Experimental Thermal-hydraulic Testing of a Prototypical Mock-up of the Fuel-breeder Pin Concept for the EU-DEMO HCPB Breeding Blanket

Ali Abou-Sena, Bradut-Eugen Ghidersa, Guangming Zhou, Joerg Rey, Francisco A. Hernández, Martin Lux, Georg Schlindwein
Karlsruhe Institute of Technology (KIT), Germany

Introduction

- The previous Breeder Unit (BU) has two U-shaped cooling plates with many small cooling channels (5 × 3 mm^2 cross sections), leading to a large pressure drop and hence a large circulating power for the coolant; in addition to a lower efficiency of the power plant.
- In 2017, a new design of the BU, namely Fuel-breeder Pin, was introduced by the design team of the Helium Cooled Pebble Bed (HCPB) Breeding Blanket.
- The relevant analyses revealed that the Fuel-breeder Pin concept produced a pressure drop significantly lower than that produced by the previous BU design.

Objectives

- To (i) perform a proof-of-concept testing of a Prototypical Mock-Up (PMU) of the HCPB Fuel-breeder Pin with relevant manufacturing technologies under the HCPB operating conditions, and (ii) use the experimental data to evaluate the PMU thermal-hydraulic performance (e.g. cooling capability) and to validate the CFD thermal-hydraulic calculations.
- The focus is on the annular gap (between tritium breeder and neutron multiplier) for the return flow and considering the possibility of enhancing the heat transfer by increasing the surface roughness.

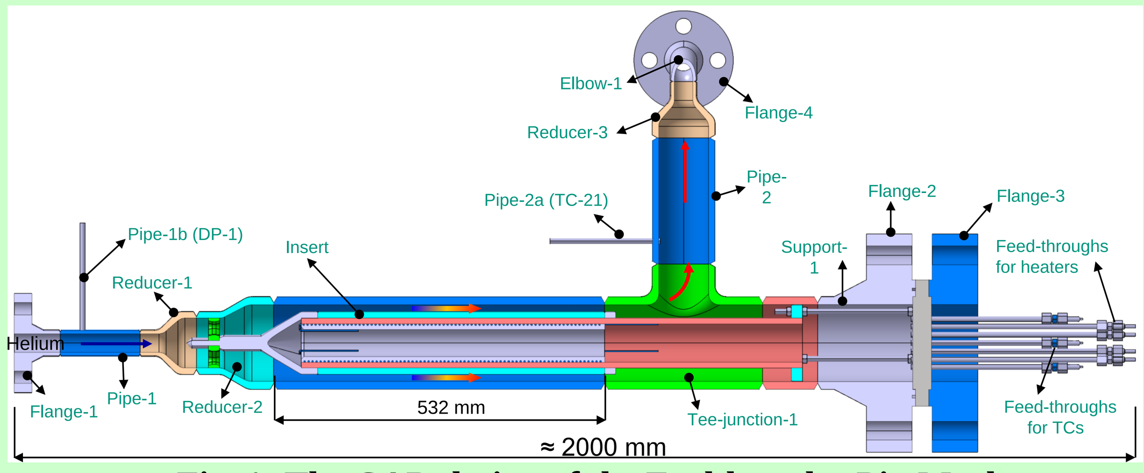

Fig. 1: The CAD design of the Fuel-breeder Pin Mock-up.

Experimental Setup

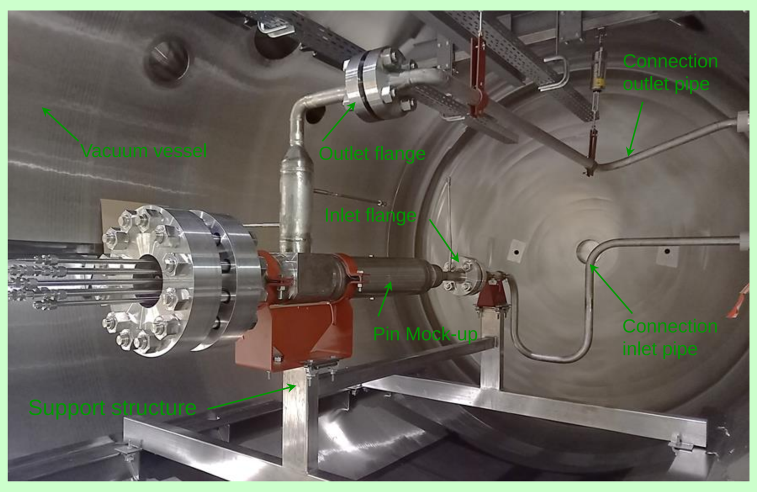

Fig. 2: Pin PMU is installed inside vacuum vessel.

