Karlsruhe Institute of Technology

Parametric CtFD analysis of pressure drop and heat transfer in the meander-flow heat exchanger of HTS current leads for fusion applications

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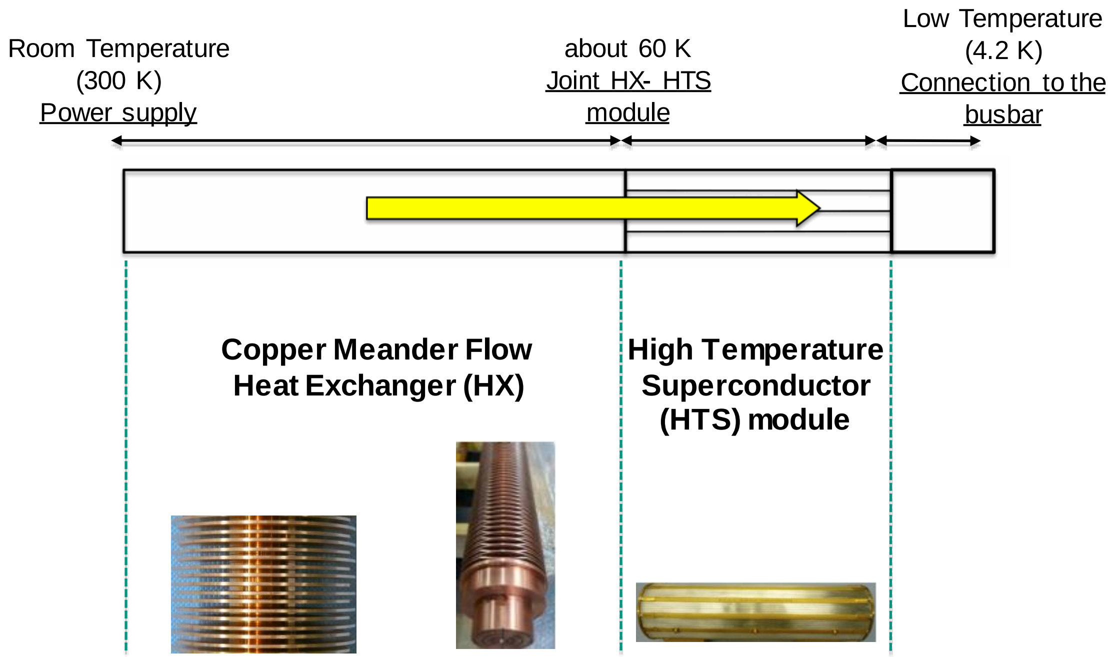
General overview on the HTS CL (fusion application)

- Current leads: current transport from the room temperature power supply down to the superconducting coils inside the cryostat
- HTS current lead is presently the leading design for current leads
- A HTS current lead requires a cooling power about 3 times lower than a conventional (metallic) current lead



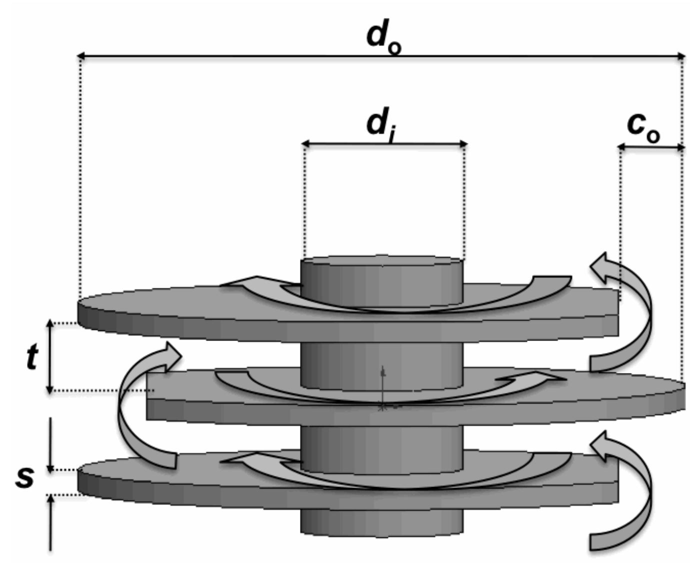
Characteristics of the MF HX

- Copper finned conductor operating between T ~60 K and RT
- Current flows in the central Cu bar
- Actively cooled by gaseous helium (He inlet at T ~50 K)

