Zachodniopomorski Uniwersytet Technologiczny w Szczecinie

Hydraulic characterization of conductor prototypes for fusion magnets

M. Lewandowska[1], A. Dembkowska[1], R. Bonifetto[2], R. Heller[3], Luigi Muzzi[4], Jacek Świerblewski[5], M. Wolf[3]

1. West Pomeranian University of Technology, Szczecin, Poland
2. Politecnico di Torino, Italy
3. Karlsruhe Institute of Technology, Germany
4. ENEA Frascati, Italy
5. Institute of Nuclear Physics Polish Academy of Sciences , Krakow, Poland

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Introduction – basic definitions

- Mathematical models used in thermal-hydraulic analyses of superconducting cables, cooled by forced flow supercritical He (SHe) are typically 1D and they require reliable predictive expressions which characterize mass, momentum and energy transfer between different cable components.
- Momentum transfer is described in terms of friction factor correlations *f*(Re), which can be obtained from the pressure drop measurements or CFD simulations.

$$f \approx -\frac{D}{2\rho v^2}\frac{\Delta p}{L}$$

Fanning friction factor (uncompressible flow)

D - characteristic dimension of the flow, usually a hydraulic diameter $D_h = 4\ A_{fluid} / P_{wet}$

$$f = -\frac{D_h \rho A_{fluid}^2}{2\dot{m}^2}\frac{\Delta p}{L} = -\frac{2\rho A_{fluid}^3}{\dot{m}^2 P_{wet}}\frac{\Delta p}{L}$$

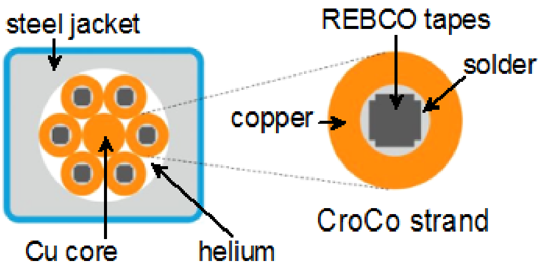
$$\mathrm{Re} = \frac{\rho v D_h}{\mu} = \frac{\dot{m} D_h}{\mu A_{fluid}} = \frac{4\dot{m}}{\mu P_{wet}}$$

Reynolds number

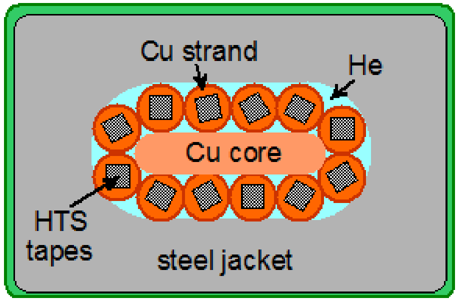
Introduction - motivation

- The European Demonstrator (EU DEMO) fusion reactor, is currently under design. Several design options of EU DEMO superconducting TF, CS and PF coils are under investigation. The reliability of thermal-hydraulic models used to compare the different solutions, is fundamental in order to support the decisions with predictive simulations.

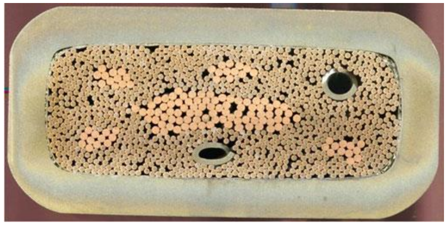
- Forced flow HTS conductors designed for the Winding Demonstrator (WD) experiment [1], as well   as for the EU DEMO TF [2] and CS [3] coils, consist of several twisted stack or CroCo monolythic strands, twisted together or located around a copper core, and embedded in a stainless steel jacket.



- CICCs for the DEMO TF coils designed by ENEA [4] have two low-impedance cooling channels, separated from the cable bundle by flat spirals, with D_{in} / D_{out} $\approx$ 5/7 mm, twisted together with the last cabling stage.

