Experimental Investigation of Heat Transfer Performance of the Helium-cooled Annular Gap in the Breeder Zone of the EU-DEMO HCPB Breeding Blanket

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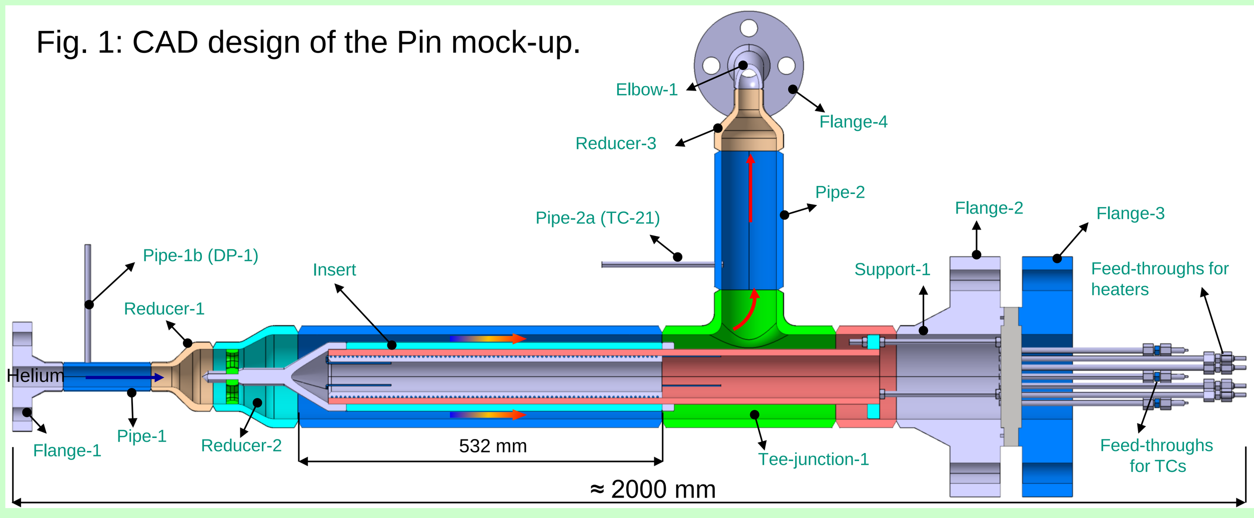
Introduction

- The conceptual design of the Helium-Cooled Pebble Bed (HCPB) breeding blanket has been modified recently (in 2017) via introducing a new design of the breeder zone that is called the Fuel-breeder Pin.
- A mock-up of this Fuel-breeder Pin has been manufactured and then tested in the Helium Loop Karlsruhe (HELOKA) facility in order to investigate its thermal-hydraulic performance under the HCPB operating conditions (i.e., coolant helium at 300 °C and 8 MPa pressure).

Objective

- The focus of this study is on the heat transfer performance of the coolant annular gap (15 mm) of the Fuel-breeder Pin mock-up.
- In particular obtaining the experimental Nusselt (Nu) numbers and investigating the possibility of enhancing the heat transfer of the coolant gap by changing the surface characteristics of its inner surface, which is formed by what is called the mock-up Tube-3.

Fig. 1: CAD design of the Pin mock-up.