- Typical meander flow path (fully 3-D)

  - **MF geometry parameters**

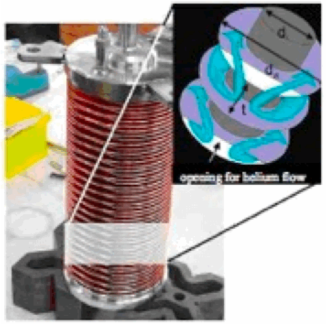
    - Outer diameter of the fins (d_o)
    - Central bar diameter (d_i)
    - Fin distance (t)
    - Fin thickness (s)
    - Cut off (c_o)



Previous works on the MF HX CtFD modelling @ KIT

- Development of the periodic model against MF mock-up experiment

L. Savoldi Richard et al. "CtFD analysis of HTS current lead fin-type heat exchanger for fusion applications", *IEEE Trans. Appl. Supercond.,* vol. 20, no. 3, pp 1733-1736, 2010



- Validation of the periodic model against W7-X HTS CL prototype experiment

E. Rizzo, R. Heller, L. Savoldi Richard, R. Zanino,
"Heat exchanger CFD analysis for the W7-X high temperature superconductor current lead prototype", Fusion Eng. Des. (2011), doi: 10.1016/j.fusengdes.2011.04.077.

Current	He m.f.r.	Δp exp.	Δp comp.
0 kA	0.53 g/s	32 mbar	25 mbar
14 kA	1.04 g/s	122 mbar	109 mbar
18.2 kA	1.37 g/s	220 mbar	212 mbar
20 kA	1.68 g/s	285 mbar	285 mbar

Objective of the present work

- CtFD periodic model for a systematic analysis of the MF geometry thermal-hydraulics
- Description of the dependence of the heat transfer process and the pressure drop on the MF geometrical parameters
- Derivation of correlations for the heat transfer coefficient and the friction factor

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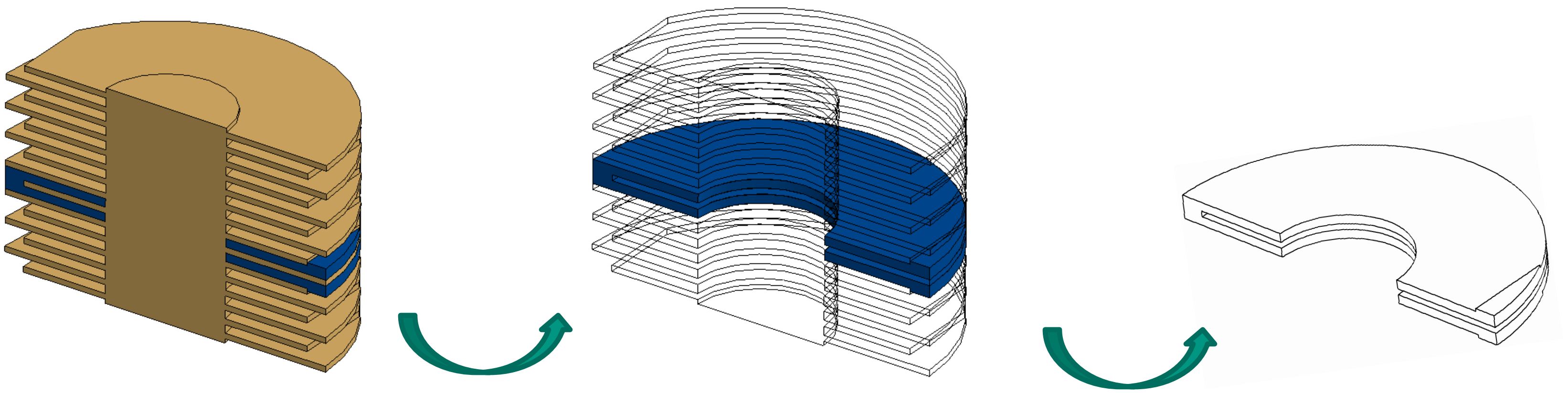
- ✓ Introduction
- **Model Description**
  - Periodic model (derivation, boudary conditions)
  - Ranges for the parametric analysis
  - CtFD analysis
- Results
- Conclusion and Perspectives

