	Coolant, c_p (J/kg.s)	$\frac{q''}{(\Delta T)u}$ (W.s/m³°C)	$\frac{Q''}{(\Delta T)u}$ (W.s/m³°C)
0.3142	0.006027	5.98 x 10⁻⁵	6.47	5197	367.98	389.1
0.6061					709.85	750.58

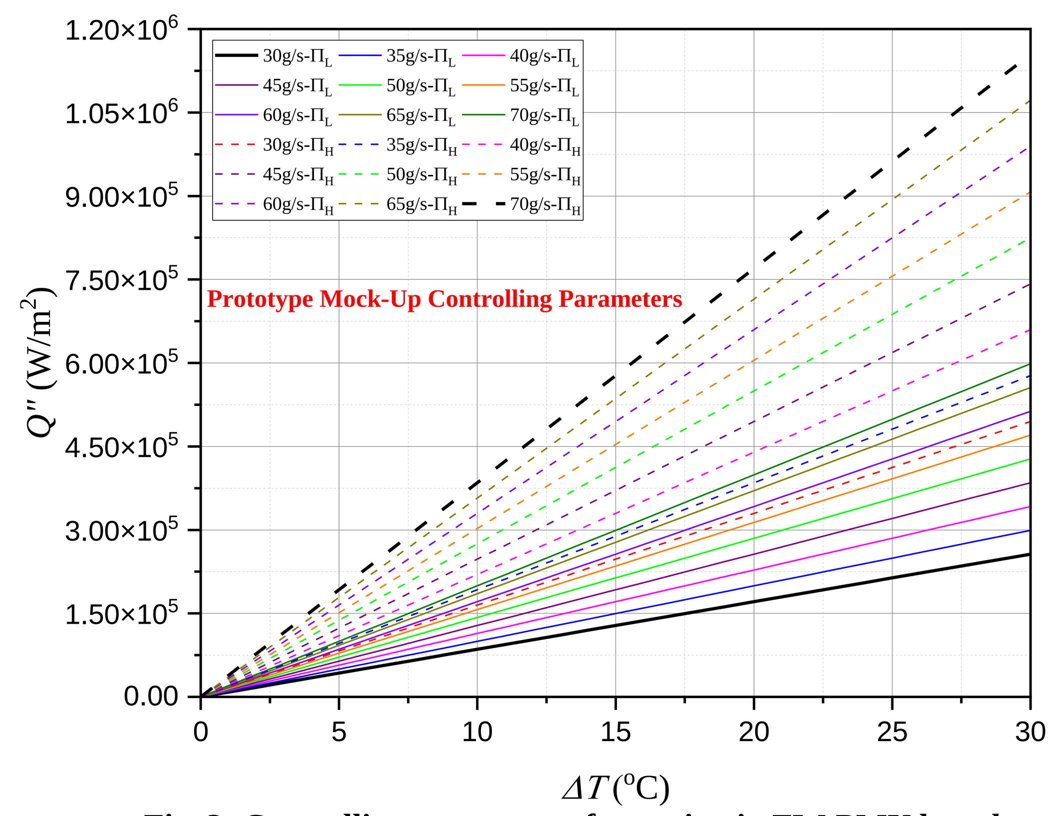

Fig. 3: Controlling parameters for testing in FW-PMU based on scaling analysis

Hydraulic Scaling For Manifold Section

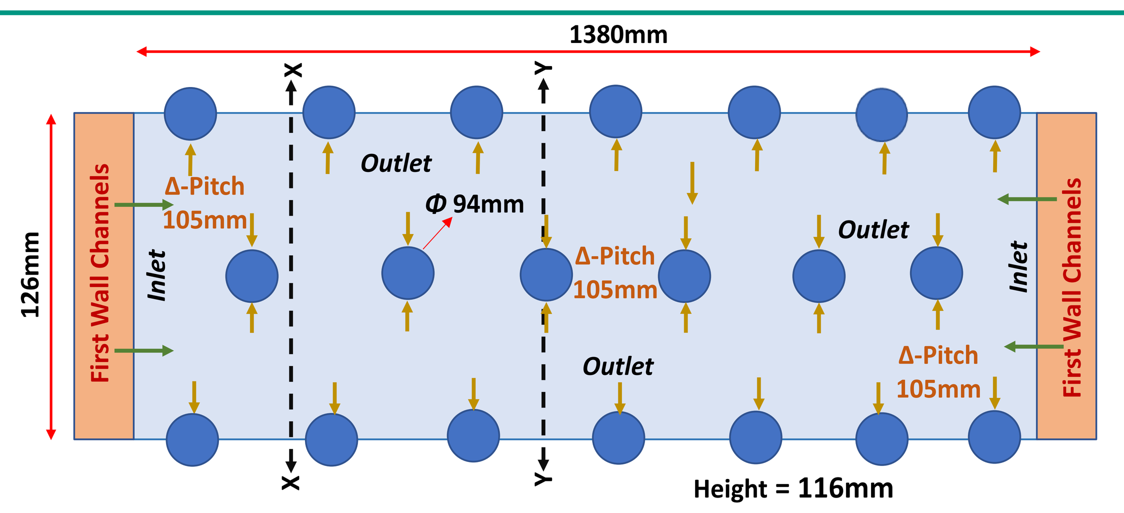

Fig. 4: Schematic geometry of DEMO HCPB Manifold Section

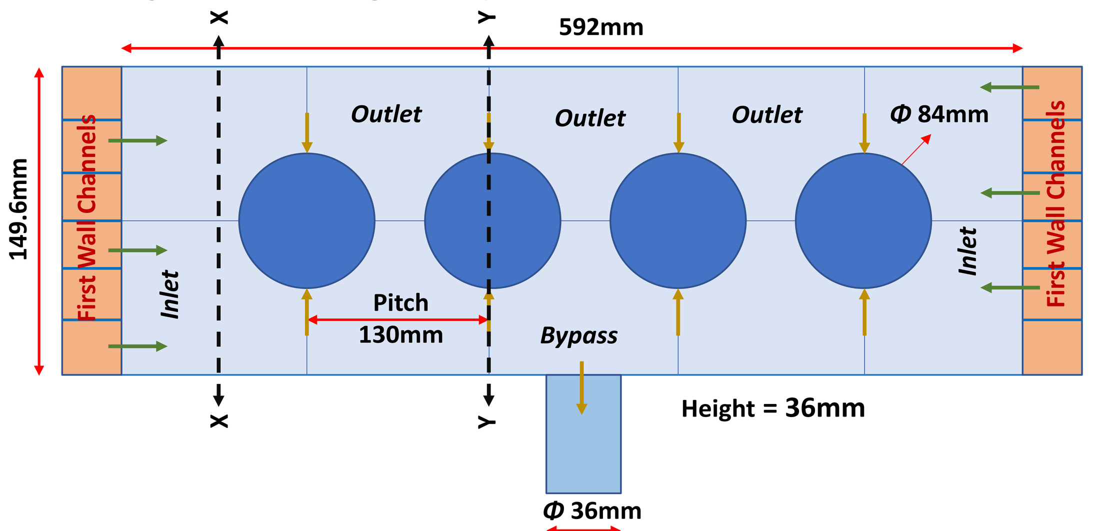

Fig. 5: Schematic geometry of FW-PMU Manifold Section

Table-6: Hydraulic scaling parameters for the PMU Manifold Section

Parameter	DEMO Breeder Zone 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 = 0.014616 m²	A_M^O = 0.0053856 m²
Cross-section Area at Y-Y	A_D^C = 0.003712 m²	A_M^C = 0.0023616 m²
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 x 35g/s = 266g/s	$\dot m_D^O$ = 98g/s
Total Mass Flow Rate at Y-Y		$\dot m_D^C$ = 169.23g/s

- Coolant mass flow for consistent velocity field in manifold at X-X is 98g /s & for Y-Y, the mass flow is 169.23 g/s.
- Average coolant mass flow at X-X is 16.33g/s per channel and at Y-Y is 28.21 g/s per channel.
- Test parameters for FW-PMU are obtained by coupling thermal-hydraulic scaling of FW channels & manifold section.