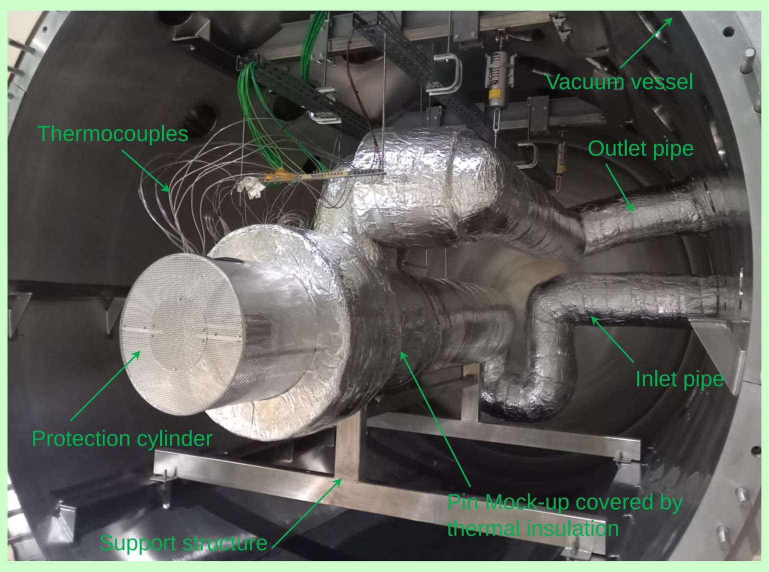

Fig. 3: Pin PMU after installing thermal insulation.

- The fuel-breeder pin PMU is tested in the Helium Loop Karlsruhe (HELOKA) facility that can provide the HCPB blanket-relevant conditions (helium at 300°C and 8 MPa pressure).
- The PMU was installed in the HELOKA Test Section 1 vacuum vessel and connected with the loop pipes via 2 connection pipes (inlet & outlet).
- The design, manufacture and installation of the connection pipes were performed by an industrial contractor. The pipes were designed to withstand a helium pressure of 110 bar and helium temperature up to 550°C.
- After installing the mock-up, a leak test was performed for the connection flanges.

Temperature Measurements

- TC-1 to TC-8 are on outer / inner surface of Tube-4.
- TC-9 to TC-12 are on the outer surface of Tube-3.
- TC-13 to TC-16 are on the outer surface of Tube-2.
- TCs-17, 18, 19 are inside Tube-2 near the heaters.
- TC-20, TC-21 for helium inlet/outlet temperatures.
- TC-22, 23, 24, 25 are on the insulation surface.

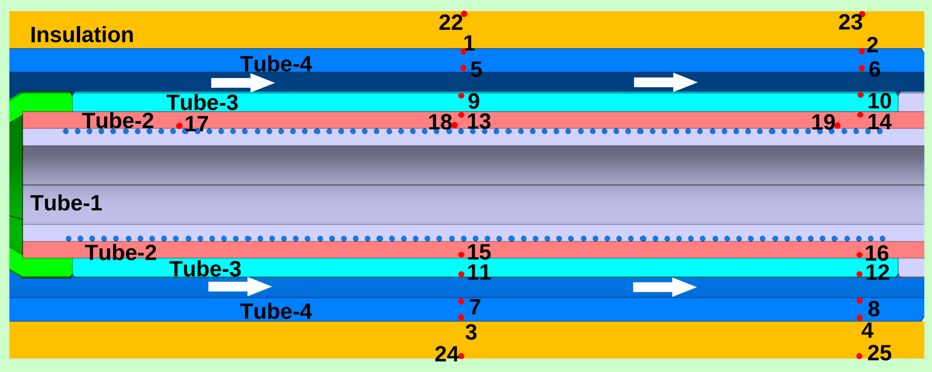

Fig. 4: The numbers indicate the thermocouples locations.