Periodic model

- The MF geometry is periodic
- Isolation of a single MF geometry “molecule” (*double-layer*)
- Copper replaced by appropriate boundary conditions
- Local CtFD analysis on the fluid domain (fully representative of the corresponding MF HX geometry)

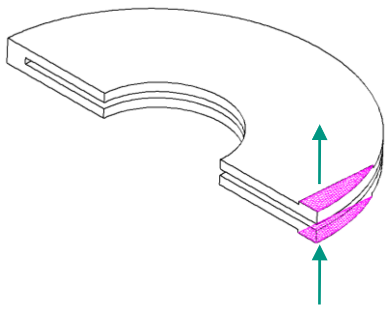


Model Description

Periodic model boundary conditions

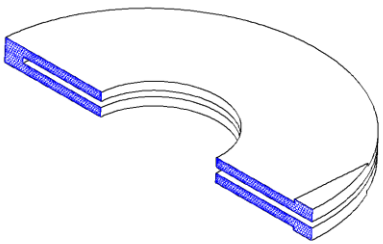
- Partially cyclic boundary conditions

  - Model the inlet and the outlet of the periodic model
  - Require the He mass flow rate, He inlet temperature and pressure to be imposed
  - Fully developed flow



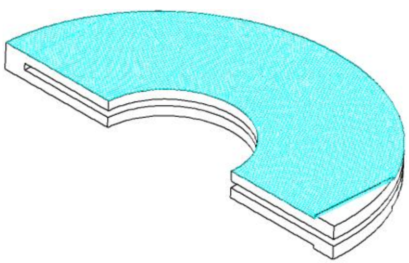
- Symmetry plane

  - He flow is assumed to be longitudinally symmetric



- Walls

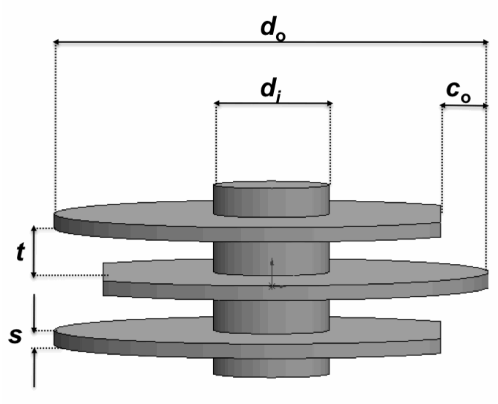
  - Replace the former Cu/He interfaces
  - Walls are assumed to be smooth
  - A fixed temperature is imposed for the thermal analysis



The definition of the parameter ranges

- Range for the MF geometry parameters

d_o	80 - 200 mm
d_i	35 – 120 mm
t	2 – 8 mm
s	2 – 6 mm
c_o	2.5 - 20 mm



- Range for the flow conditions

mass flow rate ($\dot{m}$)	0.2 – 5 g/s
temperature (*T*)	50 – 300 K
pressure (*p*)	2 – 6 bar

Both ranges are defined to cover the design values of the HTS CL mounting this type of HX presently under design/construction

CtFD analysis

- Steady state thermal-hydraulic analysis for different flow conditions
- Analysis with the commercial software Star-CD
- Set of equations
  - **Continuity equation**
  - **Momentum equation**
  - **Energy equation**

Model Description

CtFD analysis

- Steady state thermal-hydraulic analysis for different flow conditions
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HYDRAULIC ANALYSIS

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Provides the pressure drop (Δp)
on the partially cyclic boundary conditions

CtFD analysis

- Steady state thermal-hydraulic analysis for different flow conditions
- Analysis with the commercial software Star-CD
- Set of equations