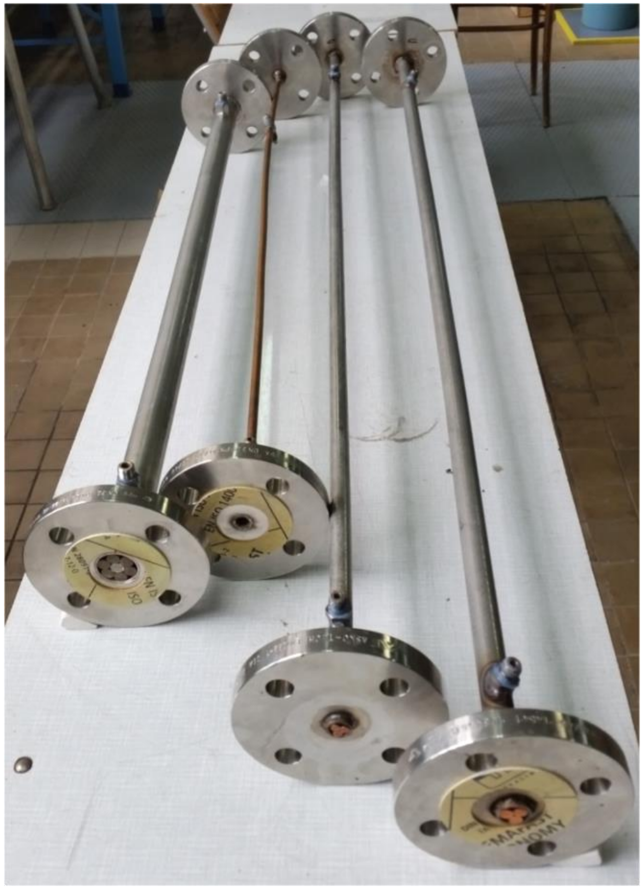


- Such type of conductors and spirals have never been tested for pressure drop yet.
- Therefore, existing friction factor correlations cannot be validated (or new ad hoc ones cannot be developed) before their use in predictive analyses supporting the conductor design.



Introduction - goal of the work

- Four dedicated short samples, namely: 3 dummy conductors with the layout similar to the DEMO HTS or WD conductors and a small spiral-walled pipe, have been prepared and tested for pressure drop using demineralized water at different temperatures.
- We present and discuss the results of these hydraulic tests and develop experimental friction factor correlations for the considered ducts in the EU DEMO relevant Re range.
- The resulting correlations will be utilized in future thermal-hydraulic studies of the DEMO coils or WD.



Introduction – friction factor correlations

The experimental friction factors of dummy conductors are compared with predictions of correlations available in the literature:

- classical correlation for laminar flow in a smooth equilateral-triangle duct [5]

$$f_{lam}(\mathrm{Re}) = 13.33/\mathrm{Re} \quad \text{for} \quad \mathrm{Re} < 2000$$

- classical Bhatti-Shah correlation for the transition and turbulent flow in smooth circular and non-circular ducts [5]

$$f_{BS}(\mathrm{Re}) = \begin{cases} 0.0054 + 2.3 \cdot 10^{-8}\,\mathrm{Re}^{1.5} & \text{for } 2100 < \mathrm{Re} < 4000 \\ 0.00128 + 0.1143\,\mathrm{Re}^{-0.311} & \text{for } 4000 < \mathrm{Re} < 10^{7} \end{cases}$$

- correlation developed for the EURATOM LCT conductor [6], which is currently used in thermal-hydraulic analyses of the HTS conductors designed for the EU DEMO TF and CS coils

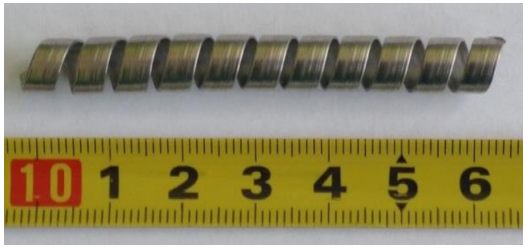
$$f_{LCT}(\mathrm{Re}) = \frac{1}{4} \cdot \begin{cases} 47.65 \cdot \mathrm{Re}^{-0.885} & \text{for } \mathrm{Re} < 1500 \\ 1.093 \cdot \mathrm{Re}^{-0.338} & \text{for } 1500 < \mathrm{Re} < 2 \cdot 10^{5} \\ 0.0377 & \text{for } \mathrm{Re} > 2 \cdot 10^{5} \end{cases}$$