Experimental Setup

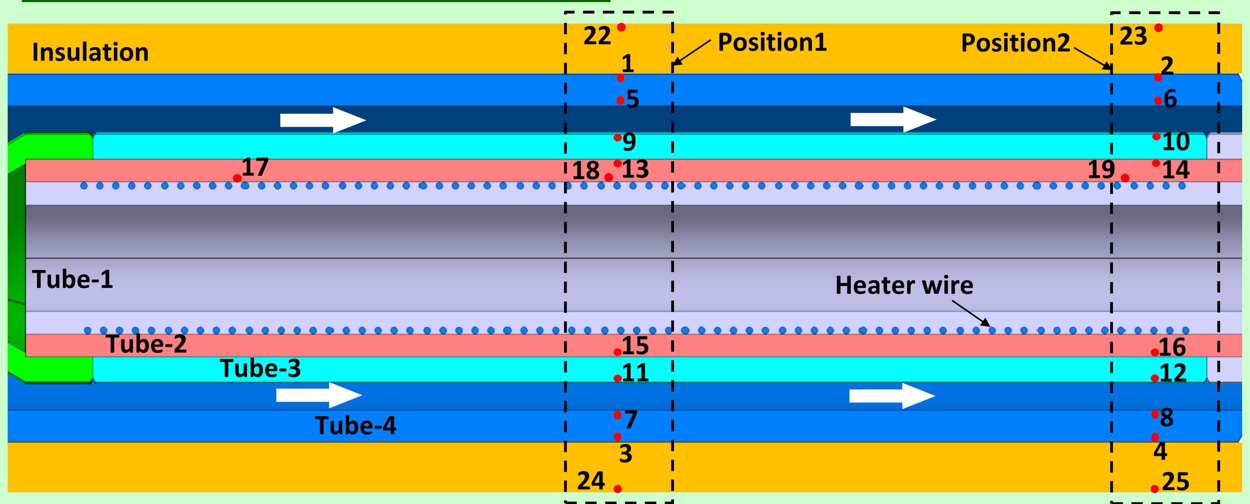


Fig. 2: The tubes & thermocouples TCs (numbers indicate TCs locations).

- Thermocouples TC-1 to TC-8 are the on outer/inner surface of Tube-4.
- Thermocouples TC-9 to TC-12 are on the Tube-3 outer surface.
- TC-13 to TC-16 on outer surface of Tube-2 and TCs-17, 18, 19 inside Tube-2 near the heaters.
- TC-20 & TC-21 for helium inlet/outlet temperatures and TC-22, 23, 24, 25 are on the insulation.
- The mass flow rate is calculated according to ISO 5167-1 from the measured differential pressure across a flow orifice and from the temperature and pressure of the flowing helium.
- Absolute pressure at the inlet and differential pressure across inlet/outlet of the mock-up are measured.

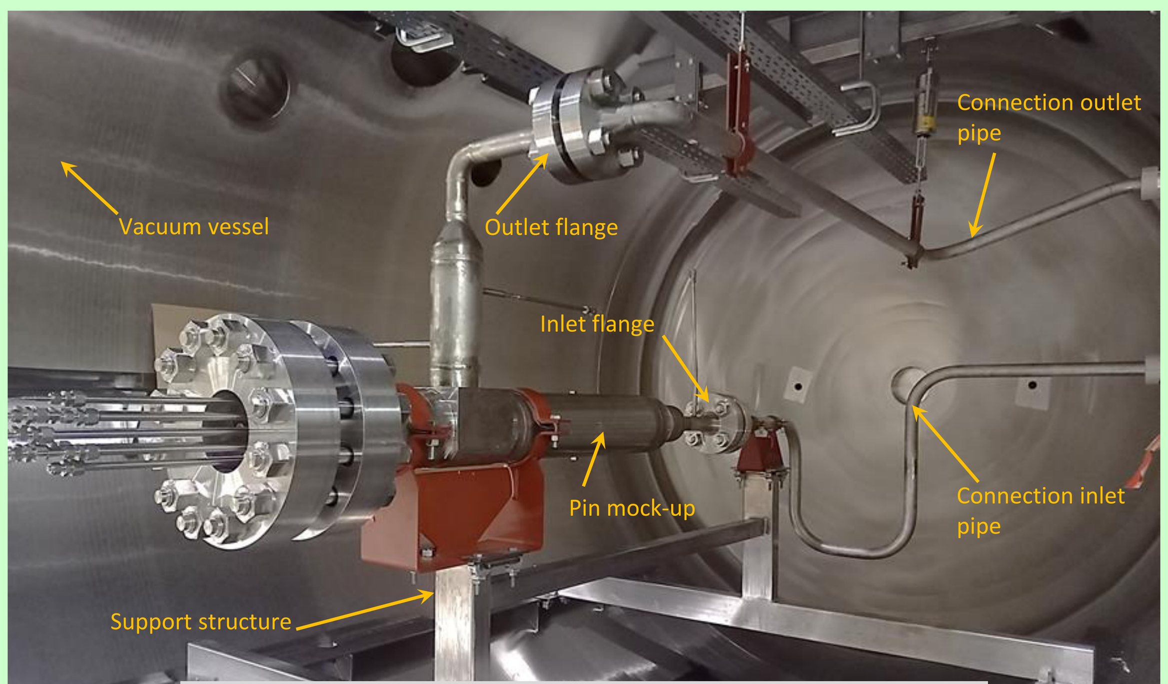


Fig. 3: Pin mock-up is installed inside vacuum vessel.