  - **Continuity equation**
  - **Momentum equation**
  - **Energy equation**

Continuity equation + Momentum equation → HYDRAULIC ANALYSIS

HYDRAULIC ANALYSIS + Energy equation → THERMAL HYDRAULIC ANALYSIS

HYDRAULIC ANALYSIS

Provides the pressure drop (Δp)
on the partially cyclic boundary conditions

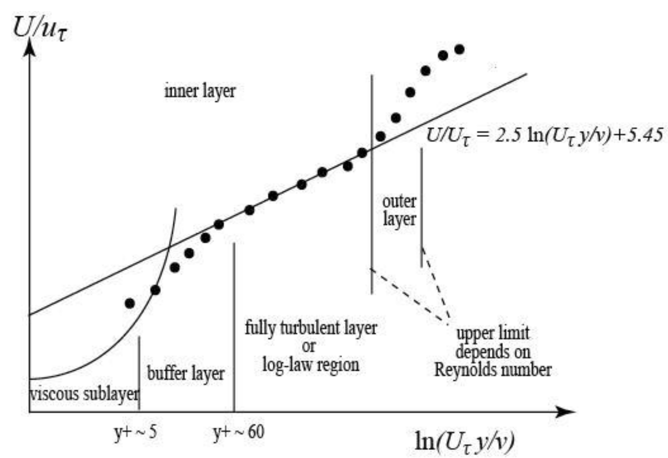
THERMAL-HYDRAULIC ANALYSIS

Provides the temperature increase (ΔT) on the partially cyclic boundary conditions for a specific temperature of the walls (T_w)

the heat transfer coefficient (h) can be derived

CtFD analysis

- The set of considered flow conditions likely covers the laminar, transition and the turbulent regime
- Additonal equations are needed for the turbulence modeling
- Turbulent CtFD model
  - **SST *k*–ω model**
    - Two equation, eddy-viscosity model
    - Combination of *k*-ω model and *k*-ε model
  - ***Hybrid* near wall treatment**
    - *y*+ ≈ 1 — Low Re number treatment
    - *y*+ ≠ 1, 0.1 ≤ *y*+ ≤ 100 — Wall functions



Mesh generation

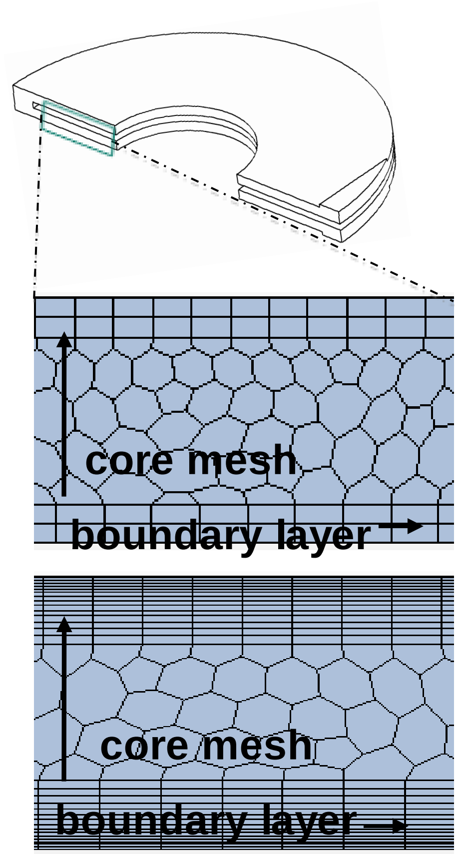
- Meshes are generated with the commercial software Star-CCM+ and tested against grid independence

- <u>Mesh characteristics for the laminar and the turbulent regime</u>

  - **Core mesh**
    - Polyhedral cells
    - Reference size: 0.5 – 0.9 mm

  - **Boundary layer**
    - **Laminar regime**
      - 2 prism layers
      - Same layer thickness

    - **Turbulent regime**
      - ~ 15 prism layers
      - Increasing layer thickness towards the core mesh



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CtFD outcomes

- The CtFD analysis provides the Δp and the h for a given MF model, at different flow conditions

- These outcomes are typically arranged in terms of dimensionless quantities:
  - Reynolds number (*Re*) – flow conditions
  - Friction factor (*f*) – pressure drop
  - Nusselt number (*Nu*) – heat transfer coefficient

- *Re*, *f*, *Nu* depends on geometrical quantities that characterize the geometry itself
  - Hydraulic diameter (d_h)
  - Flow cross section (A_{He})

  } Non trivial definition for the MF geometry

- Arrangement of the CtFD outcomes with the flow thermodynamic quantities:

$$Re^* = Re \cdot \frac{A_{He}}{d_h} = \frac{\dot{m}}{\mu} \qquad f^* = f \cdot \frac{L}{2 \cdot d_h \cdot A_{He}} = \frac{\Delta p \cdot \rho}{\dot{m}^2} \qquad Nu^* = \frac{Nu}{d_h} = \frac{h}{k}$$