Experimental friction factors of the spiral sample are compared with predictions of the correlation recently developed by CFD simulations for the spiral duct with D_{in} = 5 mm and spiral thickness of 1 mm [7]:

$$f_{spiral\ CFD}(\mathrm{Re}) = 0.042175\,\mathrm{Re}^{-0.1129}$$

Experimental – preparation of the samples

- The "6 around 1" dummy cable, consisting of six copper rods of 10 mm diameter twisted around the central aluminum rod with the same diameter, was prepared by the EPFL-SPC team.
- We cooled the 1 m long piece of the cable in the LN_2 bath and inserted it into a stainless steel pipe with the nominal diameter D_{out}/D_{in} = 33.7/29.7 mm
- The WD8 and WD6 samples were prepared by the KIT team. Each of them is made from a twisted triplet of Cu rods of 8 mm and 6 mm diameter, respectively. The triplets were inserted into the pipes with D_{out}/D_{in} = 21.3/17.3 mm or 17.2/13.2 mm, respectively, and compacted by ~ 0.2 mm.
- The spiral made of the steel strip 4.1 mm x 0.5 mm, with the gap fraction of ~26%, and the D_{out} of ~7.25 mm was inserted into a copper pipe with the nominal dimensions D_{out}/D_{in} = 9.5/7.5 mm, which was subjected to drawing until its D_{out} was reduced down to ~9.3 mm. This sample was provided by the ENEA Frascati team.



Experimental – characteristics of the samples

Parameters of dummy conductors relevant for the present study.
Assumed uncertainties are given in parentheses.

Description	Symbol	Unit	Value		
			6 around 1	WD6	WD8
Number of strands	N_{str}	-	7	3	3
Strand diameter	D_{str}	mm	10 (0.05)	6 (0.05)	8 (0.05)
Tube inner diameter	D_{in}	mm	30.0 (0.3)	12.9 (0.2)	17.1 (0.2)
Cable space area	A_{cs}	mm^2	706.9 (14.1)	130.7 (4.1)	229.7 (5.4)
Flow area	A_f	mm^2	157.1 (14.9)	45.9 (4.3)	78.9 (5.7)
Wetted perimeter	P_{wet}	mm	236.2 (18.6)	73.1 (2)	95.9 (4)
Hydraulic diameter	D_h	mm	2.66 (0.33)	2.51 (0.25)	3.29 (0.27)
Distance between the pressure taps	L	mm	820 (4)	1083 (5)	1083 (5)

Accurate estimation of P_{wet} is problematic - it depends on the unknown length of the strand-strand and strand-jacket contact perimeters ☹