Pressure Measurements

- Absolute pressure sensor at the inlet of the mock-up.
- Differential pressure sensor to measure the pressure difference across inlet/outlet of the mock-up.
- Mass flow meter (consists of flow orifice, differential pressure sensor, absolute pressure sensor & TC).

Mass Flow Measurement

- The mass flow rate is calculated according to ISO 5167-1 from the measured pressure difference across a flow orifice and from the characteristics of the flowing helium.
- Helium density is determined using the measured absolute pressure and temperature.

Test Matrix

- It is planned to test the Pin PMU with three different inserts as follows: (i) insert 1 with hydraulically smooth surface, (ii) insert 2 with middle rough surface, and (iii) insert 3 with high rough surface.
- Table 1 shows the test matrix implemented in testing the first insert. Each case was tested two times (2 runs).
- Figure 5 shows the assembly of the first insert with the other parts.

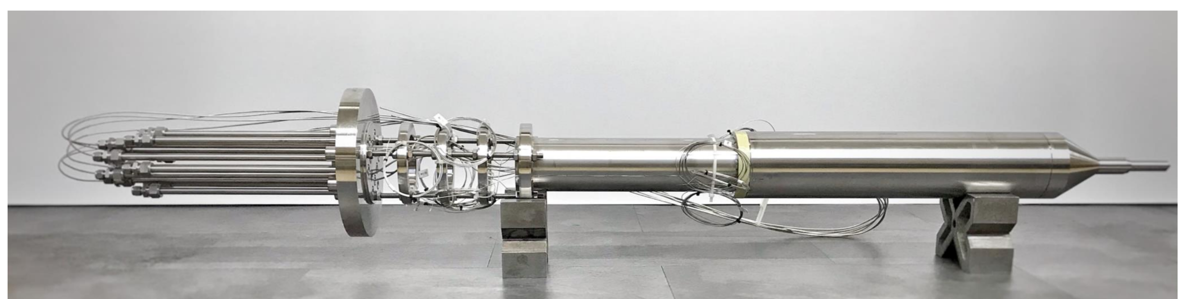

Fig. 5: The first insert assembly.

Table 1: Test matrix.

Case No.	Mass flow rate [g/s]	Heaters Power [W]	Re
1	18 - 19	528	2900 - 2970
2		793	
3		1059	
4		1325	
5		1592	
6	27 - 28	792	4325 - 4600
7		1189	
8		1588	
9		1987	
10		2388	
11	37 - 38	1056	5700 - 6060
12		1586	
13		2117	
14		2650	
15		3183	
16	46 - 47	1320	7200 - 7400
17		1982	
18		2646	
19		3312	
20		3979	

Experimental Nu Values vs. Correlations

Foust & Christian [1]:
$Nu = 0.04\, a\, Re^{0.8} Pr^{0.4} / (a + 1)^{0.2}$
a : annular diameter ratio.

McAdams [2]:
$Nu = 0.03105\, a^{0.15} (a - 1)^{0.2} Re^{0.8} Pr^{1/3} (\mu / \mu_w)^{0.14}$
μ_w : viscosity at wall temperature.

Davis [3]:
$Nu = 0.038\, a^{0.15} (a - 1)^{0.2} Re^{0.8} Pr^{1/3} (\mu / \mu_w)^{0.14}$

Wiegand [4]:
$Nu = 0.023\, a^{0.45} Re^{0.8} Pr^{n} (\mu / \mu_w)^{0.14}$
n = 0.2

[1] Foust A.S., Christian G.A., "Non-boiling heat transfer coefficients in annuli", American Institute of Chemical Eng. 36, p. 541-554, (1940).
[2] McAdams W.H., Heat Transmissions 3rd ed., p. 241-244, (1954).
[3] Davis E.S., "Heat transfer and pressure drop in annuli", Transactions of ASME, p. 755-760, (1943).
[4] Wiegand J.H. et al., "Discussion on annular heat transfer coefficients for turbulent flow", American Institute of Chemical Eng. 41, p. 147-153, (1945).