Specific f^*=f(Re^*) and Nu^*=f(Re^*) for each MF geometry model

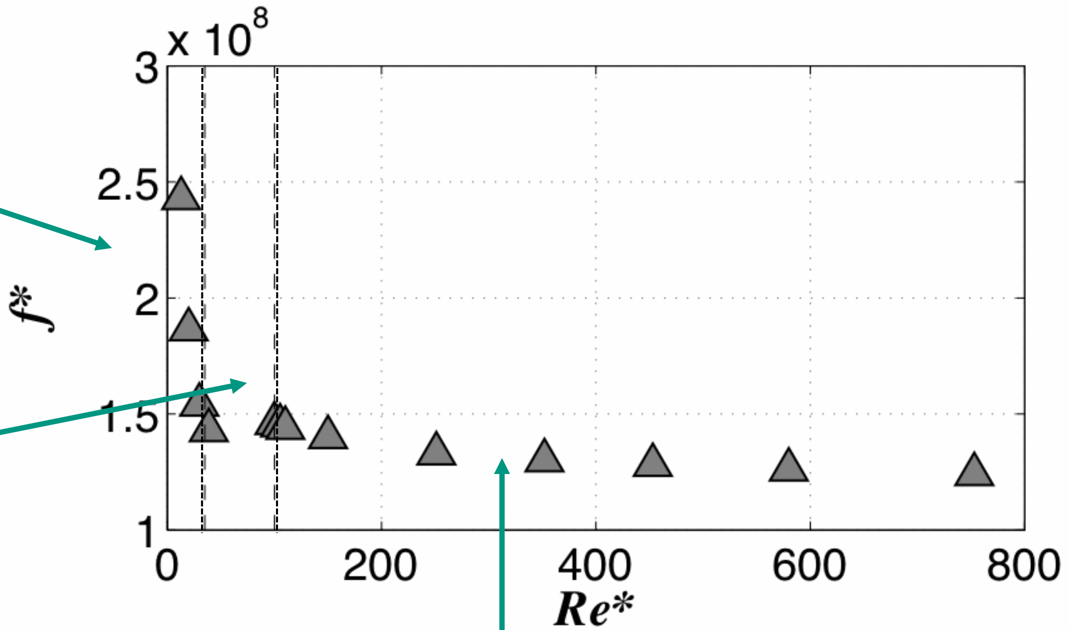
CtFD outcomes

- Laminar / turbulent regime: general behaviour

LAMINAR REGIME

TRANSITION

Departing from *Re** ~ 30 laminar runs have either a lower convergence rate or do not converge at all