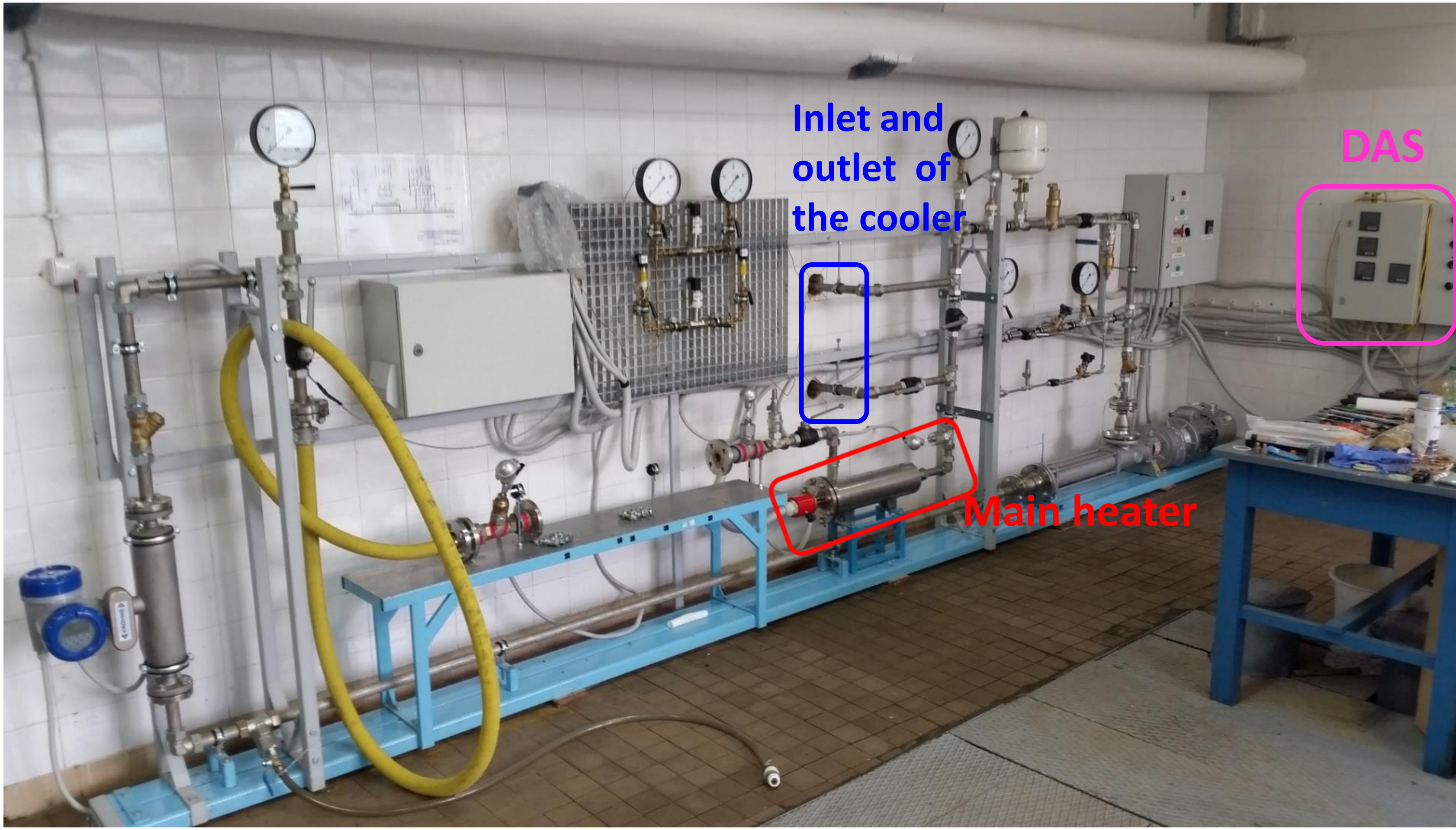
The values of P_{wet} in Table 1 were obtained by image analysis.

Spiral sample: Flow area and Re are based on D_{in} = 6.25 (0.25) mm.