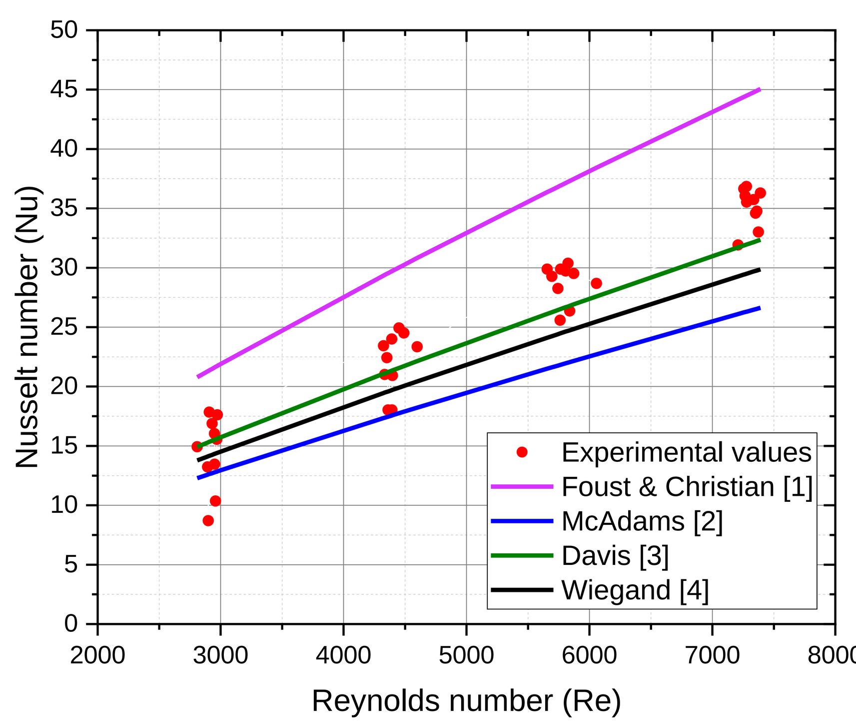

Fig. 6: Experimental values of Nusselt number (Nu) are compared with the correlations' values.

- The experimental Nusselt (Nu) values calculated from the experimental measurements and the relevant heat transfer equations are plotted versus the Reynolds (Re) numbers in Fig. 6.
- The Nu correlation by Davis [3] gives the best agreement with the experimental Nu values.
- Correlations by Wiegand [4] and McAdams [2] give lower values than the experimental ones.

Experimental Results

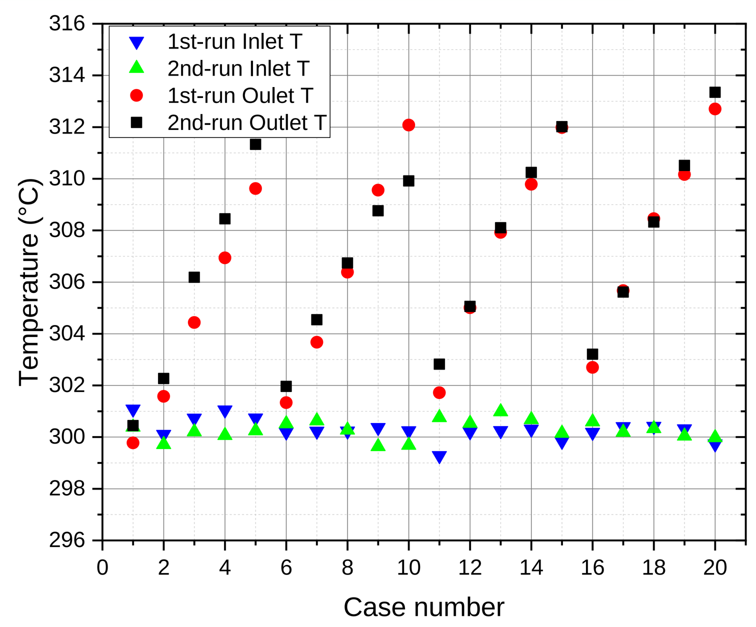

Fig. 7: The inlet and outlet helium temperatures.