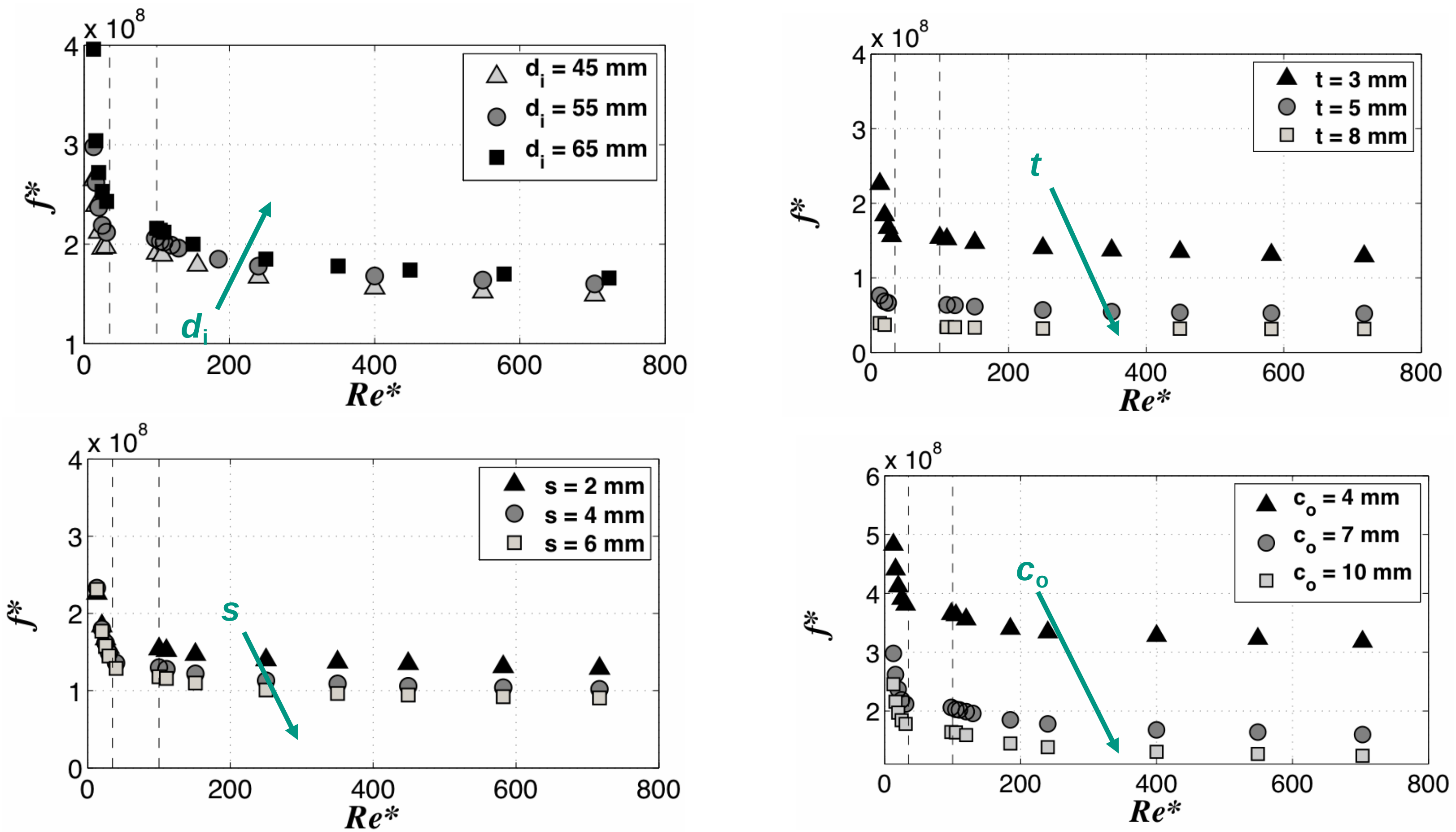
TURBULENT REGIME

The turbulent quantities computed values justify the turbulent modelling to be started from *Re** ~ 100 (turbulent viscosity larger than the molecular viscosity)