Experimental – THETIS installation

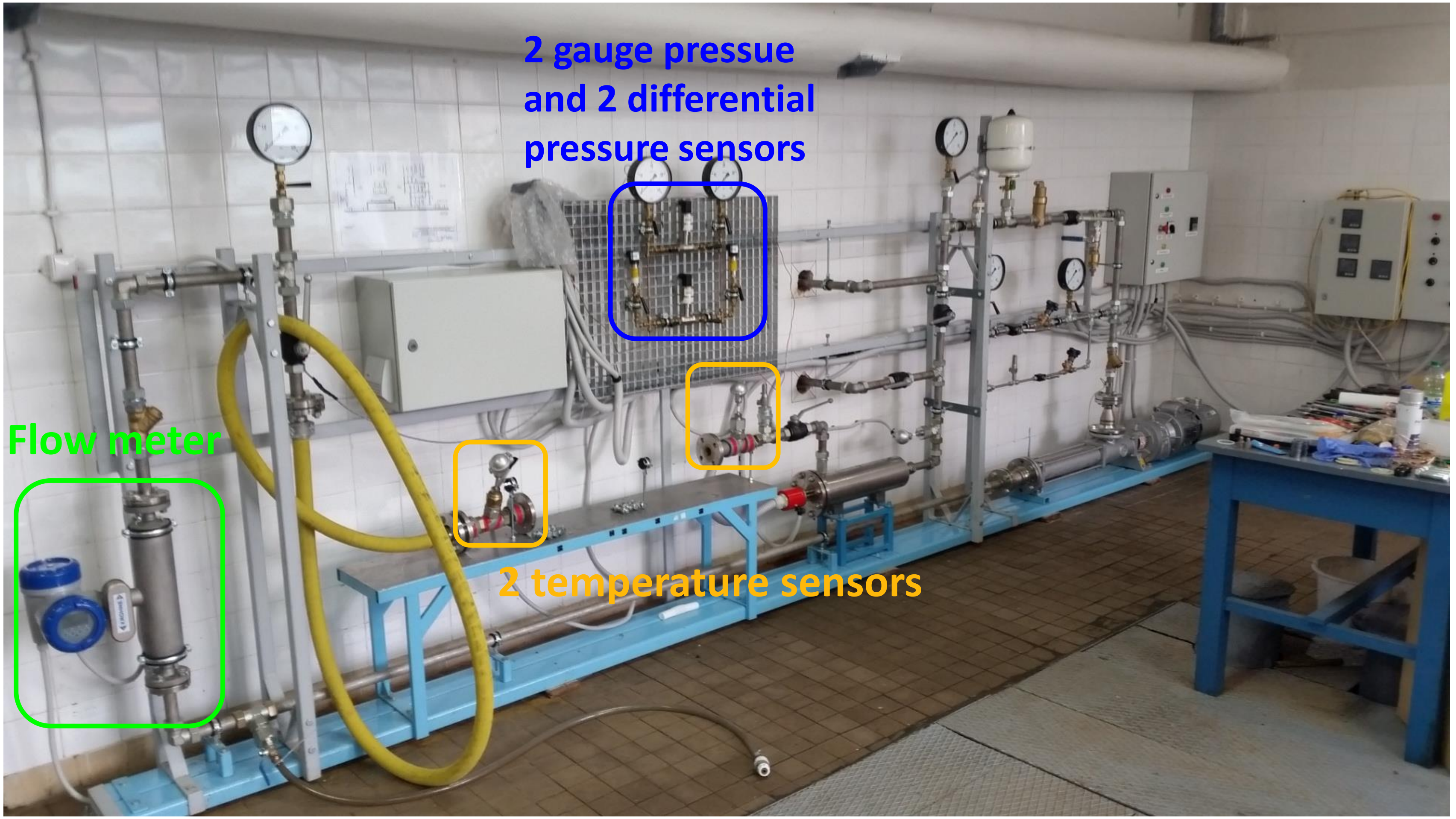
The pressure head up to 2.5 MPa in the installation is induced by a progressive cavity pump with variable speed operation. The water mass flow rate in the circuit is adjusted by changing the rotational speed of the pump in the range 10–60 Hz. Two bypasses of the pump with different diameters enable precise adjustment of small mass flow rates

Experimental – THETIS installation



The main heater and the air flow cooler enable adjustments of the water temperature in the circuit in the range from room temperature to about 70°C. DAS includes four 8-channel data recorders.

Experimental – THETIS installation



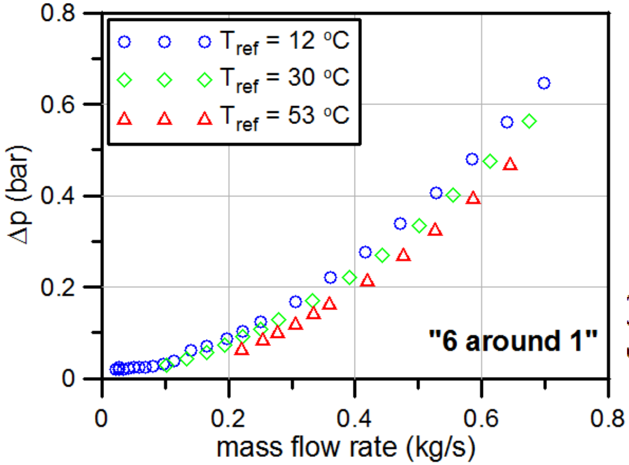
Experimental – instrumentation used in hydraulic tests

