West Pomeranian
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Task: MAG-T.01.01-T049

Hydraulic tests (2025)

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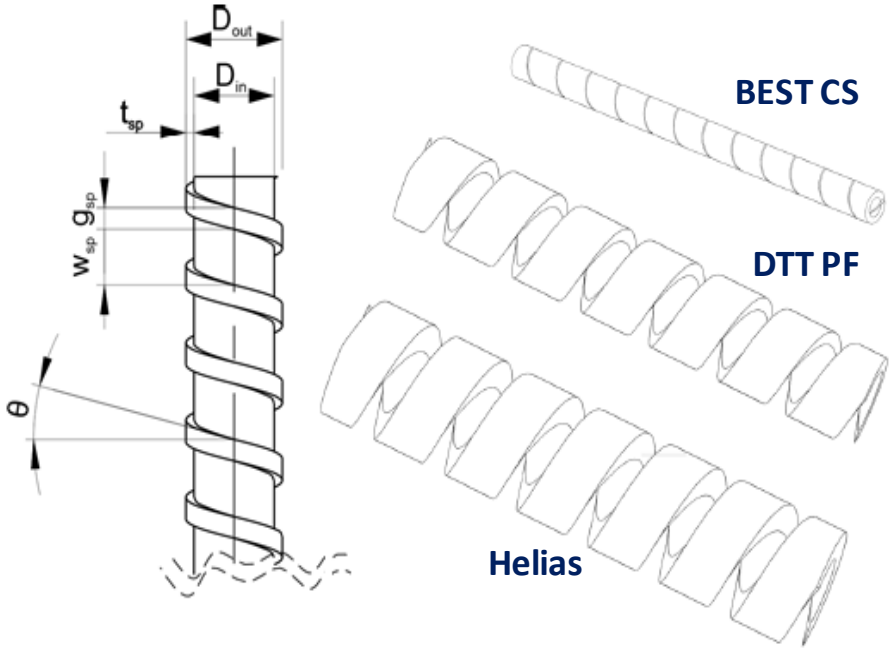
Task specification

Description:

The task will be focused on the hydraulic tests of the available short conductor samples. Two samples with geometry similar to the spiral cooling channels with a small diameter, identical to the cooling channel of the ASIIP CORC conductor and to the cooling channel of the conductor designed by SPC for the HELIAS coil, will be produced (by 3D printing). The samples will be tested for pressure drop at THETIS installation using water at different temperatures in the range from room temperature to about 60°C. The results will provide experimental friction factor correlations to be used in thermal-hydraulic analyses. If there would be such a need, hydraulic tests of short samples provided by other RUs are also possible.

Introduction

- In 2023 we developed a method of producing (by 3D printing) samples with geometry identical to spiral CICC cooling channels, suitable for hydraulic tests at THETIS.
- In 2023-24 we produced and tested 4 samples: one with geometry identical to the ITER Showa spiral (which had already been tested in the past) and 3 identical to the central spirals of the DEMO PF3, PF4 and PF6 conductors designed by CEA with large diameters (D_{out} = 13.6 - 15.8 mm). Spirals with such large diameters had not been tested for pressure drop in the past, so applicability of the available friction factor correlations for them was uncertain.



- We confirmed that the samples obtained by the new method feature the same hydraulic resistance as those produced in the traditional way (spiral insert in a tight pipe) and obtained experimental friction factor correlations for the PF3, PF4 and PF6 spirals, to be used in future TH aanalyses.
- In several conductors recently designed (Helias, DTT PF, BEST CS) there are cooling channels with small diameters (D_{out}/D_{in} = 9/5, 7/5, 4/2.4 mm). There is a lack of experimental pressure drop data for such ducts in the literature.
- **Our focus in 2025 was preparation and hydraulic tests of spiral ducts with small diameters.**