Results

CtFD outcomes – Pressure drop

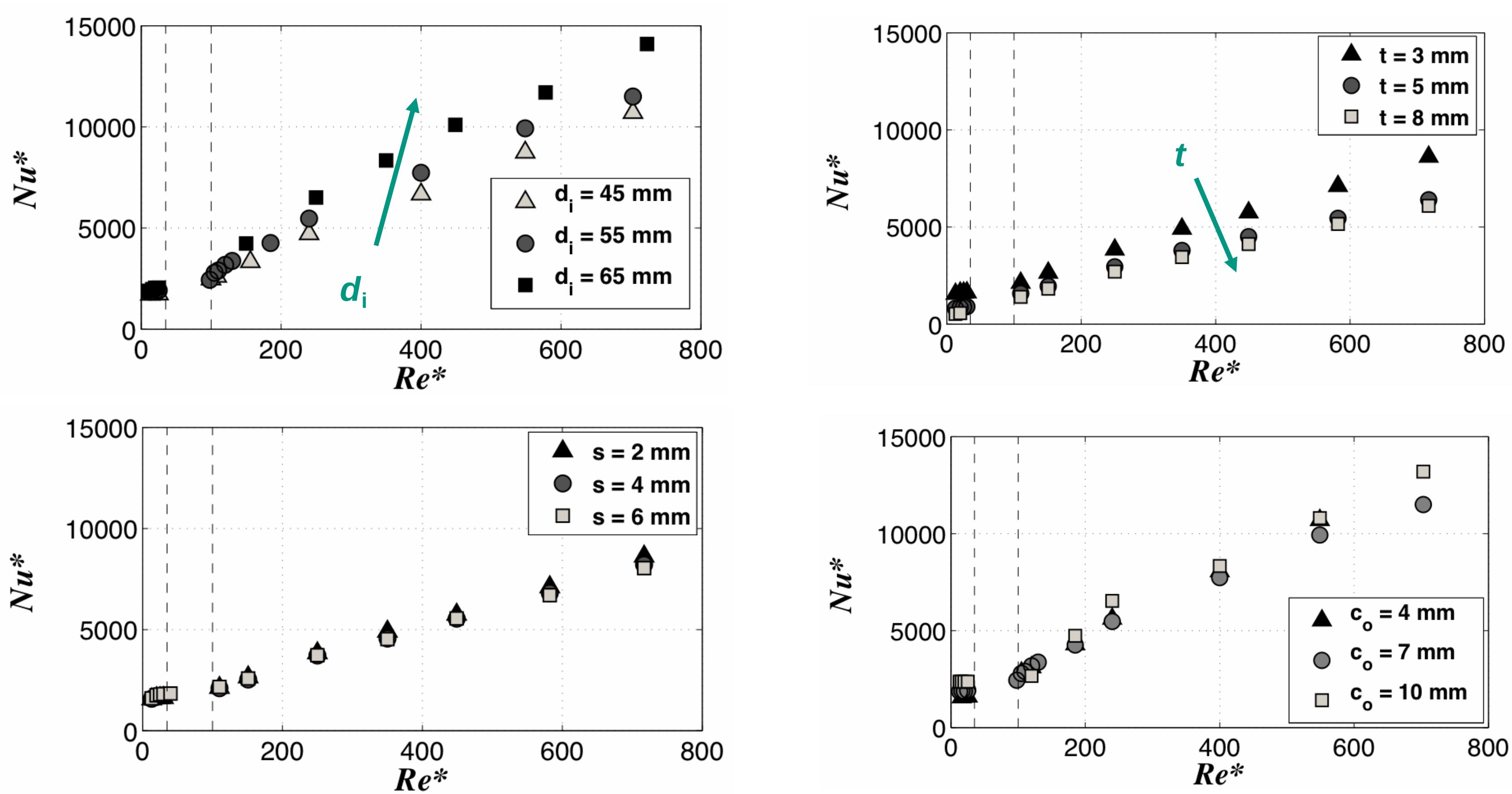
- Example of the MF geometry effect on the pressure drop



Results

CtFD outcomes – Heat transfer coefficient

- Example of the MF geometry effect on the heat transfer coefficient



Characteristic dimensions of the MF geometry

- Characteristic dimensions are necessary to suitably correlate the heat transfer and the pressure drop for the different MF geometry models

- Hydraulic diameter (d_h) and He cross section (A_{He})

  - **Required to make *Re**, *f** and *Nu** dimensionless**

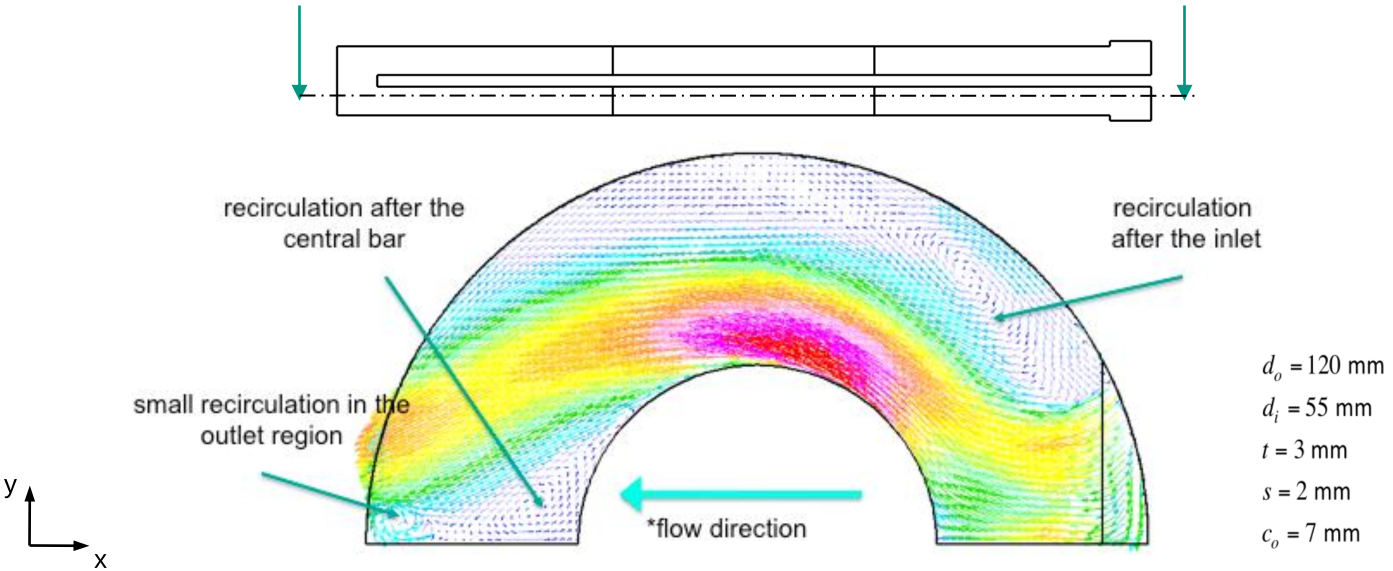
$$Re = Re^* \cdot \frac{d_h}{A_{He}} \qquad f = f^* \cdot \frac{2 \cdot d_h \cdot A_{He}}{L} \qquad Nu = Nu^* \cdot d_h$$

