Modelling and Testing of Fin-Type Heat Exchangers for the ITER Current Leads

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Background

The ITER current leads will transfer large currents of up to 68 kA into the biggest superconducting magnets ever built. A key component of the ITER HTS current leads are the resistive heat exchangers. Special R&D was conducted for these components at CERN and ASIPP in support of their designs. In particular several mock-ups were built and tested in room temperature gas to measure the dynamic pressure drop and compare to 3D CFD models. The benchmarking of the models on experimental data has helped in defining the proper modelling parameters. The experimental data from the different mock-ups are unified using scaling laws.

Objectives

- Measure heat exchanger pressure drop to calibrate CFD models and to support the design of the current leads for ITER.
- Improve the understanding of the pressure drop mechanism in zig-zag fin-type heat exchangers.

Heat Exchanger Operational Conditions in the ITER Machine

In the ITER machine the HTS current leads will be cooled with pressurized GHe entering the heat exchanger at 50 K, 0.4 MPa. The optimal flow-rate (at which the terminal temperature is stabilized at 300 K) for steady state operation at the design current was measured in the TF and CC prototypes to be 4.5 g/s and 0.65 g/s (these tests will be discussed elsewhere). The pressure drop measured in this condition is 110 kPa and 5 kPa.

For a given HX mock-up and at a given mass-flow-rate the isothermal pressure drop from one gas (e.g. GN_2) can be converted to that of a different gas (e.g. GHe) by multiplication with the inverse density ratio (Darcy-Weisbach). I.e. a conversion from RT GN2 to RT GHe this conversion at 4 bar is ≈4.495/0.64=7, so the p-drop in GHe is 7 times larger than in GN2 at the same mass-flow-rate.

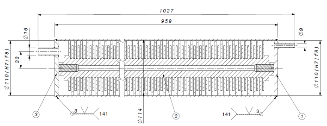
It is more complicated to convert an isothermal measurement to a measurement in nominal operating conditions, i.e. with the gas entering the HX at 50 K and exiting at 300 K.

Mock Ups

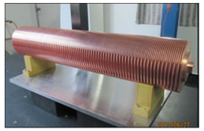
CC-type Mock-Up

There are three types of current lead and heat exchanger designs for ITER. The CC-type is for the Correction Coil Feeder systems. ITER needs 18 CC-type current leads. They are operated in pulsed mode.

Design Curr [kA]	Length (mm)	Fin Ø (mm)	Core Ø (mm)	Cut (mm)	Central hole Ø [mm]
10	903	110	38	10	10

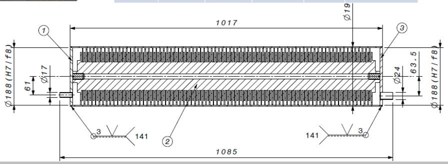


TF type mock-up



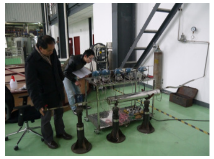
There are 18 TF-type current leads for the Toroidal Field coil feeder systems of ITER. They feed 68 kA into the TF coils in a quasi steady state regime. They will be the largest HTS leads in operation in the world.

Design Curr [kA]	Length (mm)	Fin Ø (mm)	Core Ø (mm)	Cut (mm)	Central hole Ø [mm]
68	951	188	92.4	15	16

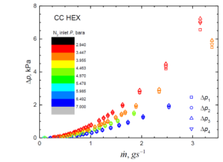


Measurements

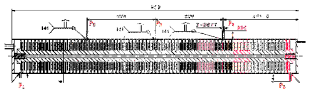
Pressure Drop Measurements



Pressure drop test set-up in ASIPP.

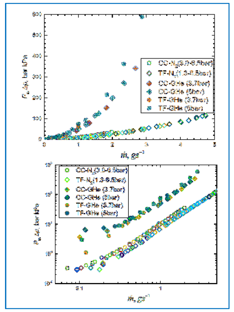


P-drop in GN2 over the individual HX segments at different inlet pressures.



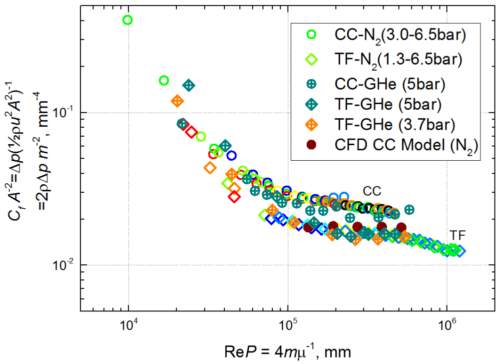
Pressure drops measured at room temperature in the CC and TF type heat exchanger mock-ups as a function of GN2 and GHe mass flow rate. All data for one type of HX converge as this representation gives the friction factor.

