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Friction factor of a forced-flow cooled HTS subsize-conductor for fusion magnets

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Outline of the presentation

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   - Sample's characteristics

2. **Experimental set-up**
   - THETIS installation
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3. **Results**
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   - Comparison of the test results with predictions of available friction factor correlations

4. **CFD simulation (ANSYS Fluent)**
   - Mesh dependence study
   - Simulation: Full Opt-3b model vs 1 channel model
   - Results - pressure drop distribution

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Introduction – basic definitions

- Mathematical models used for thermal–hydraulic analyses of superconducting cables, cooled by forced flow supercritical He (SHe) are typically 1-D and they require reliable predictive expressions which characterize mass, momentum and energy transfer between different cable components [1].

- Momentum transfer is described in terms of **friction factor correlations** *f*(Re), which can be obtained from the pressure drop measurements or CFD simulations.

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

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 sub-size conductors designed for the quench experiment [2] consist of three CroCo monolythic strands (triplet), twisted together and embedded in a stainless steel jacket.

Fig.: Layout of three HTS CroCo conductor options; left: option 1, middle: option 2, right: option 3 [2].

- The HTS sub-size conductors for quench investigations are designed for a critical current of approx. 15 kA at operating conditions (T≥4.5 K, B~12 T) with forced flow supercritical helium cooling.

- The dummy conductors, namely WD8 (option 1) and WD6 (option 2) were tested for pressure drop in 2019 [3].

Introduction - goal of the work

The short sample of dummy conductor, named Option 3b, was prepared by the KIT team and tested for pressure drop on THETIS installation using demineralized water at three different temperatures.

We present and discuss the results of these hydraulic tests and develop experimental friction factor correlation for the considered duct in the EU DEMO relevant Re range.

CFD simulations of Option 3b cooling channel were also performer using ANSYS Fluent. We studied several meshes and models in order to obtain pressure drop consistent with experimental results.

The resulting correlations will be utilized in future thermal-hydraulic studies of DEMO coils or quench experiment.

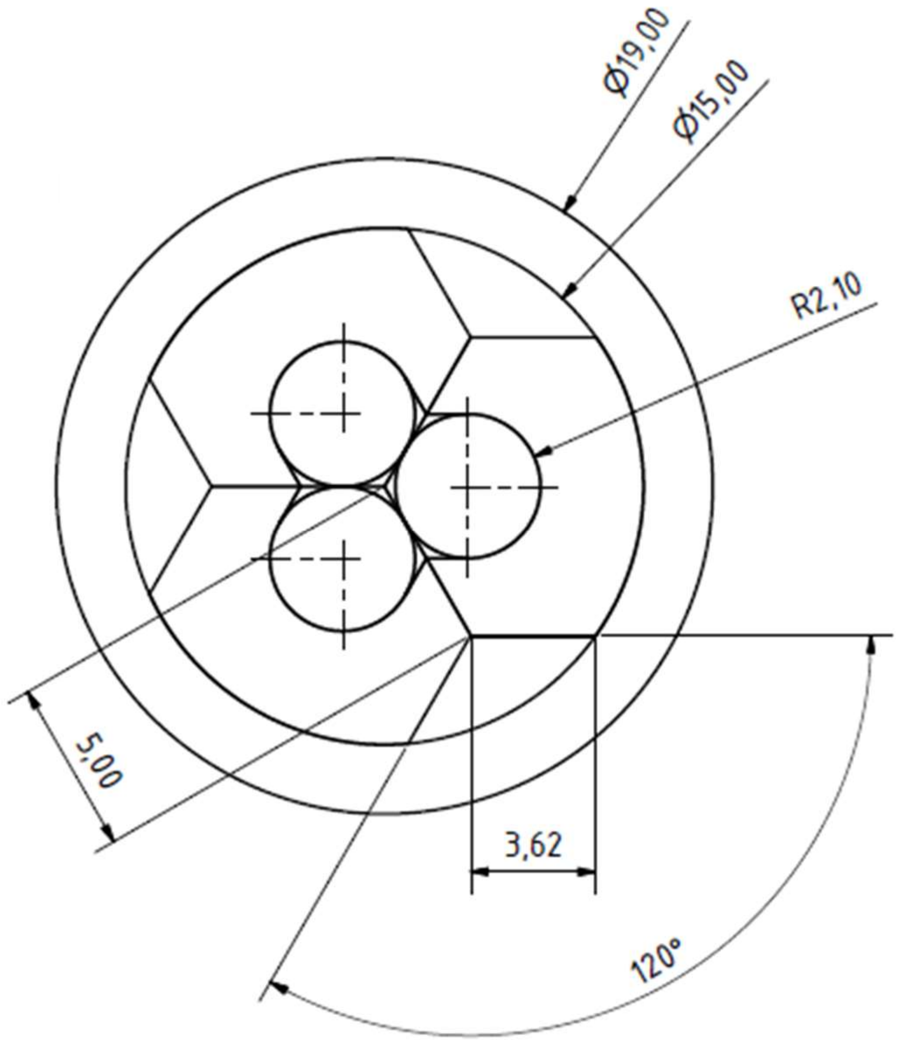

Fig.: Schematic layout of the Option 3b dummy conductor.

Parameters of dummy conductor relevant for the present study.

Description	Symbol	Unit	Option 3b
Flow area	A_f	mm^2	25.8
Wetted perimeter	P_{wet}	mm	41.2
Hydraulic diameter	D_h	mm	2.50
Distance between the pressure taps	L	mm	823 (5)

Introduction - Fanning friction factor correlations

The experimental friction factor of the **dummy conductor** was compared with predictions of correlations available in the literature:

- classical correlation for laminar flow in a smooth equilateral-triangle duct [4]

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

- classical Bhatti-Shah correlation for the transition and turbulent flow in smooth circular and non-circular ducts [4]

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

- correlation developed for the EURATOM LCT conductor [5], which is currently used in thermal-hydraulic analyses of the HTS conductors designed for the EU DEMO TF and CS coils

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

THETIS installation (I)

- For hydraulic tests of forced flow cooled cables we used THETIS installation prepared at WPUT, Szczecin.
- At the present stage THETIS enables pressure drop tests from room temperature to 70ºC.

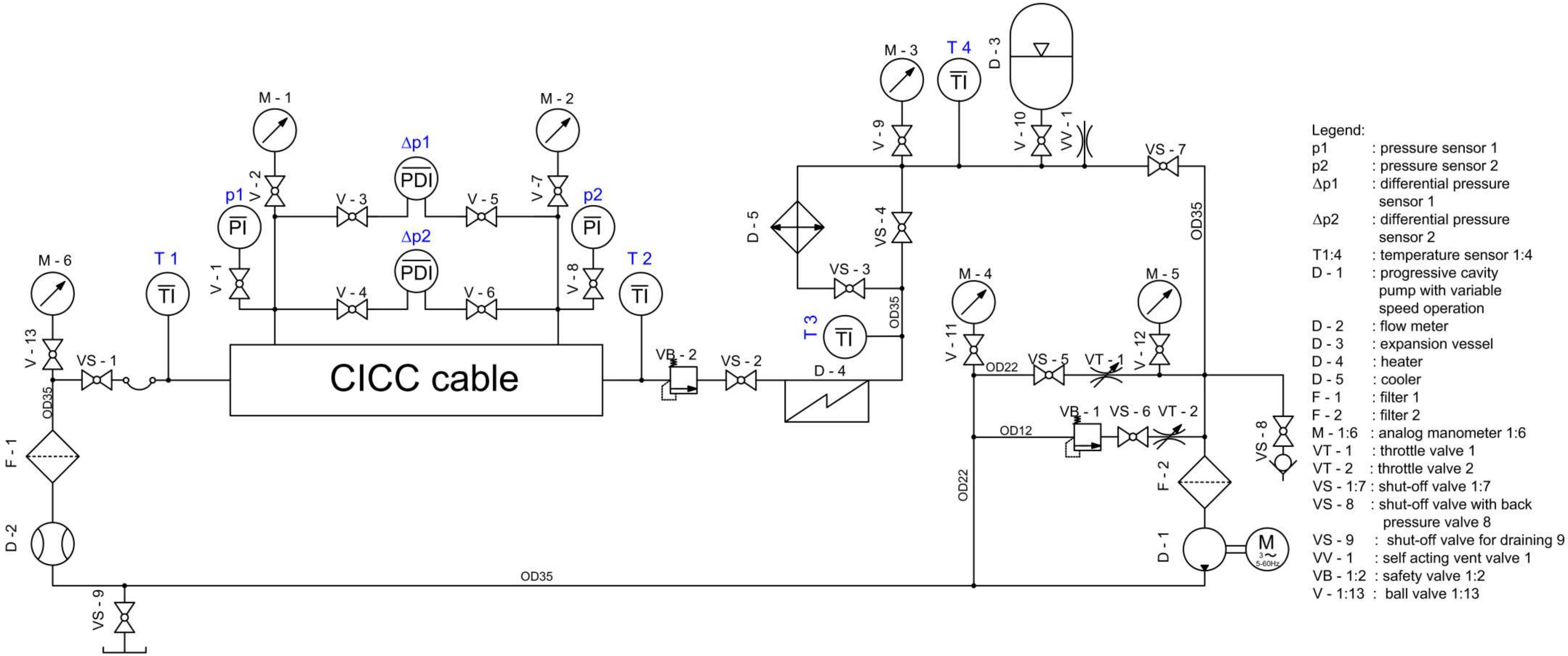

Fig. 1. Hydraulic scheme of the THETIS configuration

THETIS installation (II)