Characteristics of the considered samples

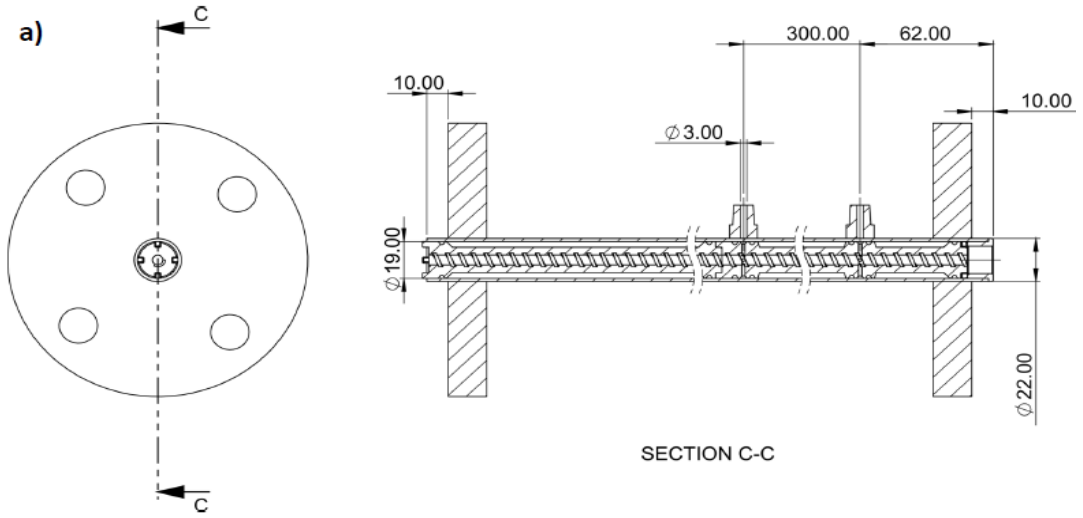
Description	Symbol	Unit	Helias	DTT	BEST
Outer diameter	D_{out}	mm	9	7	4
Inner diameter	D_{in}	mm	5	5	2.4
Spiral width	w_{sp}	mm	4	4	4.89
Gap length	g_{sp}	mm	2	2	**0.2**
Gap fraction	-	%	33.3	33.3	3.9
Flow area	A_{fluid}	mm^2	34.30	25.92	4.84
Hydraulic diameter	D_h	mm	6.89	5.82	2.50
Distance between the pressure taps	L	mm	300	300	

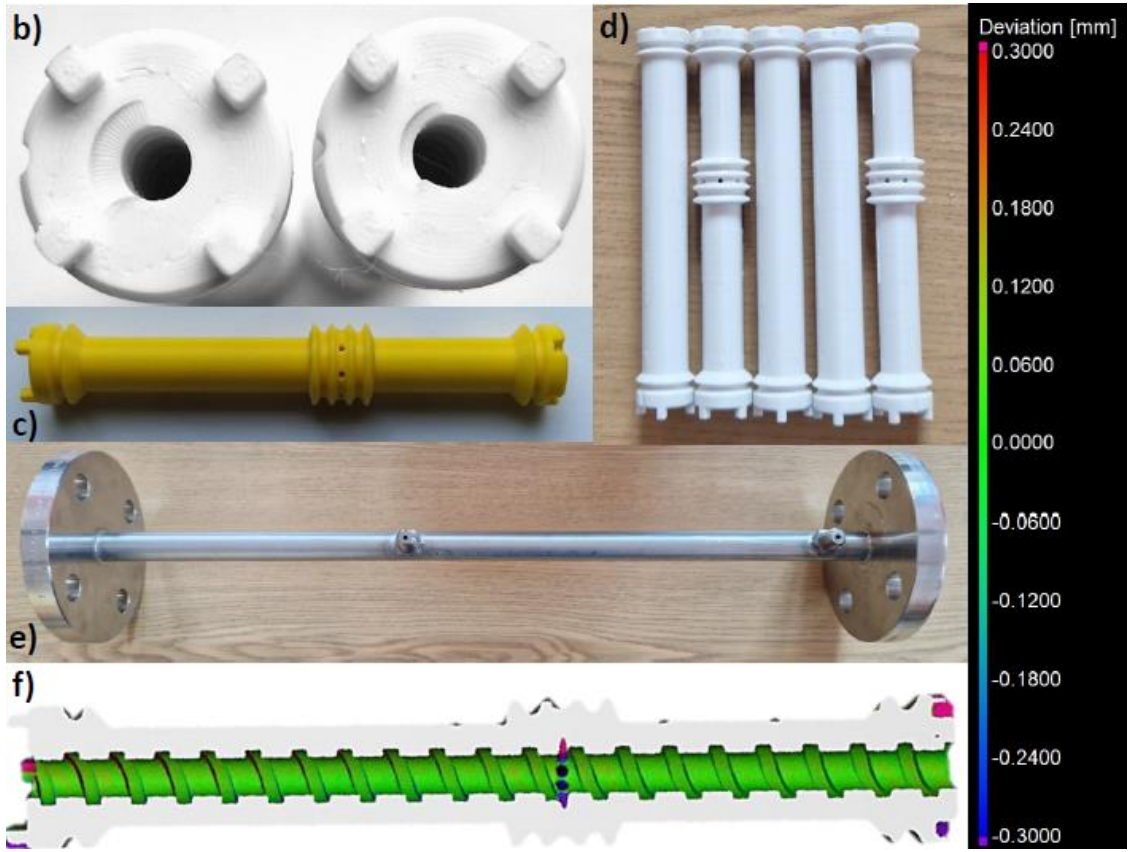
$$A_{fluid} = \frac{\pi}{4}\left[g_{sp} D_{out}^2 + \left(1 - g_{sp}\right) D_{in}^2 \right]$$