Pressure drops $P_{in}\Delta P$ (same data as in plot on the left) vs mass-flow rate in log scale. The change of friction factor in the transition from the laminar to the turbulent flow-regimes can be more easily discerned in the log scale.



Results

Discussion of the Results



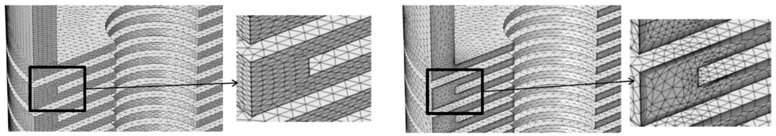
Nominal friction coefficient vs nominal Reynolds number for CC and TF HX.

At present, the experimental data lead us to the following observations: i) a satisfactory scaling of measurements at different inlet pressures; ii) as expected change in friction factor scaling with Reynolds number in transition from laminar to turbulent flow; iii) a consistent and similar behaviour shown by both CC and TF HX;

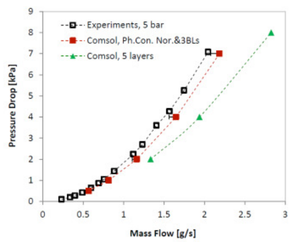
The similar friction coefficient scaling from CFD model is more likely to be significant than coincidental. To understand the difference in nominal friction factors of CC and TF HX of a factor 1.8 (at the same nominal Reynolds number), the following qualitative model is developed.

As shown in the Figure, the experimental data indicate the critical mass flow rate are $\dot{m}_{c,CC}$=0.3 g/s and $m_{c,TF}$=0.4 g/s. Therefore the ratio of flow passage perimeter between TF and CC should be PTF/PCC=4/3. Since overall diameter D of TF HX is about 1.7 times that of CC HX, the perimeter ratio of plane 2 for the U-bend zigzag flow passage between TF and CC is ≈1.6, significantly larger than the required 4/3. Similarly the relevance of the flow around the centre copper core can also be eliminated as the perimeter ratio in this case is more than 2.4. In contrast, the perimeter ratio for the narrow channel flow passage is 1.3 and fits almost perfectly with the required 4/3. Therefore the narrow channels between the fins is the only possible flow passage which potentially could underlie a common Cf(Re) correlation. Further experiments and calculations are needed to verify this hypothesis and thus improve the understanding of the pressure drop in the ITER zig-zag HX designs.

CFD Model (for turbulent flow)

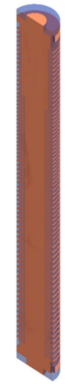


Left: original mesh (case 1 in Table 2); Right: new mesh with boundary layers and corner refinement (case 2 in Table).



Comparison between experimental data and the full model for the 10 kA CC-type mock up with N2 flow and pin = 5 bar. The triangles and the squares represent respectively the results obtained with: the original mesh (5 layers) and the physics-controlled normal mesh with 3 boundary layers. The error bar is based on the relative errors summarized in the Table.

Mesh Type	Millions of elements	Millions of DOFs	Boundary Layers	Inlet mass flow [g/s]	outlet mass flow [g/s]	% Relative error
5 layers	0.59	0.70	0	2.429	2.452	20.85
5 layers & C. Ref.	2.35	2.57	0	2.151	2.167	7.01
Finer&1BL&C. Ref.	0.86	1.17	1	2.153	2.192	7.11
Finer&2BLs&C. Ref.	0.95	1.42	2	2.078	2.107	3.38
Ph.Con. Nor.&3BLs	0.49	0.93	3	2.082	2.099	3.58
Ph.Con. Nor.	0.60	1.25	5	2.049	2.062	1.94
Ph.Con. Fine	1.67	3.16	5	2.025	2.034	0.75
Ph.Con. Finer- -	2.49	4.34	5	2.013	2.016	0.16
Ph.Con. Finer -	5.14	8.66	5	2.010	2.0146	-



10 kA short model with nitrogen flow, at inlet pressure 0.3 MPa and Δp = 733 Pa.

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