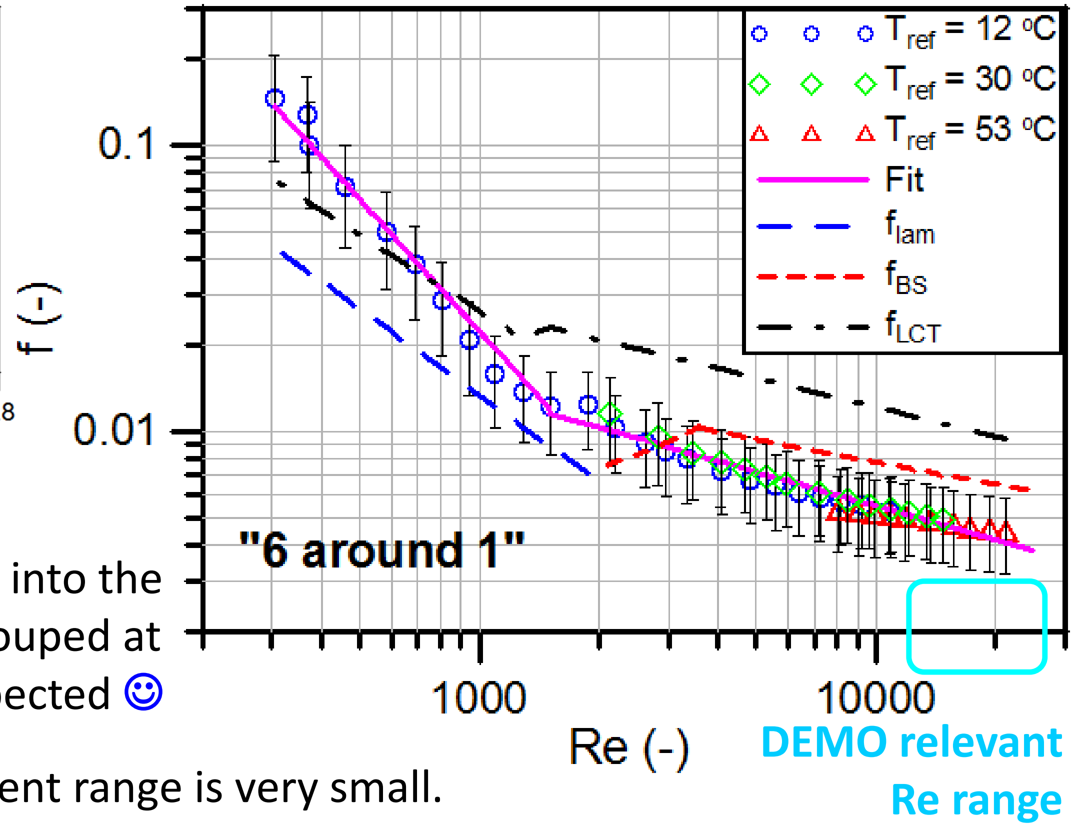
Measuring instrument	Measured quantity	Measuring range	Basic measurement uncertainty
Flow meter	$\dot{m}$	20 – 3000 kg/h	± 0.15% of measured value
Temperature sensor 1 and 2	T_{in} , T_{out}	-200 – 400 ºC	± 0.15 ºC ± 0.2% of |measured value|
Pressure sensor 1	p_1	0 – 2.5 MPa	± 0.2% of measuring range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

$$f = -\frac{2\rho A_{fluid}^{3}}{\dot{m}^{2} P_{wet}} \frac{\Delta p}{L} \qquad \mathrm{Re} = \frac{4\dot{m}}{\mu P_{wet}}$$

water density (ρ) and dynamic viscosity (μ) are calculated at the reference conditions: $p_{ref} = p_{ambient} + (p_1 + p_2)/2$ and $T_{ref} = (T_{in} + T_{out})/2$.