- Progressive cavity pump (BELLIN LZ 500L/KW) with variable speed operation induces pressure head up to 2.5 MPa
- The water mass flow rate is precisely adjusted by changing the rotational speed of the pump in the range 10 to 60 Hz or by suitable opening of one of two bypasses of the pump with different diameters.
- The main heater and air flow cooler enable adjustments of the water temperature in the circuit in the range from room temperature to 70°C.
- A conductor sample is attached to the installation using flexible hose which allows to vary the sample length.
- The applied measuring instrumentation and the automatic data acquisition system enable accurate and convenient measurements.

Fig. 2. Photo of the THETIS installation

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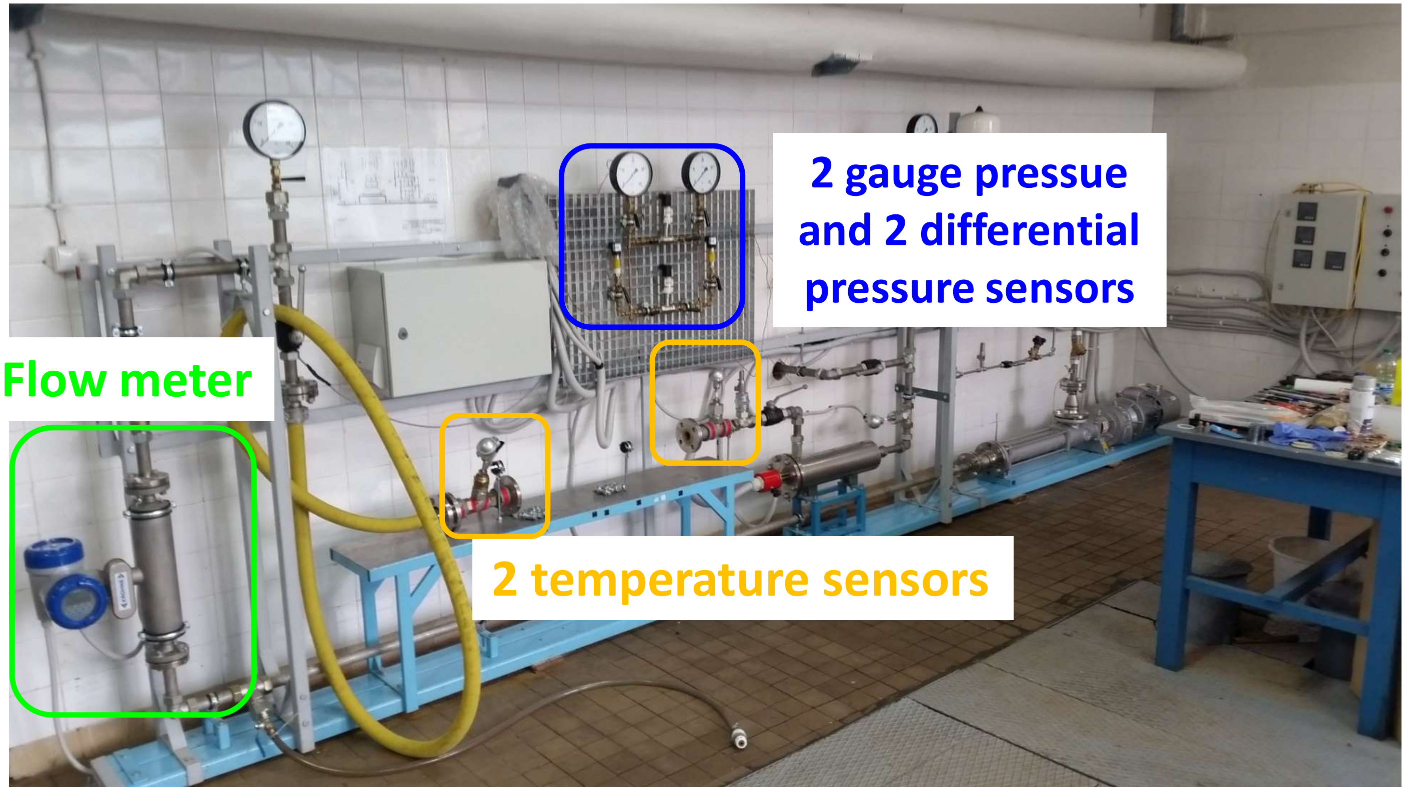
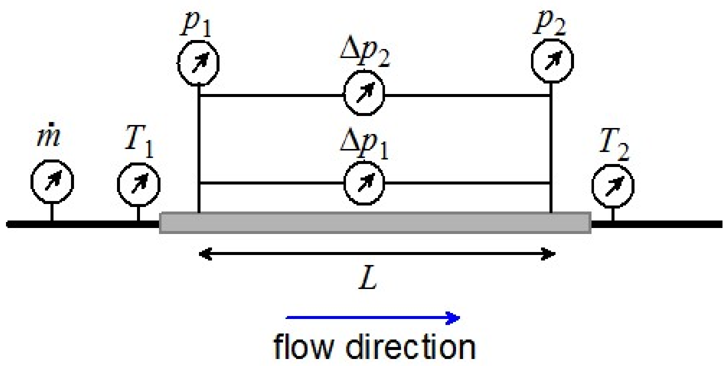