$$P_{wet} = \pi\left[g_{sp} D_{out} + \left(1 - g_{sp}\right) D_{in} \right]$$

$$D_h = \frac{4A_{fluid}}{P_{wet}}$$

Preparation of the DTT and Helias samples



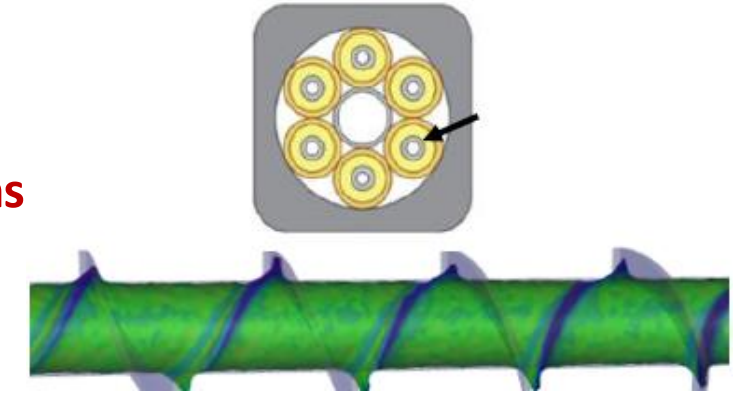


a) schematic drawing,
b)–c) details of the sample components,
d) printed components of the sample,
e) sample ready for the hydraulic test,
f) Industrial CT scanner results of DTT sample (not in scale)

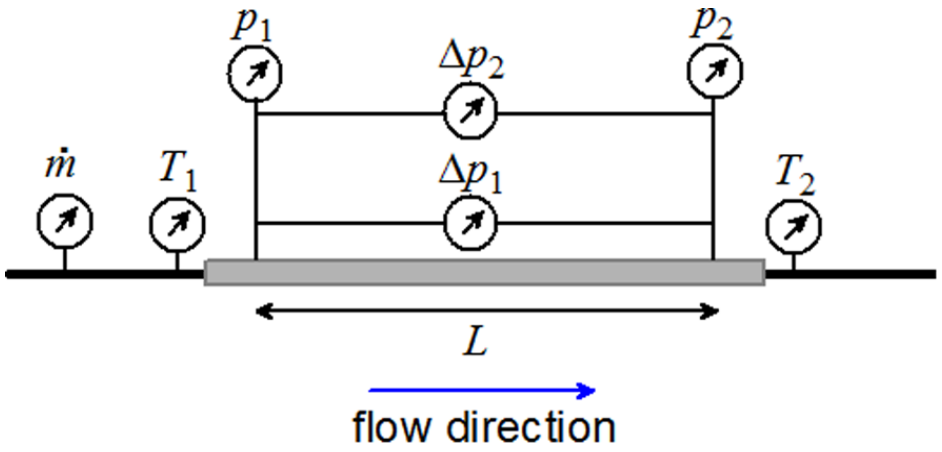
Technology: FDM (Fused Deposition Modeling) 3D printing
Material: ABS (Acrylonitrile Butadien Styrene)
3D printer: FlashForge Creator 4 (the advanced thermal-control system of Creator 4 keeps closed print chamber at 65°C, which effectively reduces model shrinkage, warping at corners, and furnish breakage)
Printing layer thickness: 0.12 mm
Component length: ~125 mm (25 spiral pitches, limited due to its slenderness to avoid deformations during printing)
Two ports for pressure measurement have been designed in the printed elements, each port has 6 holes on the circumference of the sample.

