Experimental study of steady-state transverse heat transfer in a single channel CICC

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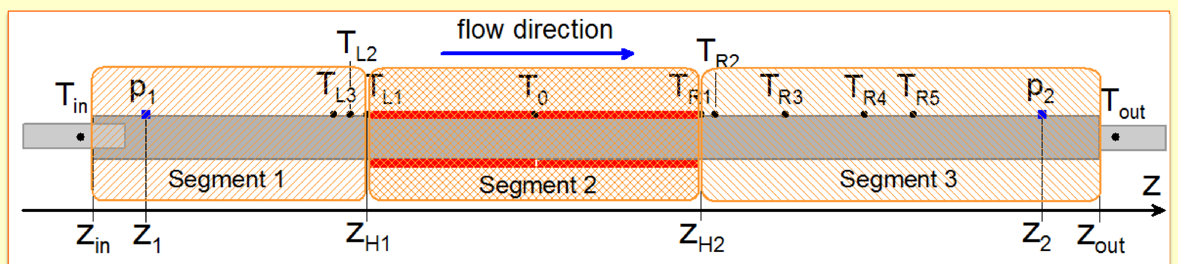
A new configuration of the THETIS installation for thermal-hydraulic tests of forced-flow superconducting cables, such as e.g. Cable-in-Conduit Conductors (CICCs) [1], has been prepared at West Pomeranian University of Technology, Szczecin. In the present form THETIS enables pressure drop and heat transfer coefficient measurements in short samples of conductors using water in a wide range of temperature and Reynolds number. We present the new configuration of the installation and demonstrate its capabilities by reporting the results of the first thermal-hydraulic test conducted on a smooth tube with a square cross section and on a reference sample (JT-60SA TF conductor). The results obtained for a smooth tube are in good agreement with predictions of the standard Dittus-Boelter heat transfer correlation, which positively verifies correctness of the applied procedures. The experimental Nu values obtained for the CICC sample remain almost constant in the considered Re range 700 – 1700, and they are about 3 times larger than those predicted by the smooth tube correlation.

GOALS

- Present the new upgraded THETIS configuration
- Reporting the results of the first thermal-hydraulic test conducted on a smooth tube with a square cross section and on a reference sample (JT-60SA TF conductor).

HEAT TRANSFER ANALYSIS



Scheme of the considered system

- Pressure profile along the sample: $p(z) = p_{in} + \frac{dp}{dz}(z - z_{in})$
- Energy balance equations for each Segment:

$$\dot{m}[i(p_{H1},T_{H1}) - i(p_{in},T_{in})] = Q_{cond1} - Q_{amb1} \quad (1a)$$

$$\dot{m}[i(p_{H2},T_{H2}) - i(p_{H1},T_{H1})] = Q_H - Q_{cond1} - Q_{cond3} - Q_{amb2} \quad (1b)$$

$$\dot{m}[i(p_{out},T_{out}) - i(p_{H2},T_{H2})] = Q_{cond3} - Q_{amb3} \quad (1c)$$

Q_H = 1201 W (smooth tube) or 1038 W (CICC) – heat released by heating modules

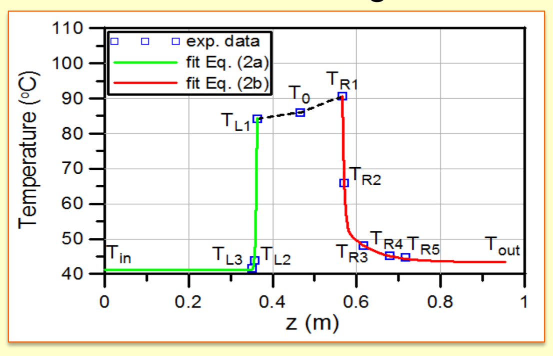
- Assumed surface temperature profiles in Segment 1 and 3