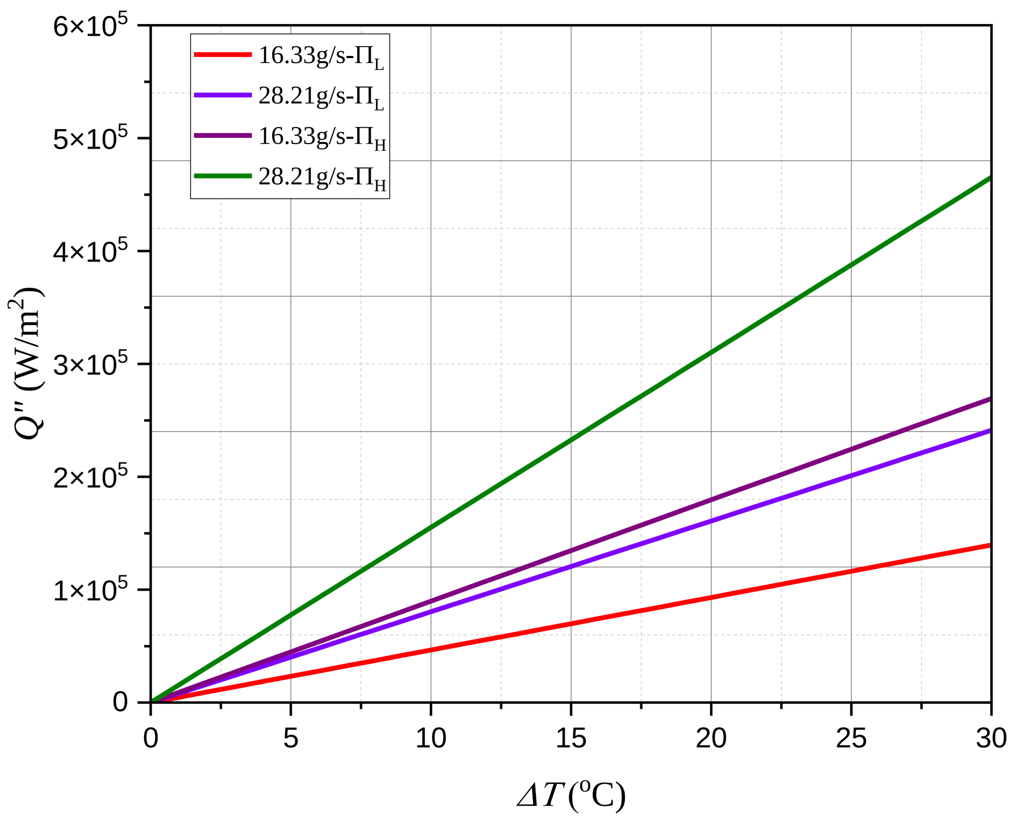

Fig. 6: Controlling parameters for testing in FW-PMU based on Coupled thermal-hydraulic Scaling

Abbreviation

- 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'': flux through the 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

Conclusion

- In the present work, scaling methodology adopted for PMU FW channels is **Power-to-Volume scaling** within Hierarchical Two-Tiered Scaling methodology (H2TS) deduced by preserving Characteristic Time Ratio for FW-PMU and the DEMO FW.
- For PMU manifold, methodology involving scaling of component dimensions is adopted to obtain consistent velocity field and mass flow distribution.
- Test parameters for PMU are obtained by coupling the thermal-hydraulic scaling parameters of FW channels and the manifold section. Using the obtained controlling parameters for tests, the data obtained from tests on FW-PMU are applicable to the DEMO HCPB FW.

[1] G. Zhou et al., Design of a prototypical mock-up of first wall for the EU-DEMO Helium Cooled Pebble Bed breeding blanket, ID 35, SOFT-2024.
[2] Zuber, N. et al., An integrated structure and scaling methodology for severe accident technical issue resolution: Development of methodology. Nuclear Engineering and Design 186 (1998) 1-21.

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