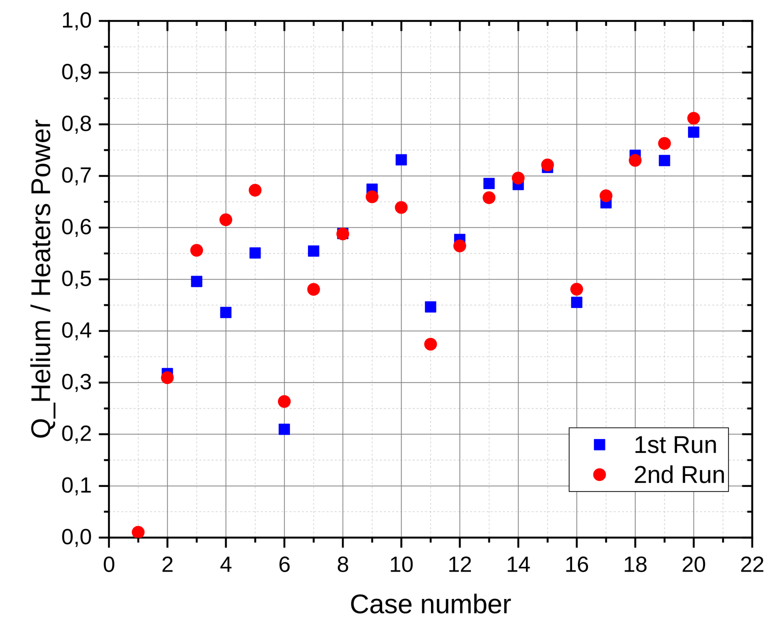

Fig. 8: Heat absorbed by helium divided by heaters power.

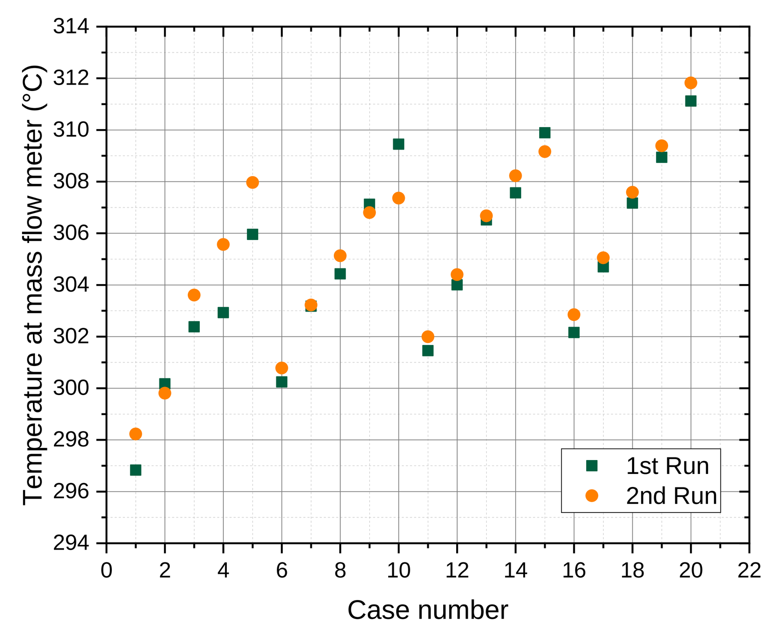

Fig. 9: Temperature used for mass flow calculation.

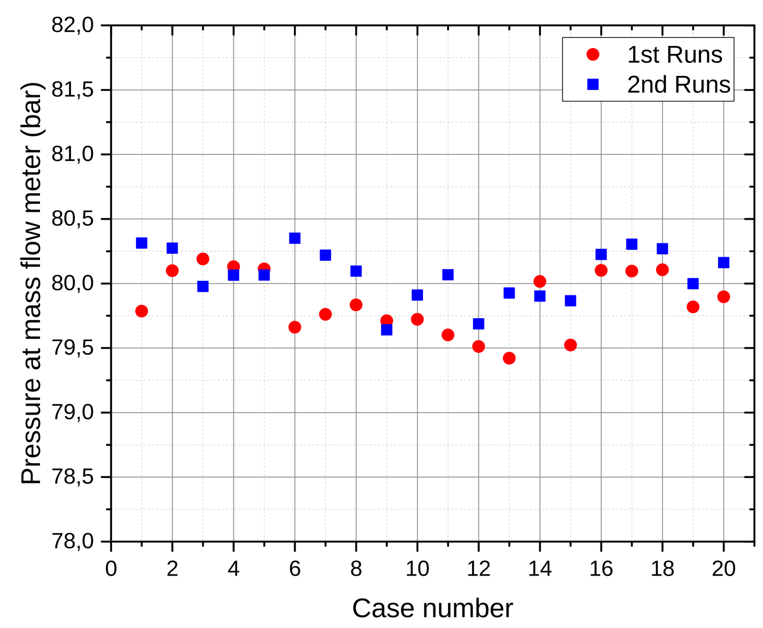

Fig. 10: Pressure used for mass flow calculation.