$$T(z) = T_{ref}(z) + A_1 \exp[(z - z_{H1})/\lambda_1] \quad z_{in} \le z < z_{H1} \quad (2a)$$

$$T(z) = T_{ref}(z) + \Delta T_{out} + A_2 \exp\left(\frac{z_{H2} - z}{\lambda_2}\right) + A_3 \exp\left(\frac{z_{H2} - z}{\lambda_3}\right) \quad z_{H2} < z \le z_{out} \quad (2b)$$

$$T_{ref}(z) = T_{in} + \alpha_{JT}(p(z) - p_{in}) \quad \alpha_{JT} = -0.021145 \text{ K/bar}$$

Values of parameters A_i, λ_i were obtained by fitting the above functions to readings of sensors $T_{L1} - T_{L3}$ or $T_{R1} - T_{R5}$



Typical computed temperature profile of the outer surface of the smooth tube sample

- Average temperature of the outer surface of j-th Segment:

$$T_{wo\,j} = \left[\int_{z_{jR}}^{z_{jL}} T(z)dz\right] / (z_{jR} - z_{jL})$$

- Heat rate transferred to the fluid, Q_f:

$$Q_f = \dot{m}[i(p_{out},T_{out}) - i(p_{in},T_{in})]$$

- Total heat loss to ambient, Q_{amb}:

$$Q_{amb} = Q_{amb1} + Q_{amb2} + Q_{amb3} = Q_H - Q_f \quad (3)$$

- Ratio of heat losses to ambient from Segments 1 and 3:

$$\frac{Q_{amb1}}{Q_{amb3}} = \frac{S_{wo1}(T_{wo1} - T_{amb})}{S_{wo3}(T_{wo3} - T_{amb})} \quad (4)$$

- System of Eqs. (1), (3), (4) was solved for the unknown: T_{H1}, T_{H2}, Q_{amb1}, Q_{amb2}, Q_{amb3}.
- Average temperature of the inner surface of the 2[nd] Segment wall, T_{wi2}, was obtained from the Fourier law:

$$\frac{Q_H - Q_{cond1} - Q_{cond3} - Q_{amb2}}{S_{wav2}} = k_{steel}\frac{T_{wo2} - T_{wi2}}{t_w}$$

- Heat transfer coefficient was calculated from:

$$Q_H - Q_{cond1} - Q_{cond3} - Q_{amb2} = h_{exp} S_{wi2}(T_{wi2} - T_f)$$

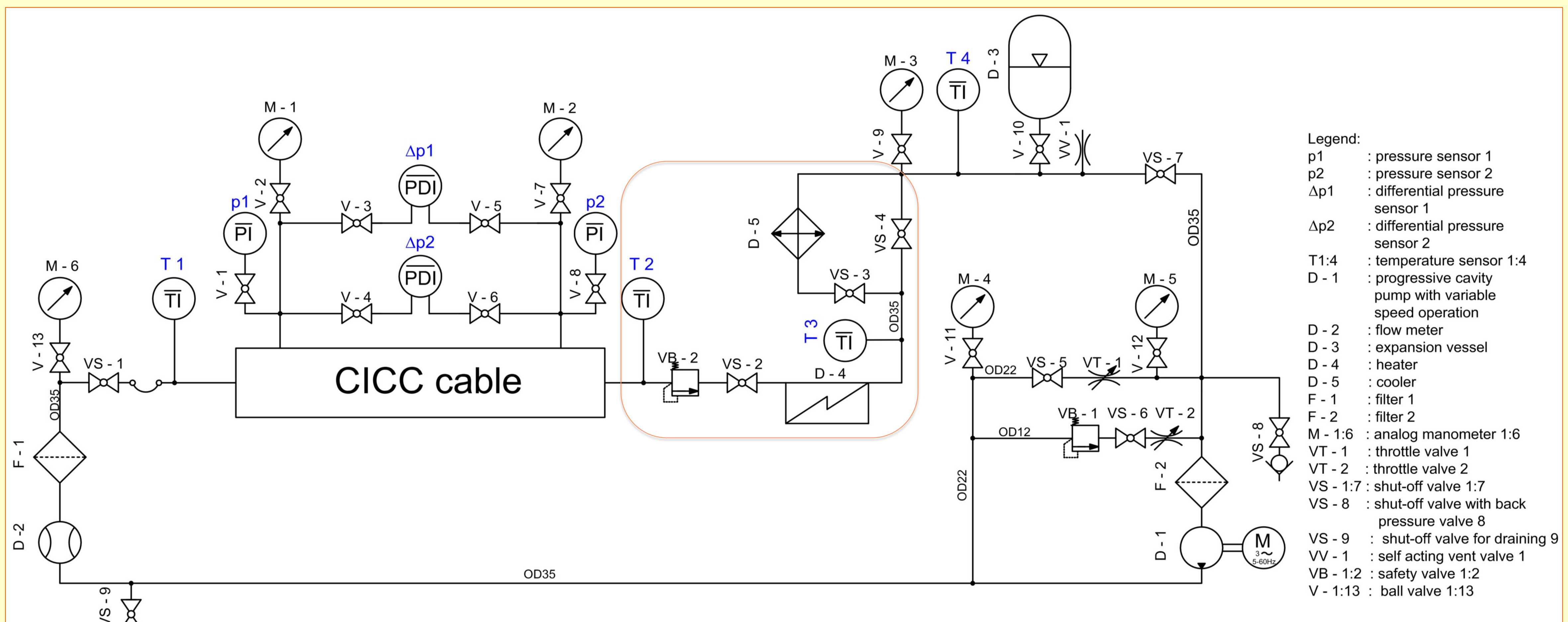
$T_f = (T_{H1} + T_{H2})/2$ - average fluid temperature in Segment 2

- Nusselt numer is calculated as:

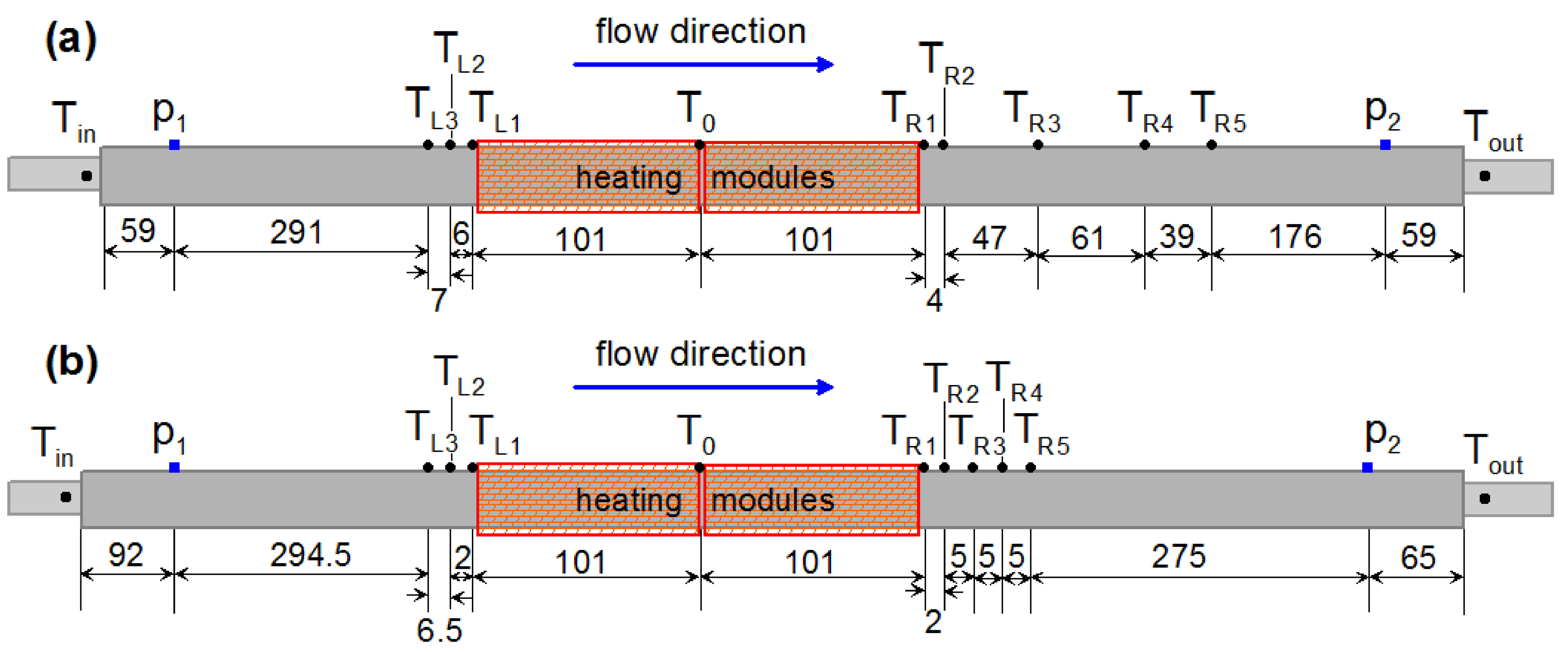
$$Nu_{exp} = h_{exp} D_h / k_{water}(p_f, T_f)$$