Fig. 2. Photo of the THETIS installation

Instrumentation used in hydraulic tests at THETIS

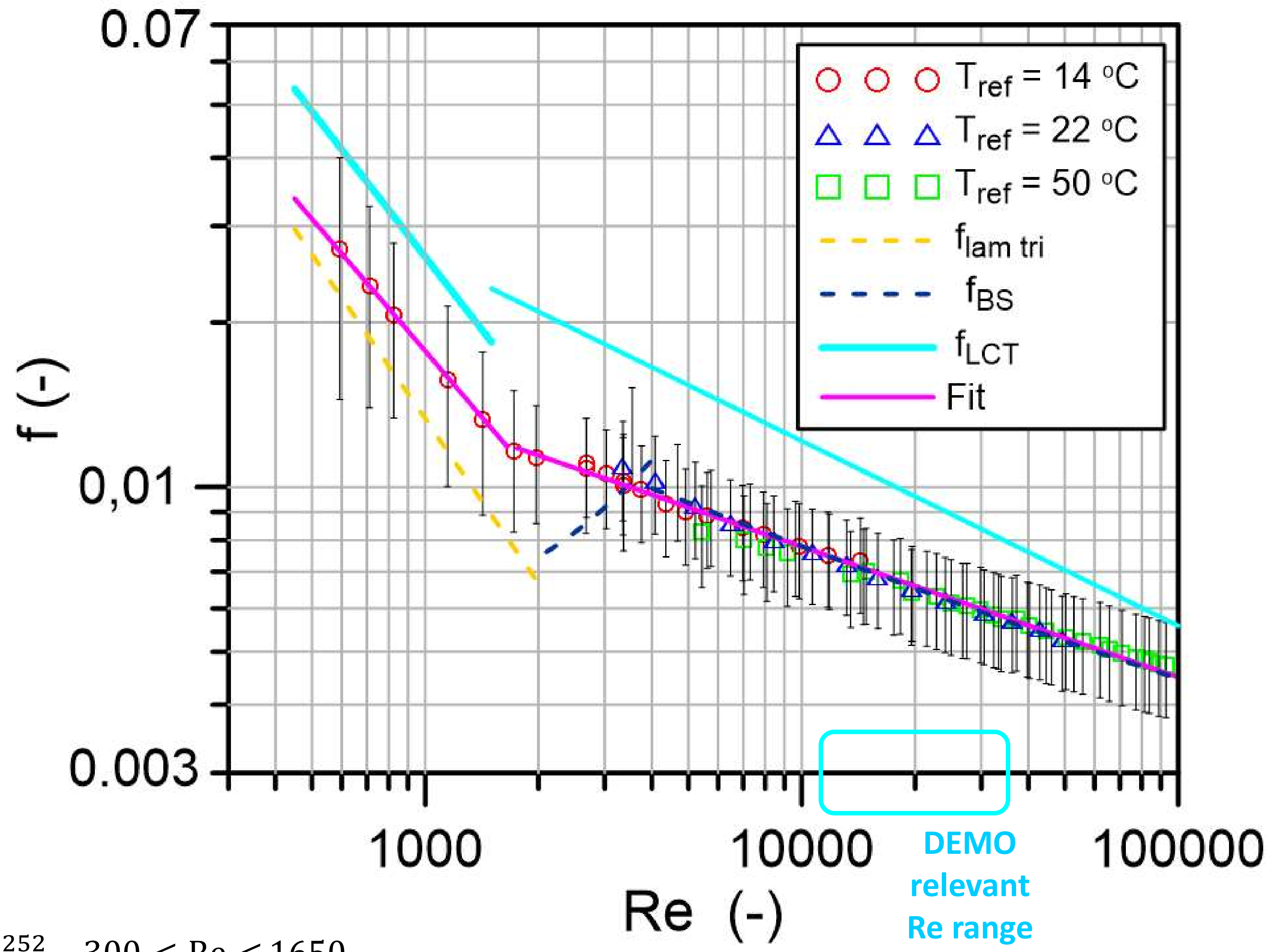


Measuring instrument	Measured quantity	Measuring range	Basic measurement uncertainty
Flow meter	$\dot{m}$	20 – 3000 kg/h	± 0.15% of measured value
Temperature sensor 1 and 2	T_1 , T_2	-200 – 400 ºC	± 0.15 ºC ± 0.2% of |measured value|
Pressure sensor 1	p_1	0 – 2.5 MPa	± 0.2% of measuring range
Pressure 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) were calculated at the reference conditions: $p_{ref} = p_{ambient} + (p_1 + p_2)/2$ and $T_{ref} = (T_1 + T_2)/2$.

Experimental results – ”Option 3b” dummy conductor



- ❑ Data measured at different temperatures, transformed into the dimensionless form, are grouped at the single trend line, as expected
- ❑ The results are well fitted ($R^2 >$ 0.96) by the following power law:

$$f_{Opt3b}(\mathrm{Re}) = \begin{cases} 4.5563 \cdot \mathrm{Re}^{-0.803252} & 300 < \mathrm{Re} < 1650 \\ 0.07005 \cdot \mathrm{Re}^{-0.2386} & 1650 < \mathrm{Re} < 10^5 \end{cases}$$

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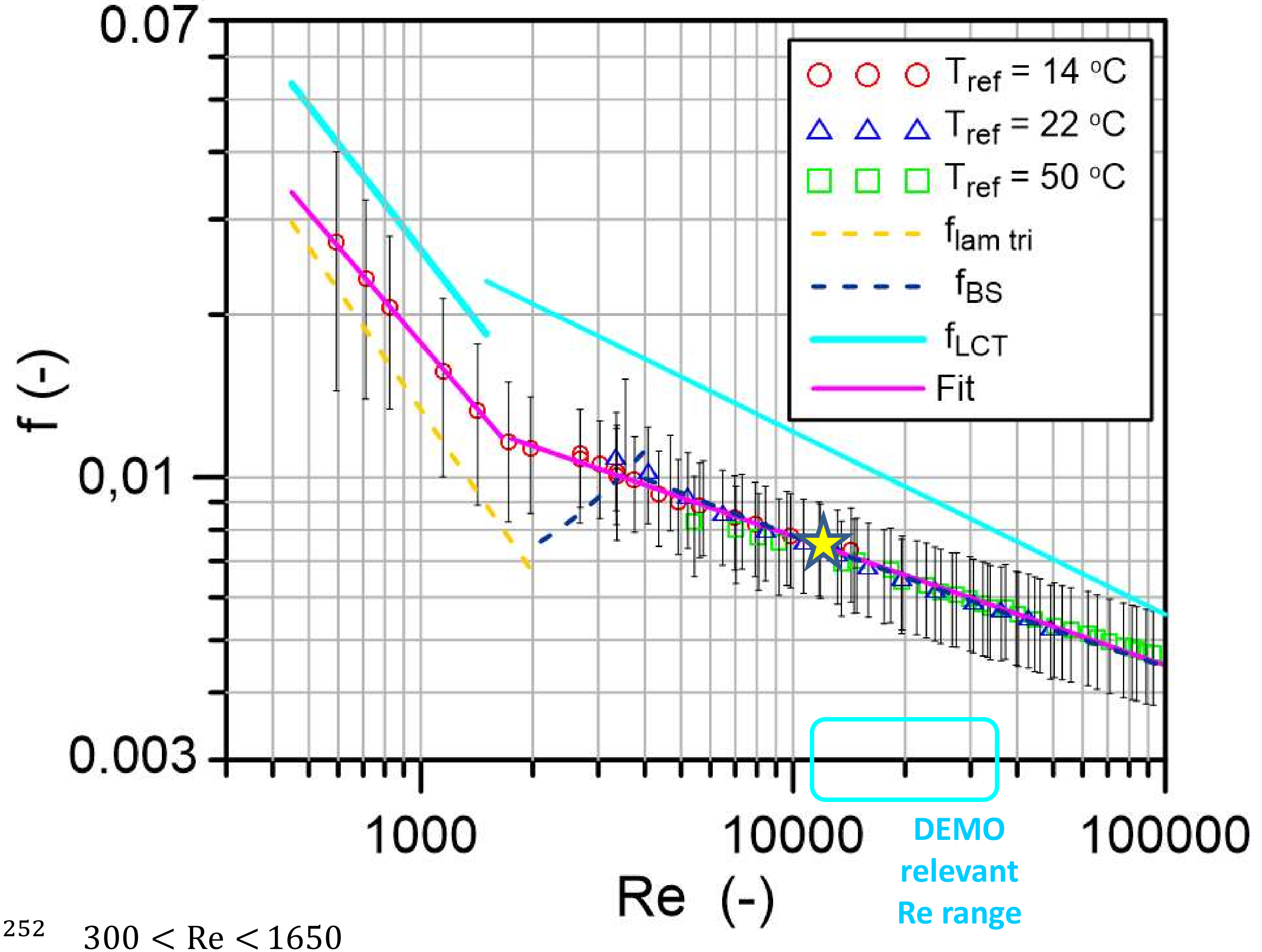
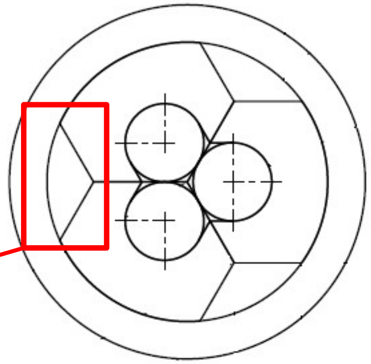


CFD simulations: 1 cooling channel of „Option 3b”

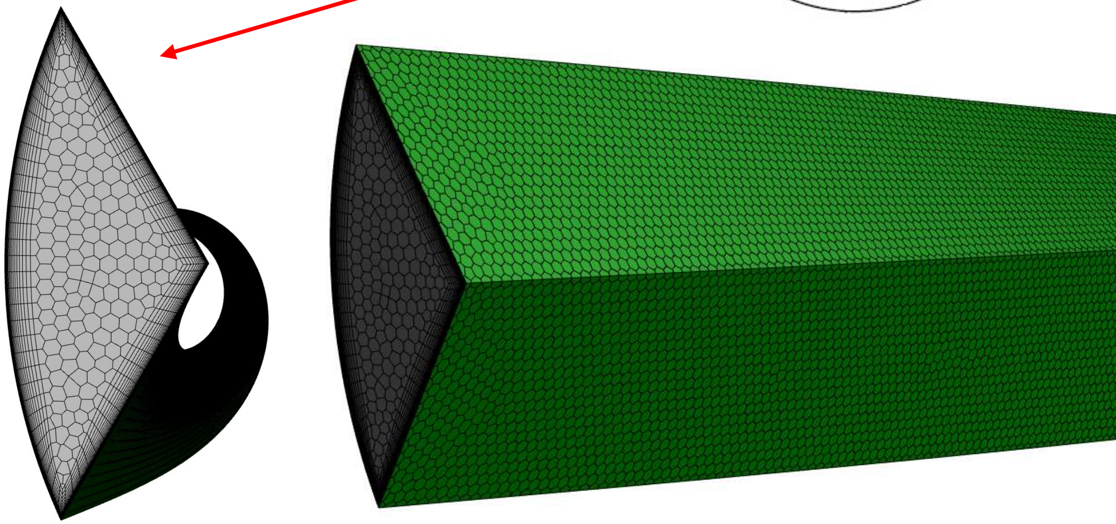
Model Setup

Inlet velocity: 5.44 m/s
Turbulence model: SST k-ω
BCs: velocity inlet and pressure outlet
Solver setup: pseudo-transient solver with coupled pressure-velocity formulation
Number of iterations to converge (residuals stabilize, pressure drop no longer changes): ~250
Precision: SP (single precision)
Fluid properties: default in Fluent (water at 20°C)