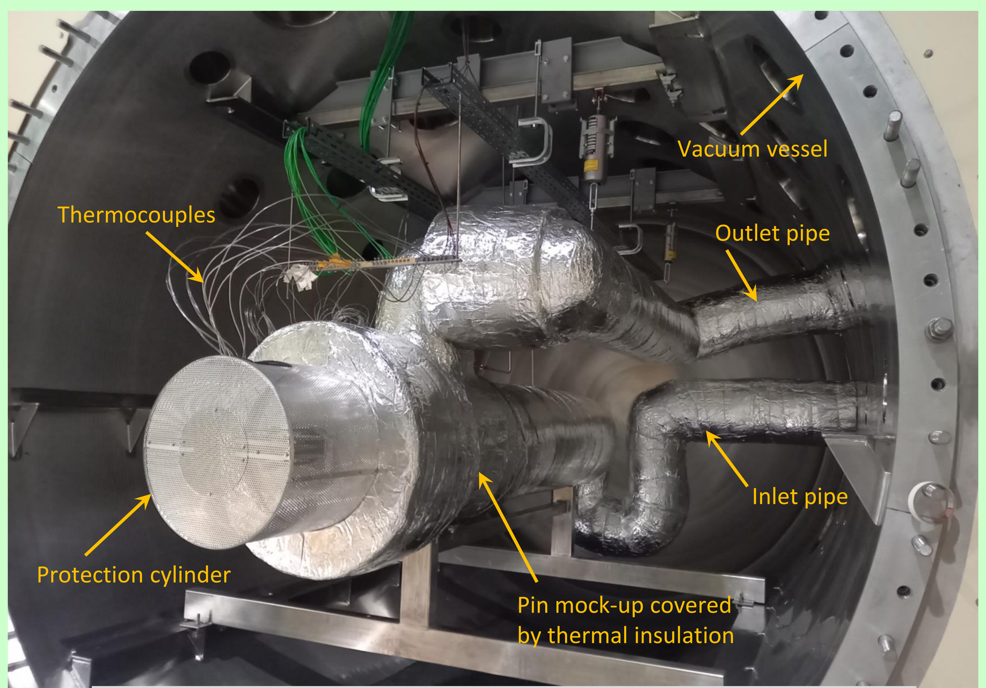


Fig. 4: Pin mock-up after installing thermal insulation.

- The Pin mock-up was installed in the HELOKA Test Section 1 vacuum vessel and connected with the loop pipes via 2 connection pipes (inlet and outlet).
- Thermal insulation was implemented around the mock-up and its pipes in order to maintain the mock-up at high temperature and minimize the heat loss during testing.

Test Matrix

- The Pin mock-up is tested with three different versions of Tube-3 with surfaces as follows: (i) smooth surface, (ii) thread surface, and (iii) high-thread surface as shown below in Fig. 5.
- Table 1 shows the test matrix implemented in testing the Pin mock-up; where each case is tested twice (2 runs).
- The Nu number is calculated using the experimental measurements of the temperatures, mass flow rate and heating power.

Table 1: Test matrix.

Case No.	Mass flow rate [g/s]	Heaters Power [W]	Re
1	25	448	4000
2		672	
3		897	
4		1122	
5		1348	
6	38	671	6000
7		1008	
8		1345	
9		1683	
10		2022	
11	51	895	8000
12		1344	
13		1794	
14		2245	
15		2696	
16	64	1119	10000
17		1680	
18		2242	
19		2806	
20		3370	