$p_f = (p_{H1} + p_{H2})/2$ - reference pressure in Segment 2

EXPERIMENTAL SET-UP



Hydraulic scheme of the new configuration of the THETIS installation

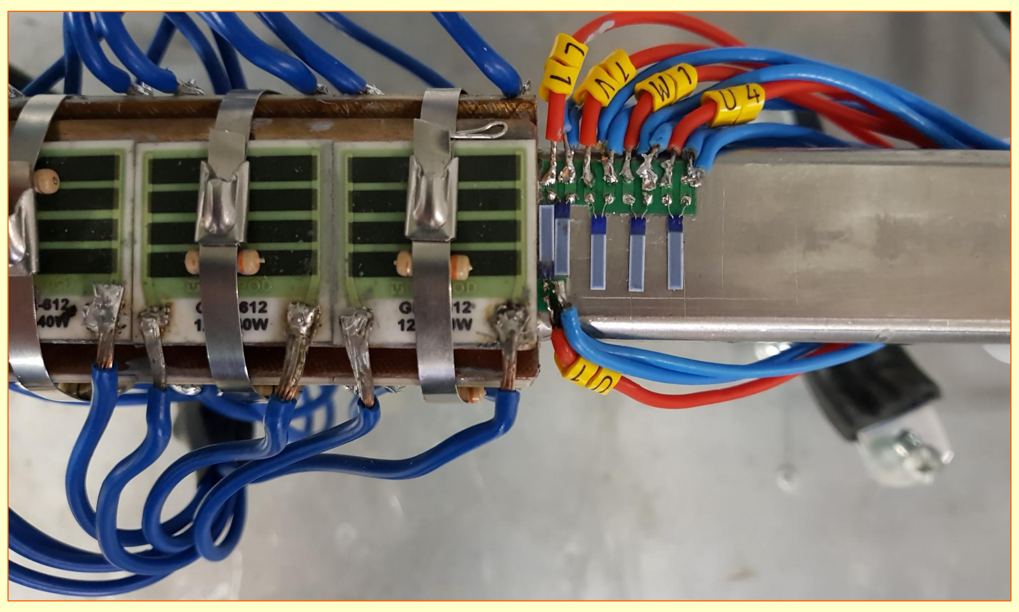


Left: Instrumentation scheme of the (a) smooth tube, (b) CICC sample. Figures not in scale. Dimensions in mm.