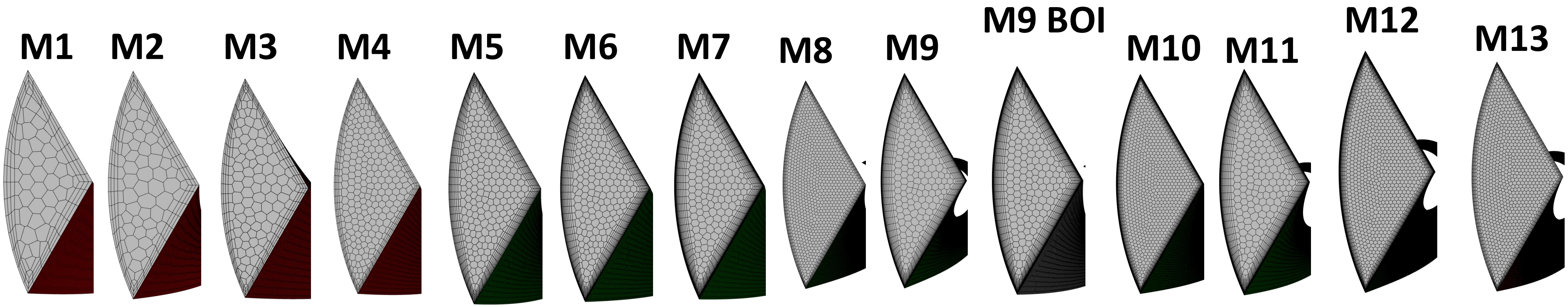


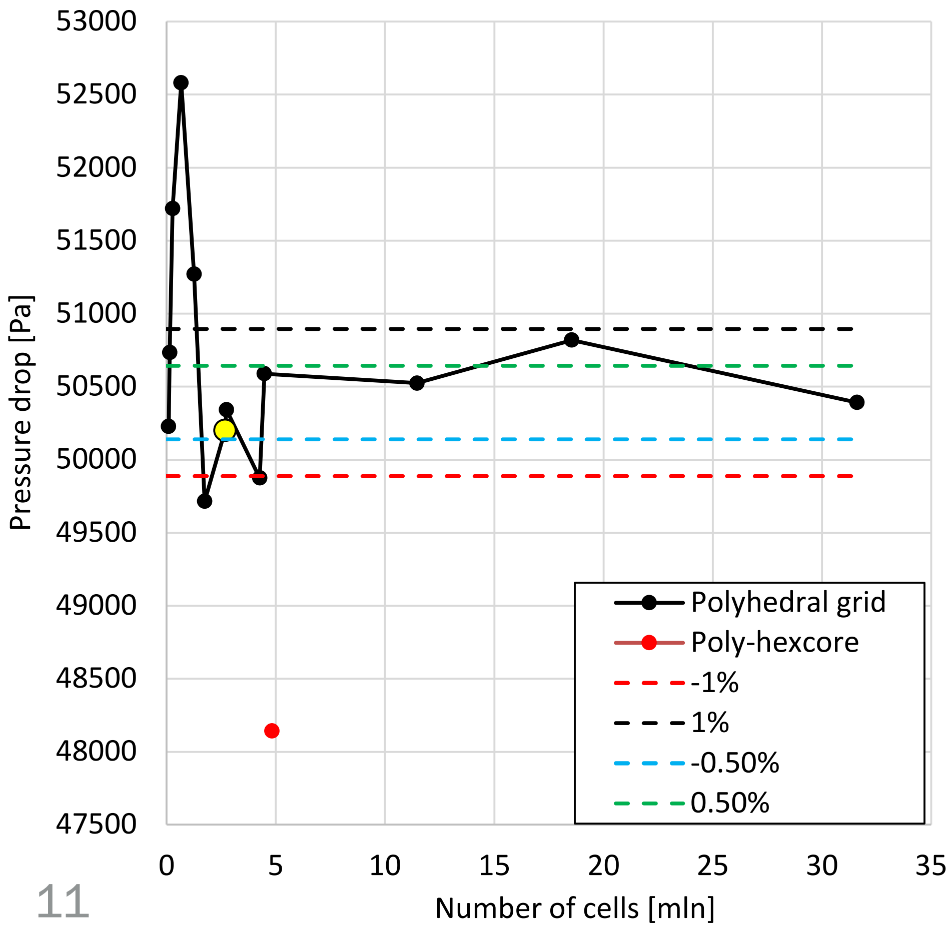
Parameters of 1 cooling channel relevant for the present study.

Description	Symbol	Unit	1 channel Option 3b
Flow area	A_f	mm^2	8,592
Wetted perimeter	P_{wet}	mm	13,724
Hydraulic diameter	D_h	mm	2.50
Length	L	mm	**300**



CFD simulations: summary of the mesh dependence study





Mesh	N_cell [mln]	Δp [Pa]	Δp difference w.r.t. M12 mesh [%]	Min. orthogonal quality [-]	Maximum aspect ratio [-]	Grid type
M1	0.09	50227	-0.3	0.40	14.9	Polyhedral
M2	0.15	50733	0.7	0.43	14.8	Polyhedral
M3	0.28	51720	2.6	0.35	14.8	Polyhedral
M4	0.67	52581	**4.3**	0.43	14.9	Polyhedral
M5	1.26	51271	1.7	0.22	32.2	Polyhedral
M6	1.75	49714	-1.3	0.21	65.5	Polyhedral
M7	2.74	50342	-0.1	0.13	181.8	Polyhedral
M8	4.27	49874	-1.0	0.32	18.8	Polyhedral
M9	4.48	50588	0.4	0.13	181.8	Polyhedral
M9 BOI	2.68	50201	-0.4	0.14	181.8	Polyhedral
M10	11.46	50524	0.3	0.15	182.2	Polyhedral
M11	18.55	50818	0.8	0.07	181.8	Polyhedral
M12	31.61	50391	0.0	0.09	182.2	Polyhedral
M13	4.83	48141	**-4.5**	0.25	19.3	Poly-hexcore

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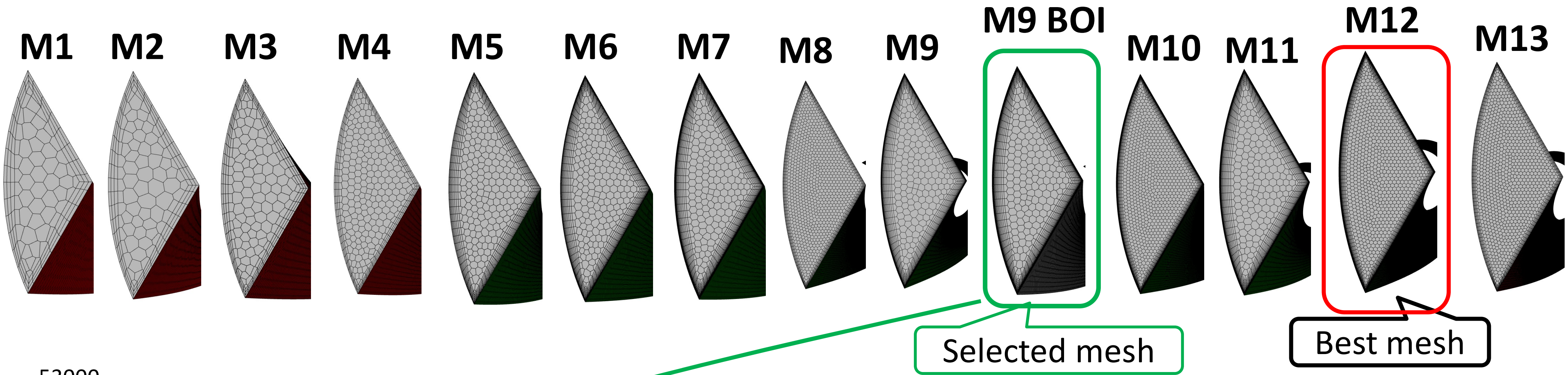