Results – ”6 around 1” dummy conductor

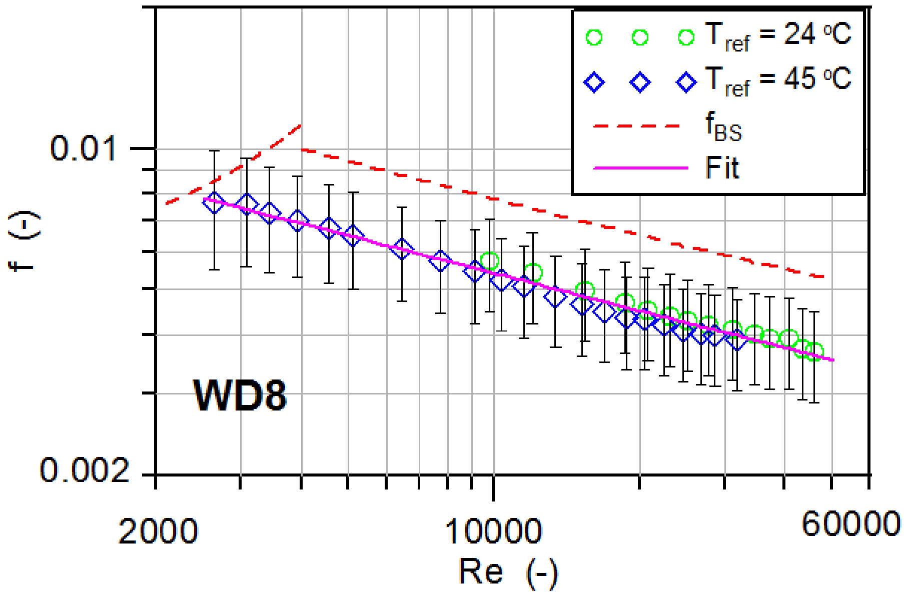




- Data measured at different temperatures, transformed into the dimensionless form, are grouped at the single trend line, as expected ☺
- Friction factor in the turbulent range is very small.
- **The results in the dimensionless form are sensitive to the value of P_{wet}** ☹
- The results are well fitted by the following power law:

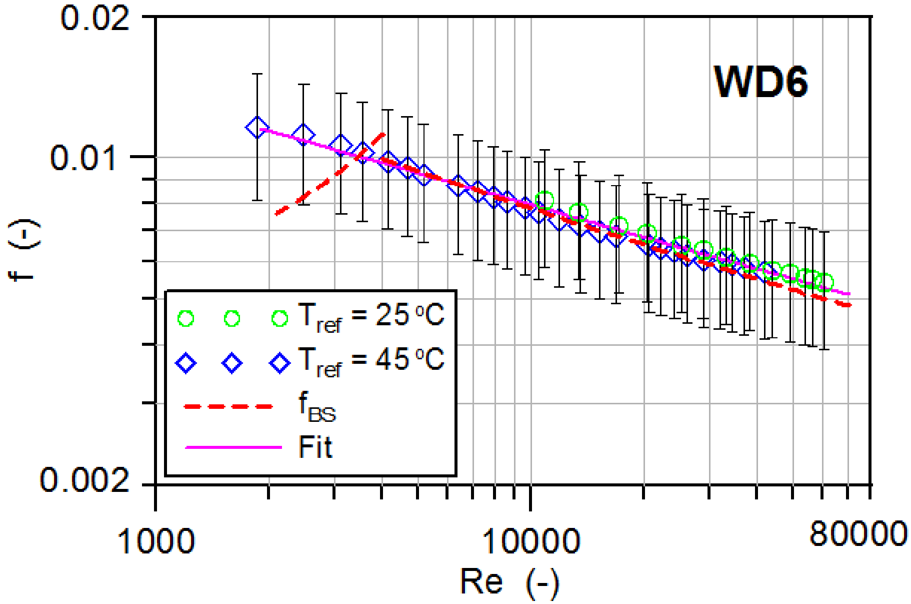
$$f(\mathrm{Re}) = \begin{cases} 860.3\,\mathrm{Re}^{-1.5280} & \text{for} \quad \mathrm{Re} < 1500 \\ 0.2051\,\mathrm{Re}^{-0.3932} & \text{for} \quad 1500 < \mathrm{Re} < 25000 \end{cases}$$