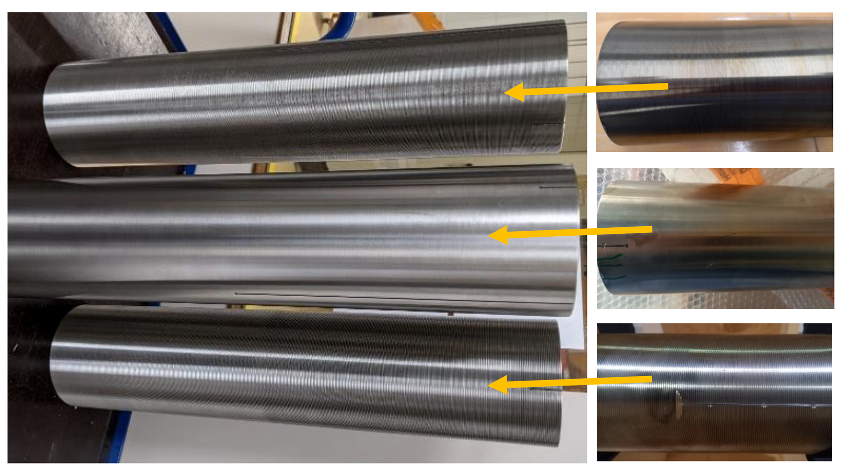


Fig. 5: Tube-3 with smooth and thread surfaces.

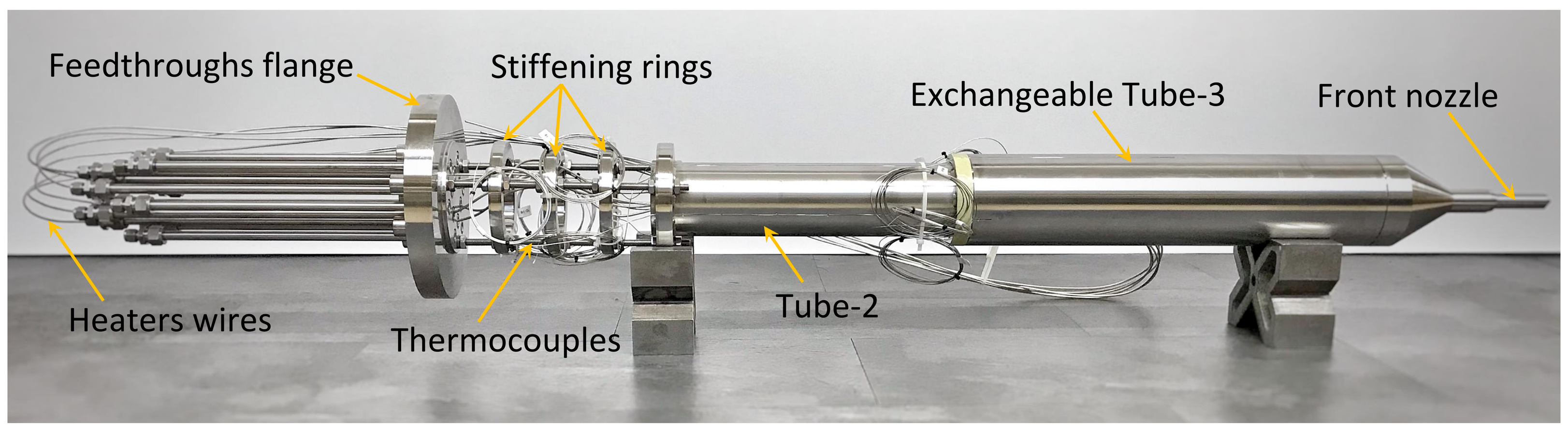


Fig. 6: The insert assembly with smooth-surface Tube-3.

Fig. 7: Installing the coiled heaters on of Tube-1.

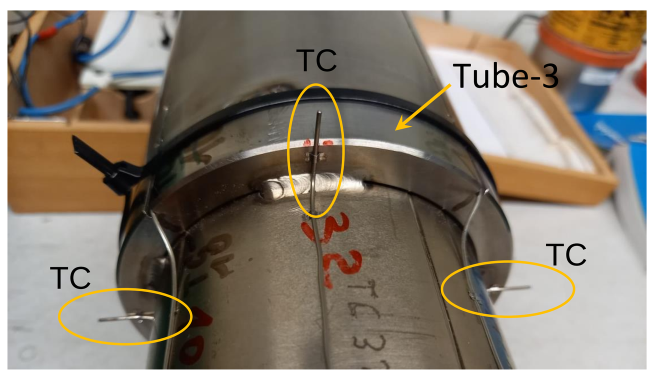


Fig. 8: Four TCs for helium bulk temperature.