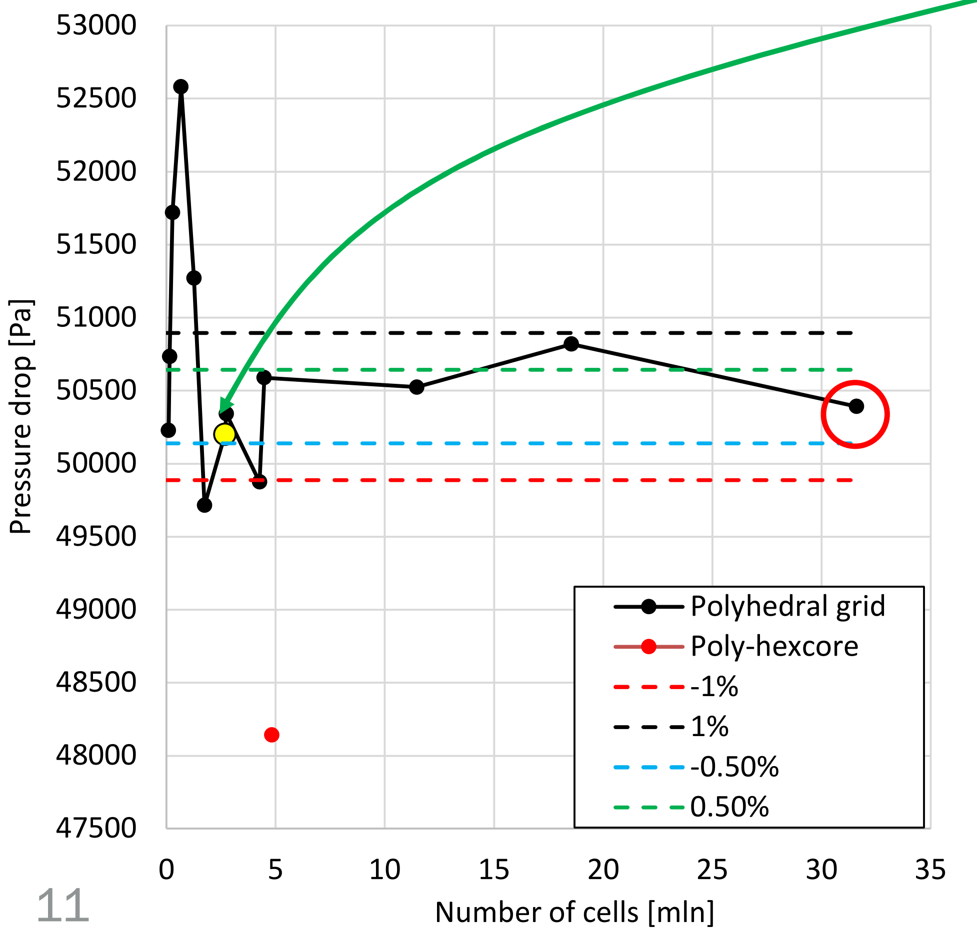

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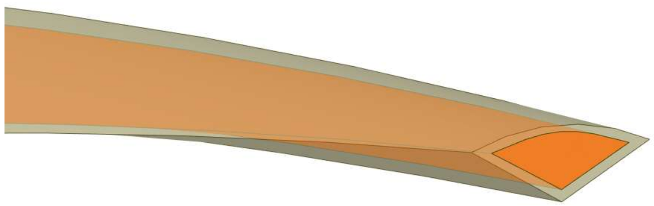
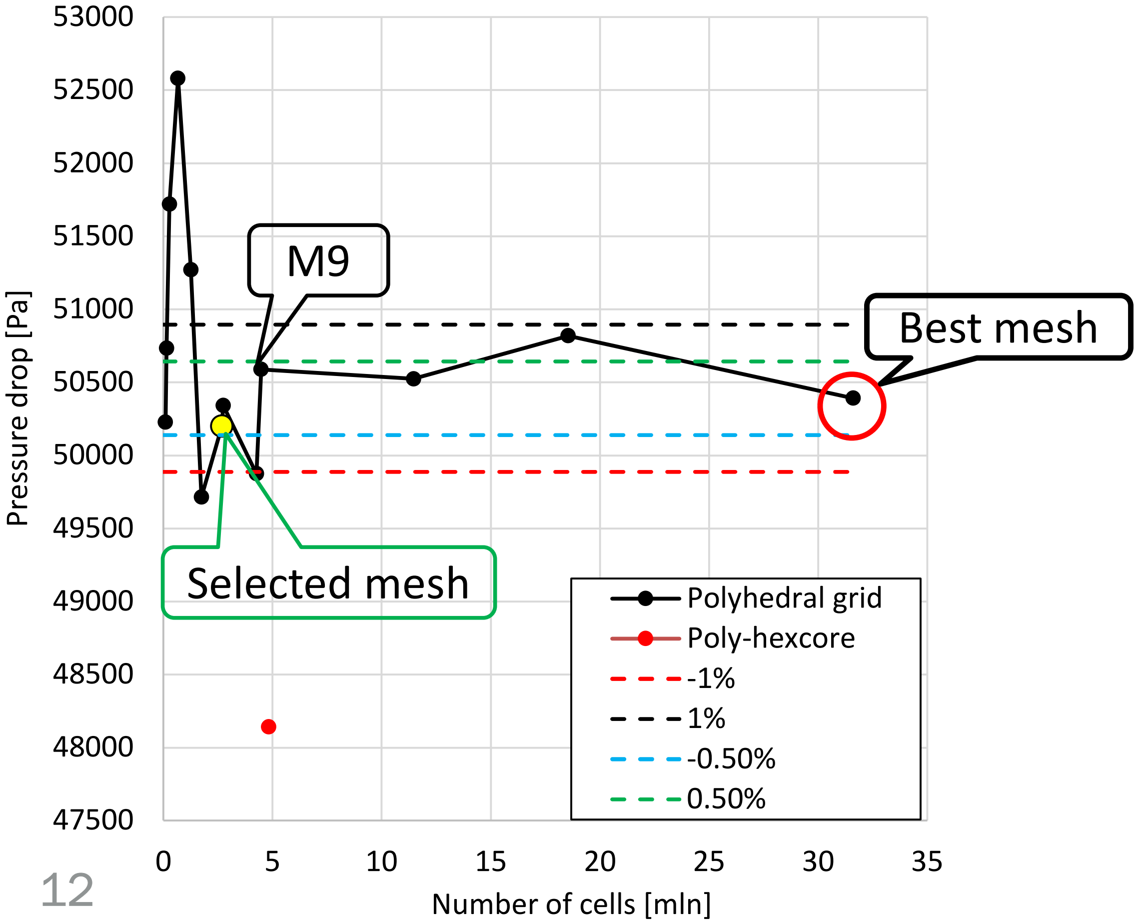
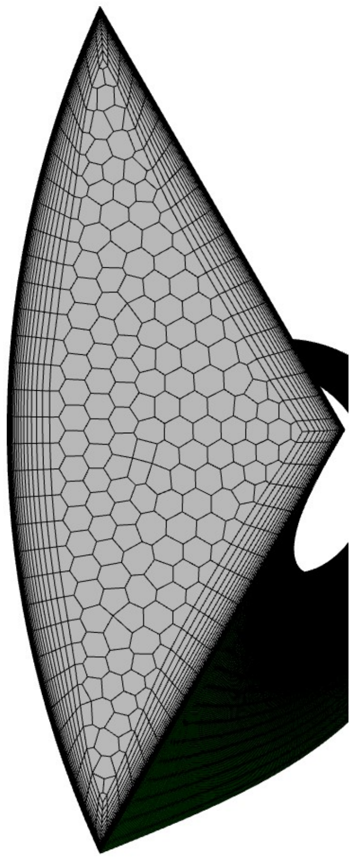
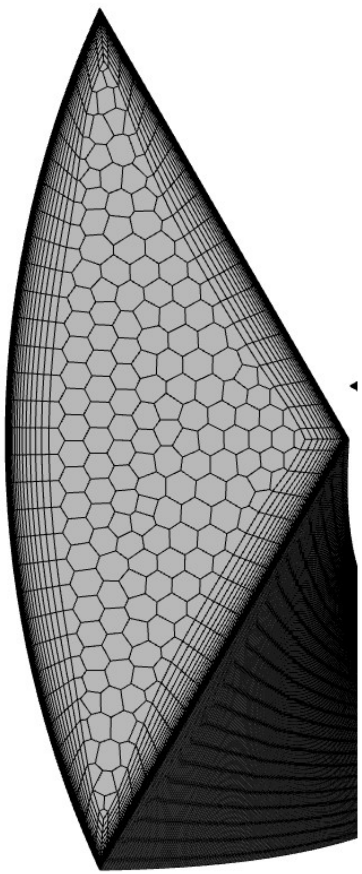