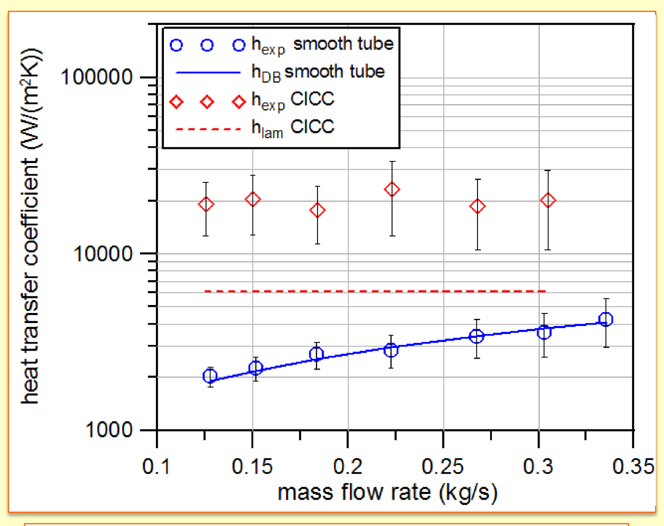
Below: Photo of a piece of the instrumented CICC sample without the thermal insulation showing the part of the right heating module and the sensors $T_{R1} - T_{R5}$.

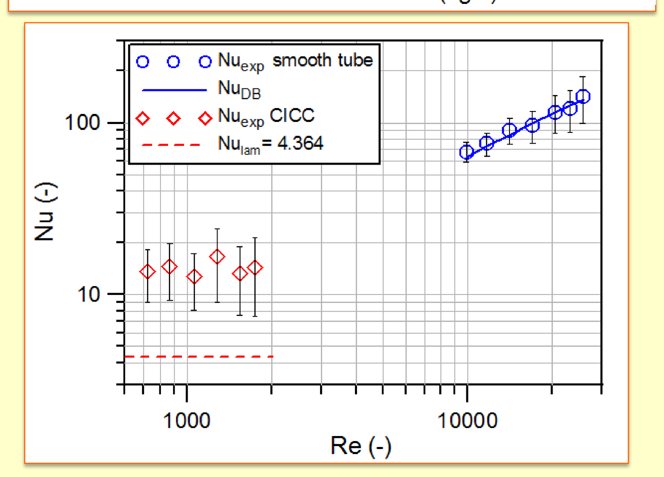
Characteristics of the smooth tube and JT-60SA TF samples used in the experiment

Quantity, unit	Symbol	Smooth tube	CICC JTF 091 [2]
Inner dimensions, mm × mm	$x \times y$	21 × 21	18 × 22
Void fraction, %	φ	100	32
Flow area, mm²	A_f	440	126
Hydraulic diameter, mm	D_h	21.3	0.454
Wall thickness, mm	t_w	2	2



RESULTS





SUMMARY CONCLUSIONS and PERSPECTIVES

- The new configuration of the THETIS installation for thermal-hydraulic tests of forced-flow superconducting cables, using water at various temperatures, has been assembled.
- The first measurements of the transverse heat transfer coefficient between the wall and the fluid were performed in the smooth tube and in the CICC sample.
- The results obtained for the smooth tube agree well with predictions of the standard Dittus-Boelter correlation, which positively verified correctness of the applied test and analysis procedures.
- The experimental values of the heat transfer coefficient remain at the constant level in the considered Re range 700-1700, and they are about 3 times larger than those predicted by the smooth tube correlation for the laminar flow, which is consistent with the results obtained in [3].
- Further systematic measurements of the heat transfer coefficient at different values of the water inlet temperature are planned to obtain the results in a wide range of Pr and Re numbers.
- In future experiments adding least one more heating module is planned to achieve larger values of T_{out}, which should result in reduction of h_{exp} and Nu_{exp} error bars.

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