Results – WD8 and WD6 dummy conductors



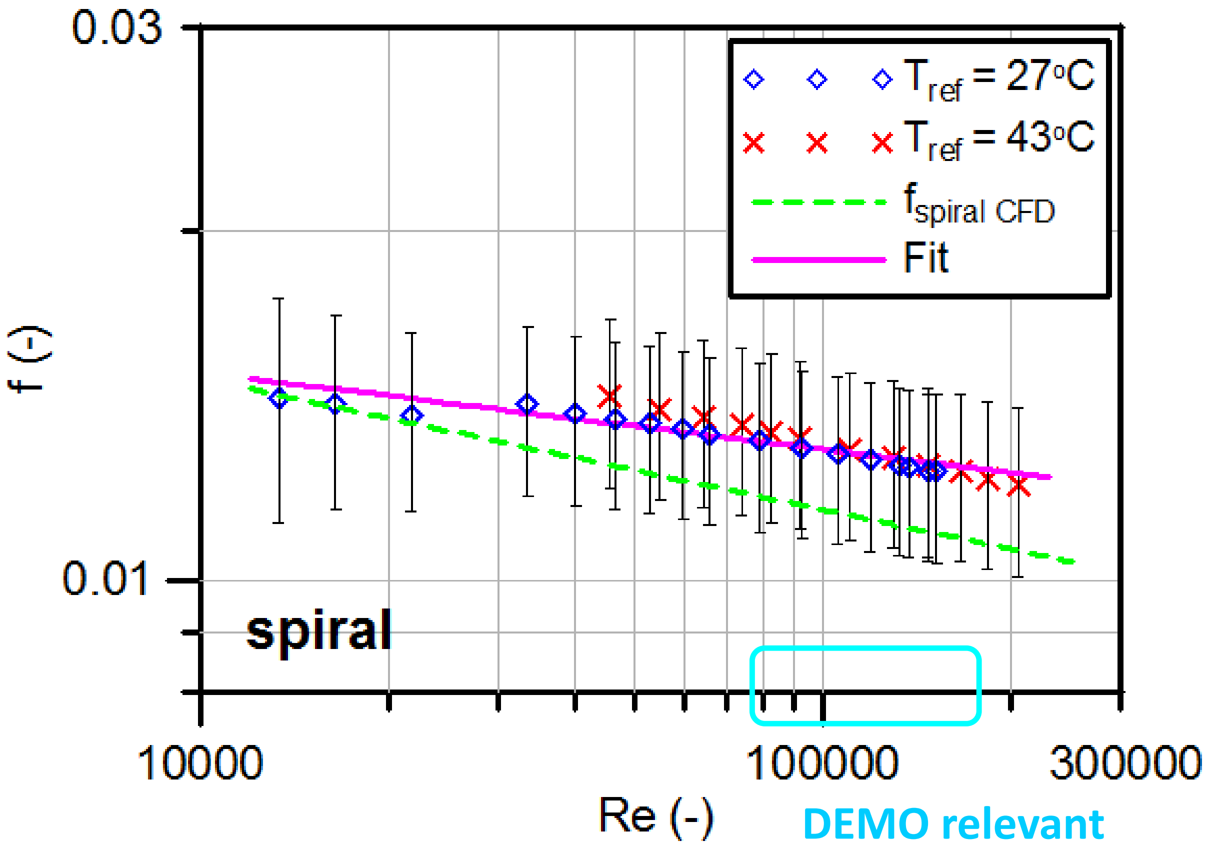
In both conductors, the laminar regime has not been reached

$$f_{WD8}(\mathrm{Re}) = 0.06308 \cdot \mathrm{Re}^{-0.2665}$$



$$f_{WD6}(\mathrm{Re}) = 0.06414 \cdot \mathrm{Re}^{-0.2270}$$

Results – spiral



DEMO relevant Re range

$$f_{WD6}(\mathrm{Re}) = 0.02780 \cdot \mathrm{Re}^{-0.06627}$$

Summary and conclusions

- Three short dummy conductors with the layout similar to HTS conductors designed for the EU DEMO coils and for the WD experiment, as well as a spiral sample with the diameter similar to that used in the cooling channels of WP#2 EU DEMO TF conductors have been prapared and tested for pressure drop using water at different temperatures.
- In the tests of the „6 around 1" conductor and spiral sample the EU DEMO relevant Re range has been reached.
- It was observed that the experimental values of friction factor in the turbulent regime in all considered dummy conductors are small (close to or even below the respective values predicted by the smooth tube correlation). Thus, in thermal-hydraulic analyses the smooth tube friction factor correlation could be used.
- For dummy conductors, the experimental values of friction factor are very sensitive to the value of the wetted perimeter which is problematic to be estimated accurately.
- It would be interesting to test the same samples using another fluids or to study by CFD simulations to obtain friction factor values in wider Re range, particular in the laminar regime.

Acknowledgments

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Thank you for your attention

Question Time