M9



M9 BOI



4.27 mln cells **2.68 mln cells**

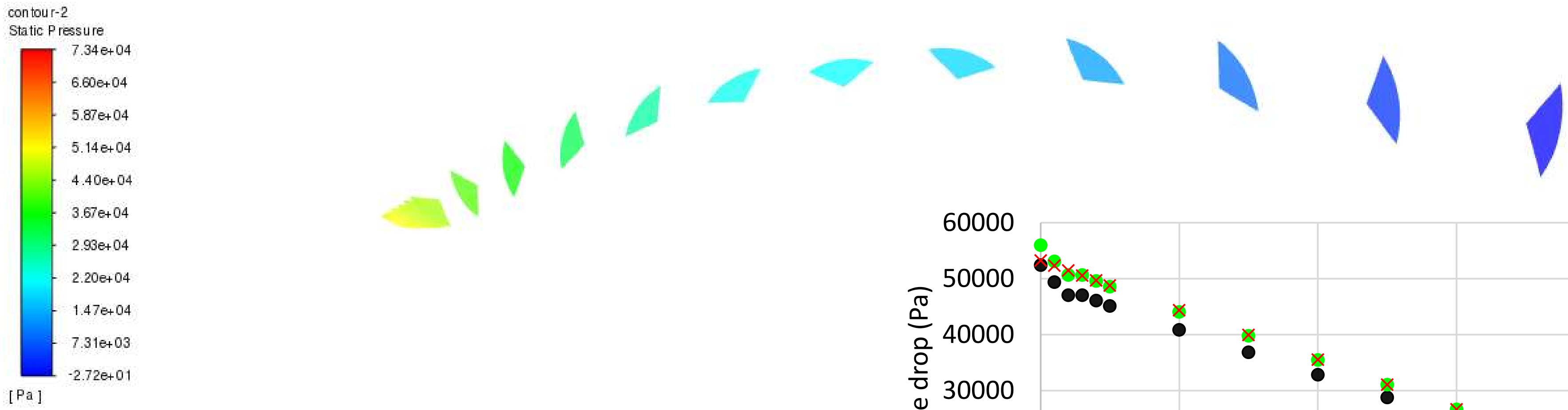
Computation times:

29 min 30 sec* 14 min 23 sec*

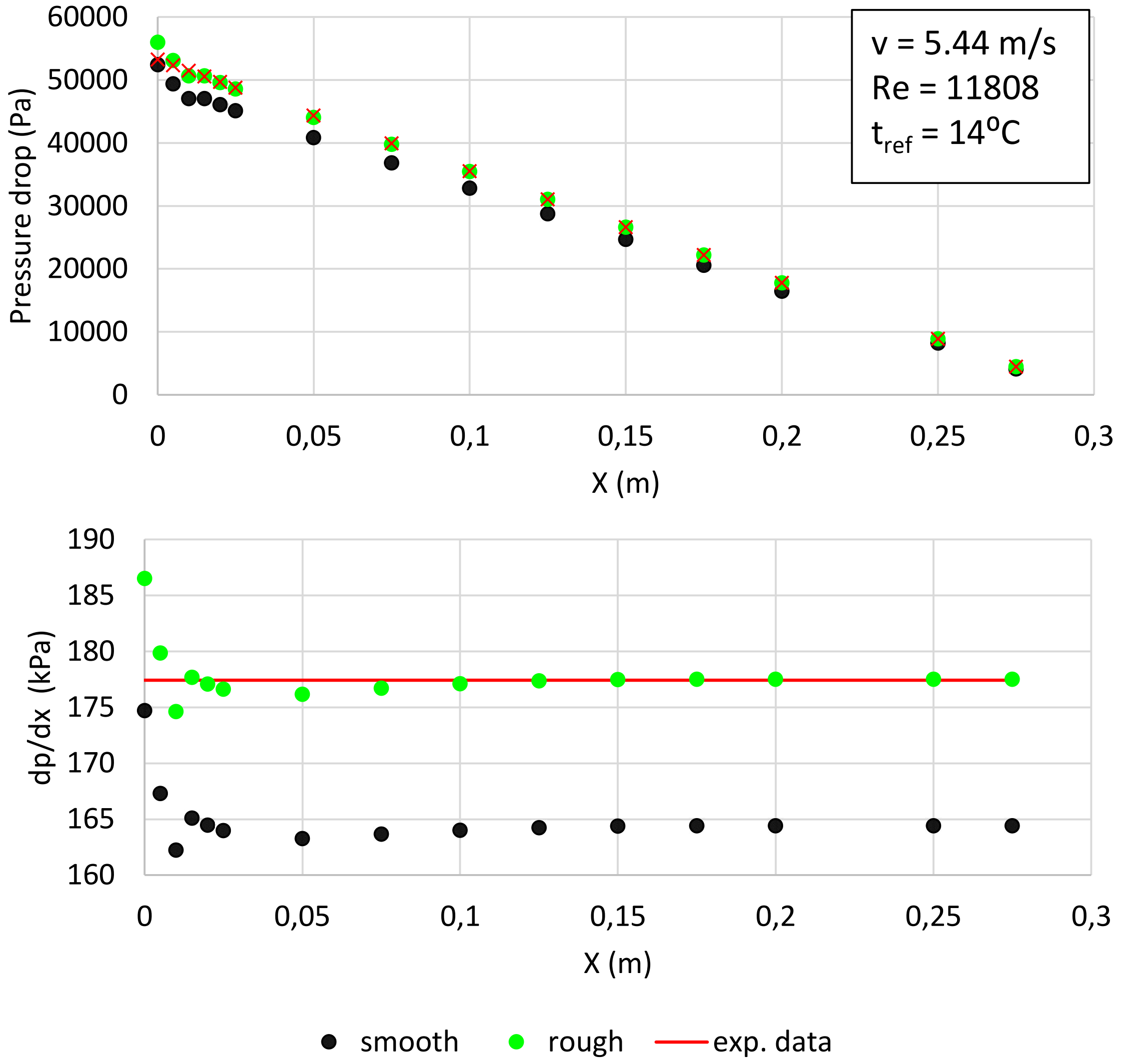
Looks almost identical to M9-> but the use of BOI decreased the cell count by almost 2 milion.

*The simulations were performed on a system with 16 3.5 GHz CPUs, 192 GB DDR RAM (2666 MHz).

CFD simulations: pressure drop distribution



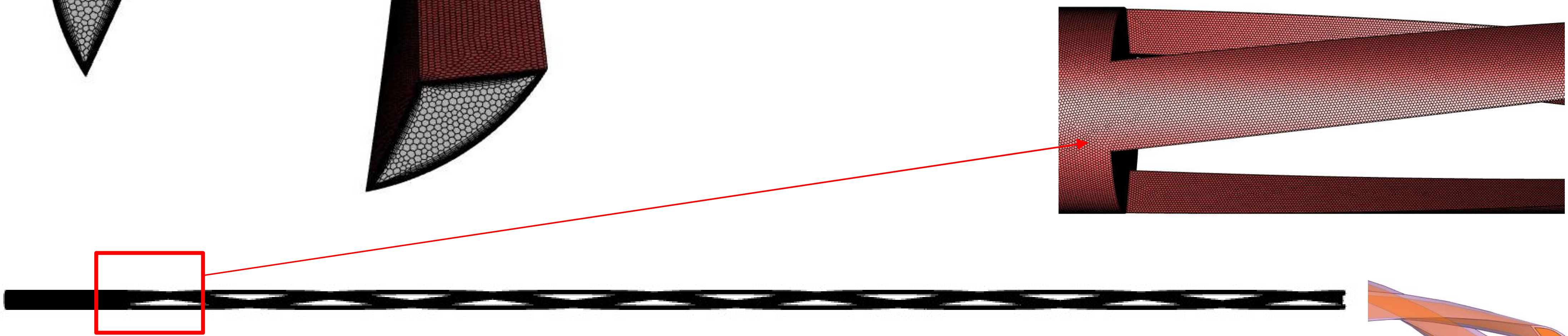
- Fluid properties consistent with the water properties from experiment.
- Stabilization of dp/dx after ~200 mm (differences below 0.5 kPa/m) → full development of the velocity profile
- Pressure drop in smooth channel is below experimental data
- Pressure drop in rough channel (Roughness Heigh = 8e-6 m) is consistent with experimental data