Experimental Results

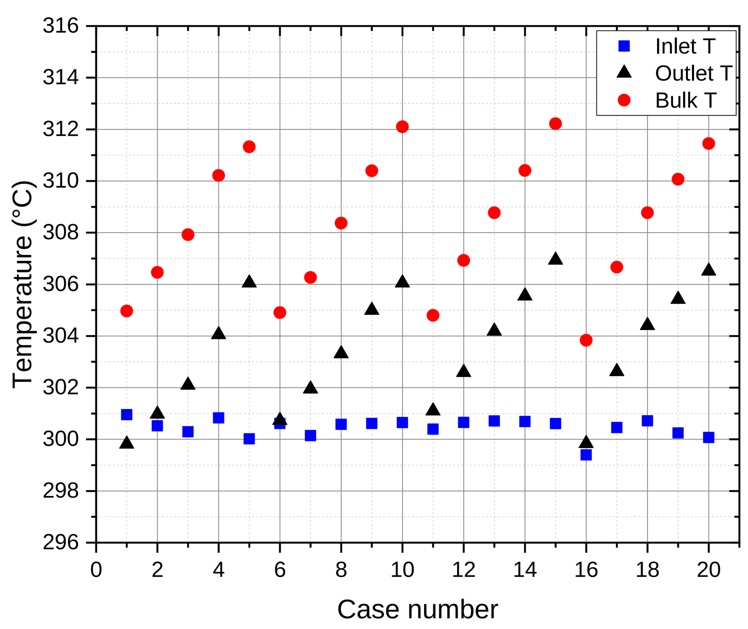


Fig. 9: Inlet, outlet & bulk helium T for smooth-surface Tube-3.

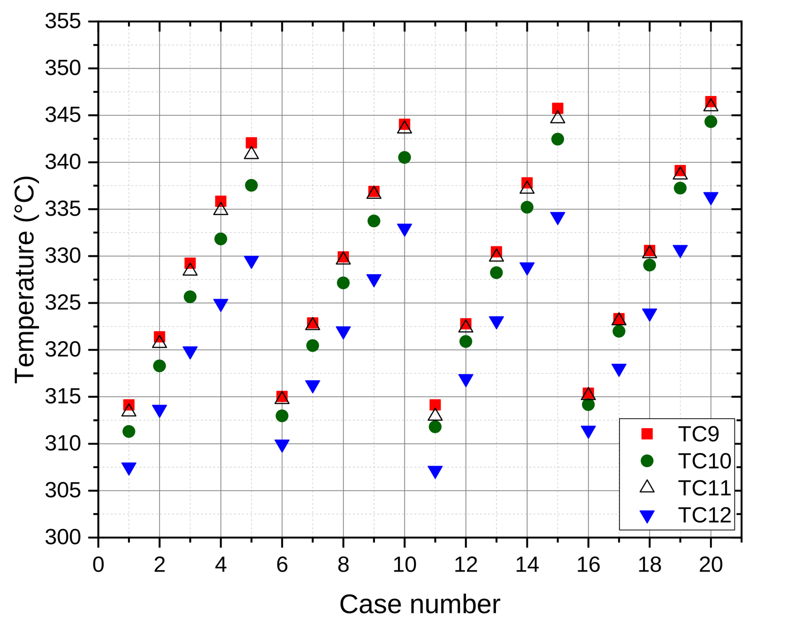


Fig. 10: TCs 9 to 12 for the high-thread-surface Tube-3.