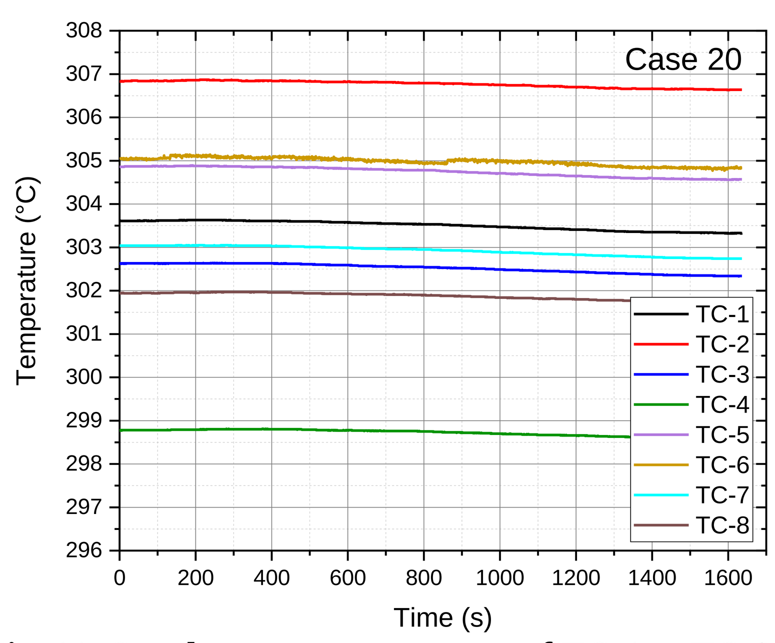

Fig. 11: Steady state temperatures of TC-1 to TC-8.

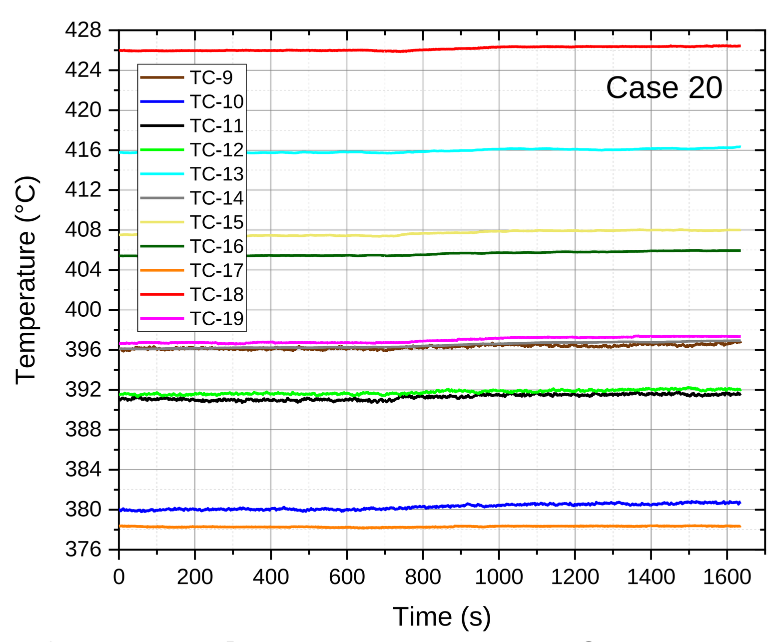

Fig. 12: Steady state temperatures of TC-9 to TC-19.

Summary

- This poster presents: (i) the integration of the fuel-breeder Pin PMU into the HELOKA loop, (ii) the test matrix and the planned experimental campaigns, and (iii) the experimental results with focus on aspects relevant for the validation of the thermal-hydraulic design of the HCPB breeder zone.
- The experimental testing of the Pin PMU with the first insert (smooth surface roughness) was successfully completed in March 2022.
- In the next experimental campaigns, the second insert (with middle rough surface) and third insert (with high rough surface) will be tested.

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