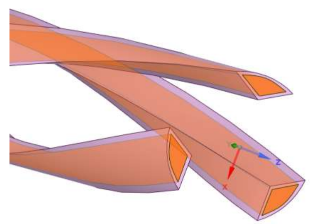
CFD simulations: full model of Option 3b vs. 1 channel model

Model Setup

Constant inlet mass flow rate: 0.14 kg/s
Turbulence model: SST k-ω
BCs: velocity inlet and pressure outlet
Solver setup: pseudo-transient solver with coupled pressure-velocity formulation
Number of iterations to converge (residuals stabilize, pressure drop no longer changes): ~250
Precision: SP (single precision)
Fluid properties: Fluid properties consistent with the water properties from experiment.



~30.1 mln polyhedral cells



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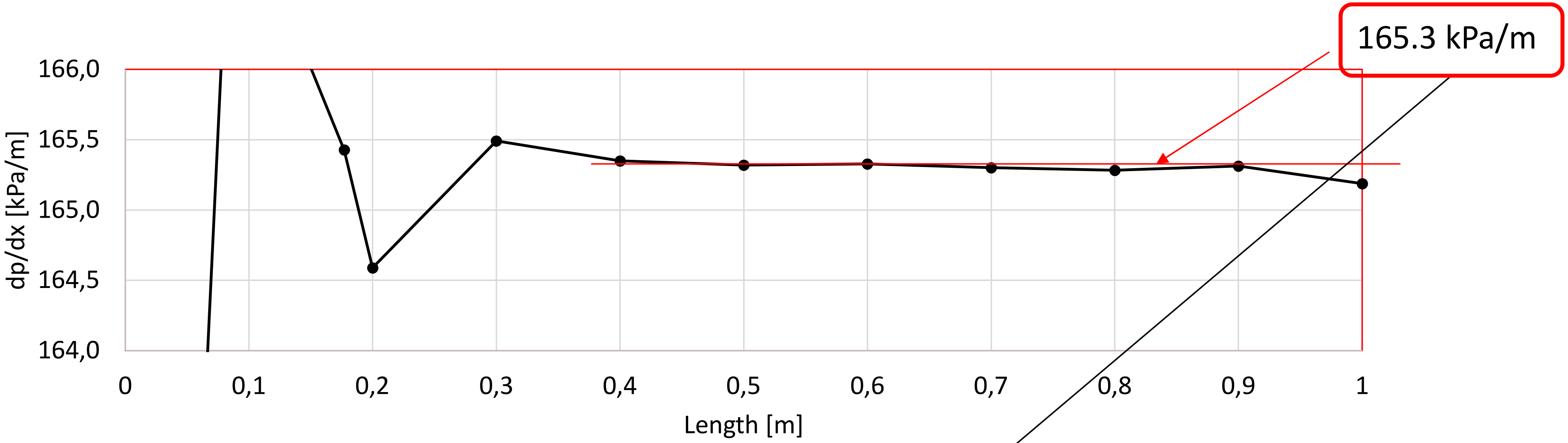
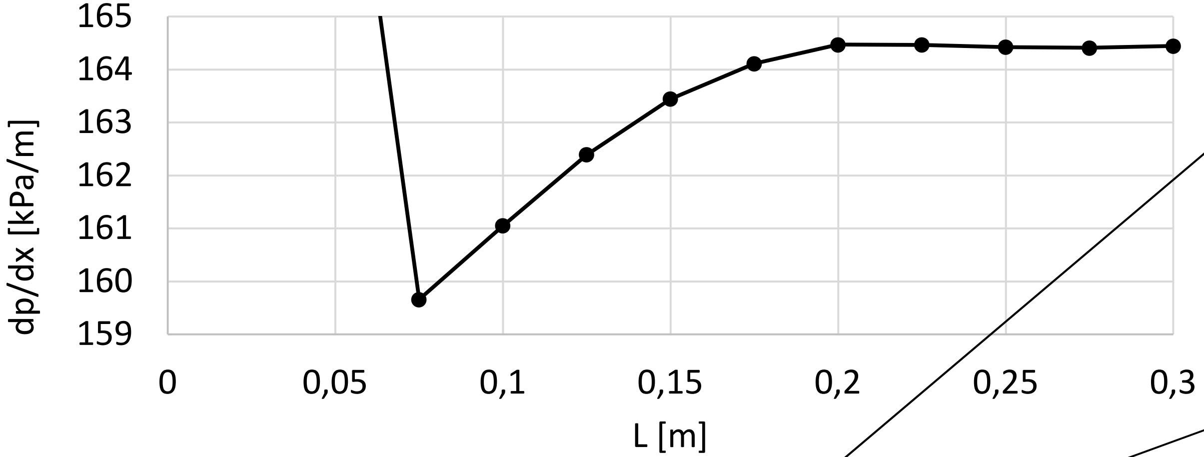
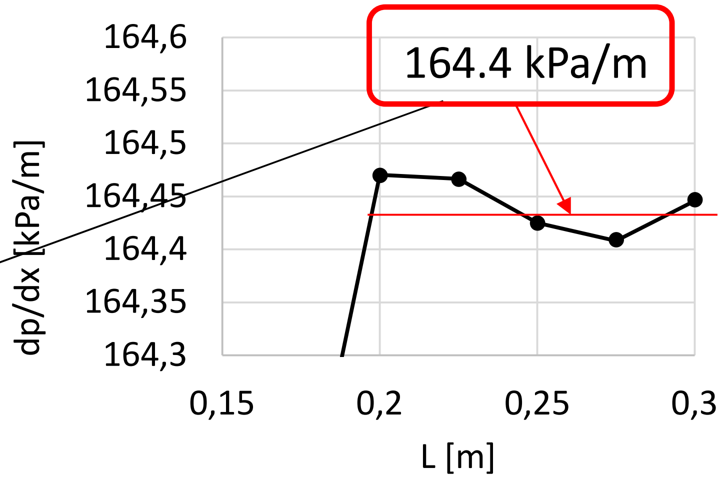