Data Processing

$$Nu = \frac{D_h}{\lambda_f} * \frac{q''_w}{T_w - T_f} \qquad q''_w(r) = -\frac{\lambda}{r}\frac{T_2 - T_1}{\ln(r_2/r_1)}$$

$$T_{wall} = T_2 - \left|\frac{q''_w(r_{wall})}{\lambda} \cdot r_{wall} \cdot \ln\left(\frac{r_{wall}}{r_2}\right)\right|$$

$$T_f(x) = T_{inlet} + \frac{Q(x)}{c_p \cdot \dot{m}} \qquad Q(x) = Q_{in}(x) - Q_{loss}(x)$$

$$Q_{in}(x) = \frac{x}{L} Q_{measured}$$

$$Q_{loss}(x) = -2\pi x \cdot \lambda \frac{T_2 - T_1}{\ln(r_2/r_1)}$$

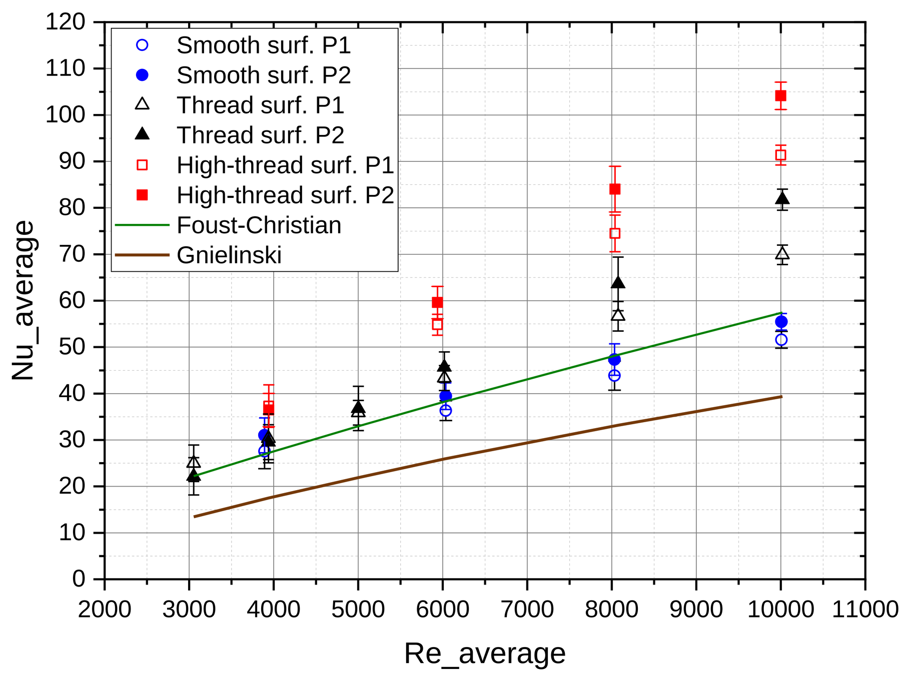


Fig. 11: Nu numbers obtained for the 3 different surfaces of Tube-3 (P1: Position1 & P2: Position2).

Gnielinski correlation:

$$Nu = \frac{\frac{\varepsilon}{8}(Re - 1000)Pr}{1 + 12.7\sqrt{\frac{\varepsilon}{8}}\left(Pr^{\frac{2}{3}} - 1\right)}\left[1 + \left(\frac{d}{L}\right)^{\frac{2}{3}}\right]K$$

Foust-Christian correlation:

$Nu = 0.04\, a\, Re^{0.8}\, Pr^{0.4} / (a + 1)^{0.2}$

a : annular diameter ratio.

- The Nu numbers increase with the change of Tube-3 from smooth surface to thread surface to high-thread surface as shown in Fig. 11.
- The Nu numbers show a similar trend of almost linear increase with the increase of Re numbers.
- The Foust-Christian correlation gives the best agreement with the experimental Nu numbers of the smooth-surface Tube-3; while Gnielinski correlation gives lower Nu numbers.
- The uncertainty of experimental Nu numbers range from 2% to 12% for all given values in Fig. 11.

Summary

- The Pin mock-up was tested in HELOKA (using helium at 300 °C and 8 MPa pressure) with different surfaces (smooth and thread) of the coolant gap.
- The experimental Nu numbers as a function of Re numbers are presented and compared with those calculated by the relevant Nu correlations.
- Particularly, the impact of the different surface characteristics of the coolant gap on the Nu numbers is discussed.
- The next testing of the Pin mock-up will include Tube-3 with random high surface roughness (with Rz up to 1300 μm).

EUROfusion

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