Quality assessment of 3D printed samples geometry using X-ray micro-computed tomography (micro-CT)

- Short pieces of the considered spiral samples (dimensions of 135 x 70 x 70 mm) were scanned using Waygate Technologies VItomeIxS (Bruker)
- Operating voltage of the lamp: 120 kV
- Current intensity: 150 μA
- Magnification: x 1.5
- Voxel size: 19.7 μm^3
- 3D images were saved in 8-bit format, utilizing 256 grayscale values to denote the density of the sample. To enhance the visualisation inside geometry, image segmentation was performed using the BHC method in combination with manual 3 sigma threshold adjustments. The reconstructed 3D images of each specimen comprised 950 x 500 x 500 voxels with a pixel size of 7.3 μm. These 3D volume datasets were further exported to Volume Graphic Metrology software to perform more detailed analysis of the helical grove geometry.
- **It was confirmed that the quality of the Helias and DTT samples geometry was satisfactory ☺**
- **This was not the case with the first BEST CS specimens printed by us ☹.** 3 more specimens were prepared using different nozzles and materials and are ready for scanning.



Instrumentation used in hydraulic tests at THETIS [1,2]



Measuring instrument	Measured quantity	Measuring range	Nominal measurement uncertainty
Flow meter	$\dot{m}$	20 – 3000 kg/h	± 0.15% of measured value
Temperature sensor 1 and 2	T_{in} , T_{out}	-200 – 400 ºC	± 0.15 ºC ± 0.2% of |measured value|
Pressure sensor 1	p_1	0 – 2.5 MPa	± 0.2% of measuring range
Pressure sensor 2	p_2	0 -1 MPa	± 0.2% of measuring range
Differential pressure sensor 1	Δp_1	0 – 0.25 MPa	± 0.1% of measuring range
Differential pressure sensor 2	Δp_2	0 – 1.6 MPa	± 0.1% of measuring range
DAS	-	-	± 0.1% of measuring range

$$f \approx -\frac{\rho D_h A_{fluid}^2}{2\dot{m}^2}\frac{\Delta p}{L}$$

$$\mathrm{Re} = \frac{\dot{m} D_h}{\mu A_{fluid}}$$

water density (ρ) and dynamic viscosity (μ) are calculated at the reference conditions:

$p_{ref} = p_{ambient} + (p_1 + p_2)/2$

$T_{ref} = (T_1 + T_2)/2$.

[1] M. Lewandowska, W. Rachtan, A. Dembkowska, L. Malinowski, L. Zani, Fusion Eng. Des. 124 (2017) 1191–1194.
[2] M. Lewandowska, A. Dembkowska, L. Malinowski, IEEE Trans. Appl. Supercond. 28 (4) (2018) Art. No 4800905.

Friction factor correlations

Experimental friction factors are compared with predictions of correlations for spirals with small diameters available in the literature:

- Correlation for the spiral cooling channel of the DEMO TF CICC (ENEA design) with D_{out}/D_{in} = 6.6/4.6 mm, obtained by CFD simulations [3]:

$$f_{Bon}(\mathrm{Re}) = \frac{1}{4} 0.1687 \cdot \mathrm{Re}^{-0.1129} \qquad \text{for } 2.4 \cdot 10^4 < \mathrm{Re} < 1.6 \cdot 10^5$$

- Empirical friction factor correlation obtained from the hydraulic test of the spiral sample with D_{out}/D_{in} = 7.25/6.25 mm [4]:

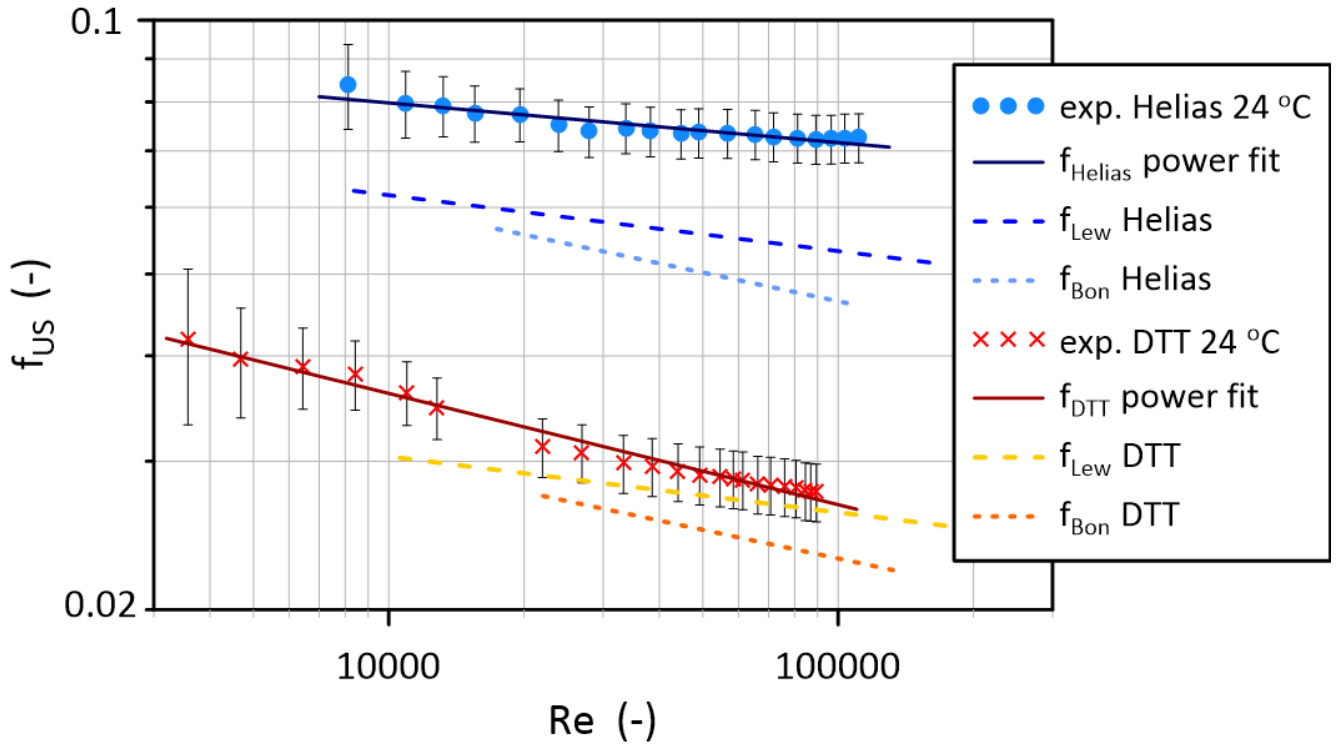
$$f_{Lew}(\mathrm{Re}) = 0.02780 \cdot \mathrm{Re}^{-0.06627} \qquad \text{for } 1.2 \cdot 10^4 < \mathrm{Re} < 2.3 \cdot 10^5$$

[3] R. Bonifetto, P. Bruzzone, V. Corato, L. Muzzi, L. Savoldi, B. Stepanov, IEEE Trans. Appl. Supercond. 28 (2018) Art. No. 4204509.
[4] M. Lewandowska, A. Dembkowska, R. Heller, M. Wolf, J. Świerblewski, Cryogenics 105 (2020) Art. No. 103013.

Test results

$$f_{Helias}(\mathrm{Re}) = 0.1230 \cdot \mathrm{Re}^{-0.04705}$$

$$f_{DTT}(\mathrm{Re}) = 0.1217 \cdot \mathrm{Re}^{-0.1319}$$



- Existing friction factor correlations for small-diameter spirals were found to be inaccurate for the spiral with t_{sp} = 2 mm.
- Friction factors measured at 50–60°C were higher than those at RT. Such a phenomenon had never been observed in our previous tests. This was likely caused by thermal expansion. In high-resistance, small-diameter spirals, even minor dimensional changes can noticeably affect hydraulic test results.
- Given that, we decided to produce and test another pair of DTT and Helias samples to check if the there is any discrepancy in the test results for samples with nominally identical geometry.

Summary and conclusions

- We produced (via 3D printing) two samples with geometries identical to the central cooling channels of the DTT PF conductor (ENEA design) and the Helias conductor (SPC design). Their geometric integrity was confirmed by micro-CT scanning.
- Both samples were tested for pressure drop at the THETIS facility using demineralised water at three different temperatures, ranging from RT to approximately 60^{o} C.
- Unexpectedly, friction factors obtained at higher temperatures were significantly higher than those measured at RT. Such an effect had never been observed in our earlier hydraulic test campaigns. It was most likely due to the thermal expansion of the sample material, which can noticeably affect the pressure drop in high-resistance spirals with small diameters.
- Given the sensitivity of the results to minor changes in spiral geometry, discrepancies between different samples of the same nominal geometry may be expected. To verify this, we recently produced and tested additional DTT and Helias samples.
- The fabrication of a spiral with a very narrow gap (0.2 mm) by 3D printing is highly challenging. Efforts to produce a representative BEST spiral sample are still ongoing.

Thank you very much for your attention

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