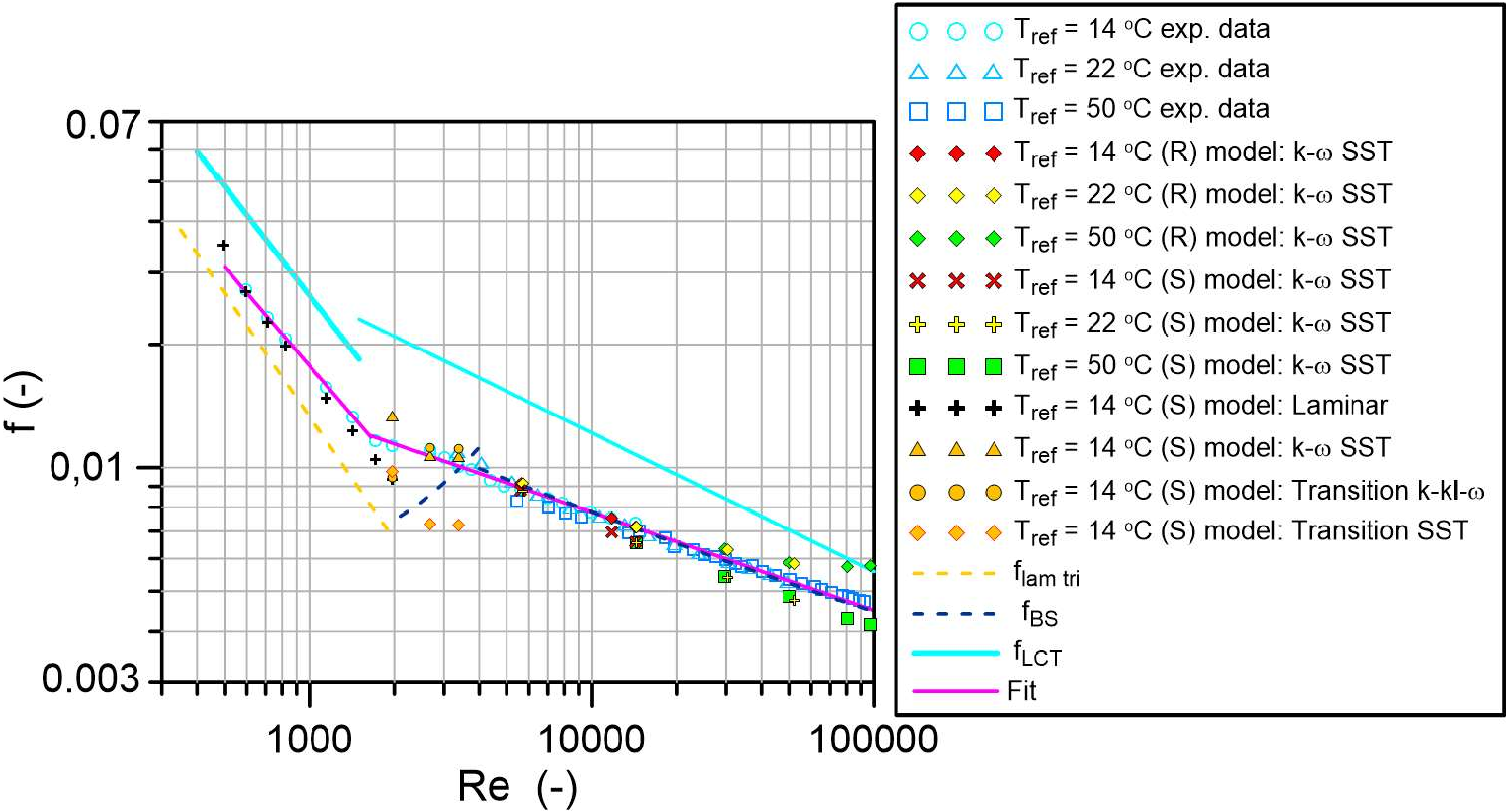




$$Difference = \frac{164.4 - 165.3}{165.3} * 100\% = \mathbf{-0.54}\%$$

The short single channel of conductor (300 mm) was selected for further simulations.

CFD simulations: Results – friction factor ”Option 3b”

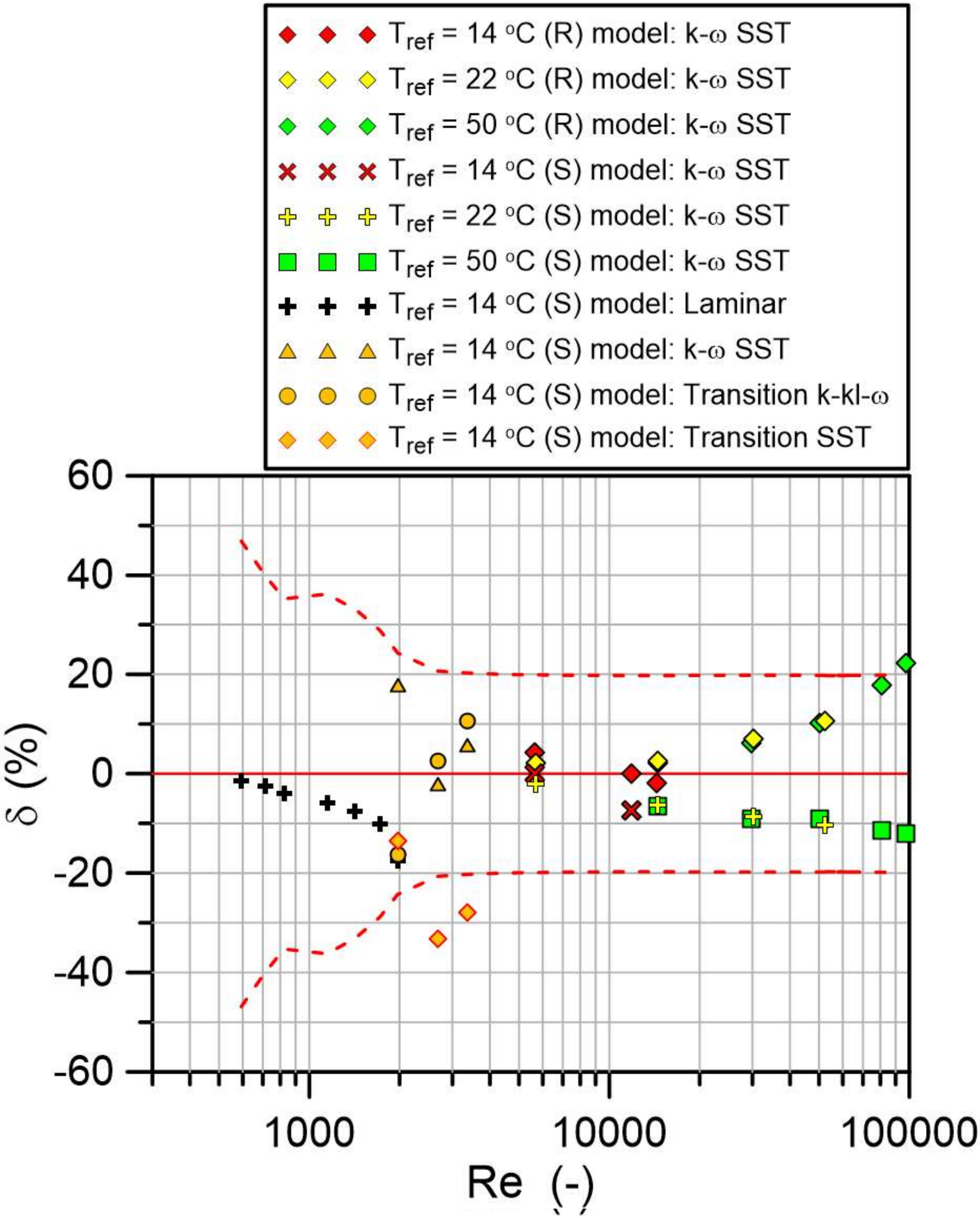


CFD simulations: the simulation results vs. experiment results

- Discrepancy between friction factor from the simulation and from the experiment:

$$\delta = \frac{f_{sim} - f_{exp}}{f_{exp}} \cdot 100 \ (\%)$$

- We obtained a good agreement of experimental and simulation results for the **k-ω SST model** for the number Re 2500 – 30 000 (δ < 10%).
- The discrepancy between the simulation and the experiment results increases with the number of Re for both smooth and rough channel. For a smooth channel, we observe an underestimation of the pressure drop, and for rough channel the pressure drop is overestimated.
- The **laminar model** was used for Re < 2000
- In laminar flow, the discrepancy between the simulation results and the experiment results also increases with the number of Re (δ < 10%).
- CFD simulations in transitional flow were problematic. For 2000 < Re < 3500 we tested three models: **k-ω SST, transition k-kl-ω** and **transition SST**. The lowest discrepancy is observed for k-ω SST, transition k-kl-ω, especially for higher Re.



Summary and conclusions

- Option 3b - the dummy conductor with the layout similar to HTS conductor designed for the quench experiment have been prepared and tested for pressure drop using water at three different temperatures.
- In the tests of the conductor sample the EU DEMO relevant Re range has been reached.
- It was observed that the experimental values of friction factor in the turbulent regime are small (close to the respective values predicted by the smooth tube correlation). Thus, in thermal-hydraulic analyses the smooth tube friction factor correlation could be used.
- CFD simulations were also performed to study the flow through the single cooling channel of the conductor and through full model of Option 3b for one experimental point. The short single channel of conductor (300 mm) was selected for further simulations due to the small difference (~0.5 %) in the pressure drop per unit length obtained with these two models.
- We studied laminar, transitional and turbulent flow though the short single channel of conductor using, respectively, laminar, transition k-kl- ω, transition SST and k-ω SST models.
- The discrepancy between the simulation and the experiment results increases with the number of Re for both smooth and rough channel, in laminar and turbulent regime. For a smooth channel, we observe an underestimation of the pressure drop, and for rough channel (constant roughness height) the pressure drop is overestimated.
- CFD simulations in transitional flow were problematic. The lowest discrepancy For $2000 < Re < 3500$ is observed for k- ω SST, transition k-kl-ω, especially for higher Re.
- The friction factor obtained by the CFD simulations is within the measurement uncertainty of the hydraulic tests performed on the THETIS installation (excluding the results obtained by the Transition SST model).

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EUROfusion

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Thank you for your attention

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