- A detailed analysis of the flow fields is required

  - A_{He} ↔ flow distribution and core flow velocity
  - d_h ↔ velocity distribution

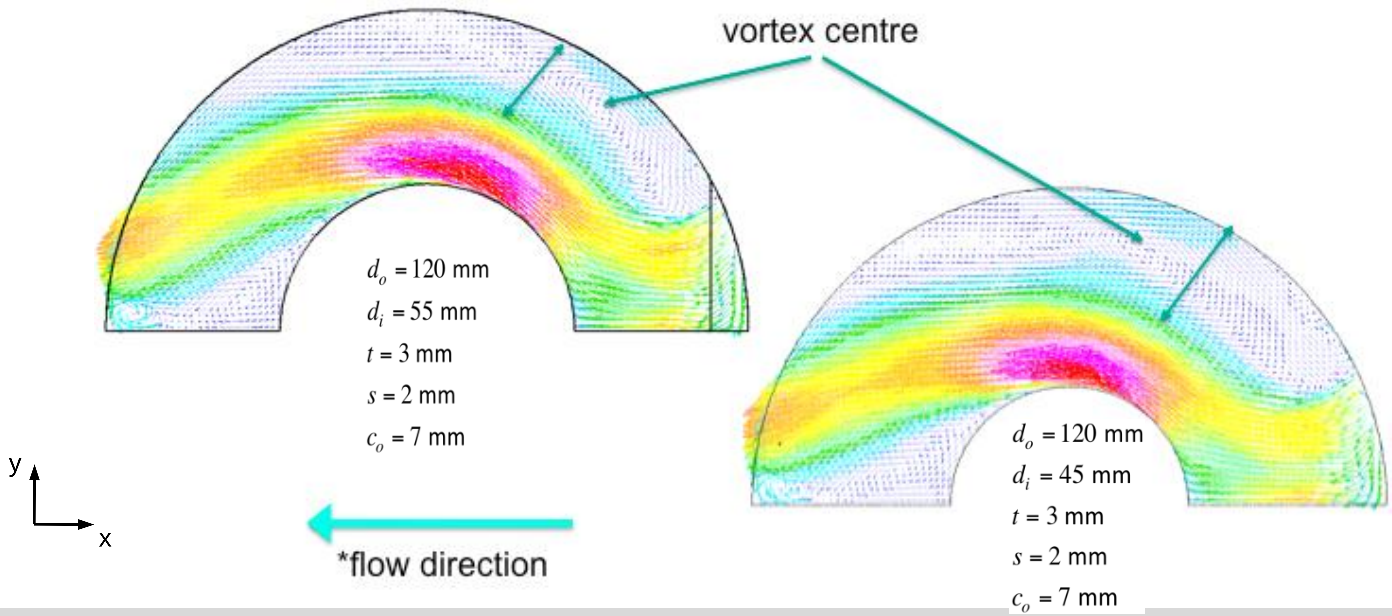
Flow field analysis – Flow on the plates

- The flow field analysis aimed at defining the characteristic dimensions is performed on the turbulent regime results
- Analysis of the flow on the plates for a generic case
- Flow field is characterized by a main flow region (yellow/red) and several recirculation regions (blue/green)



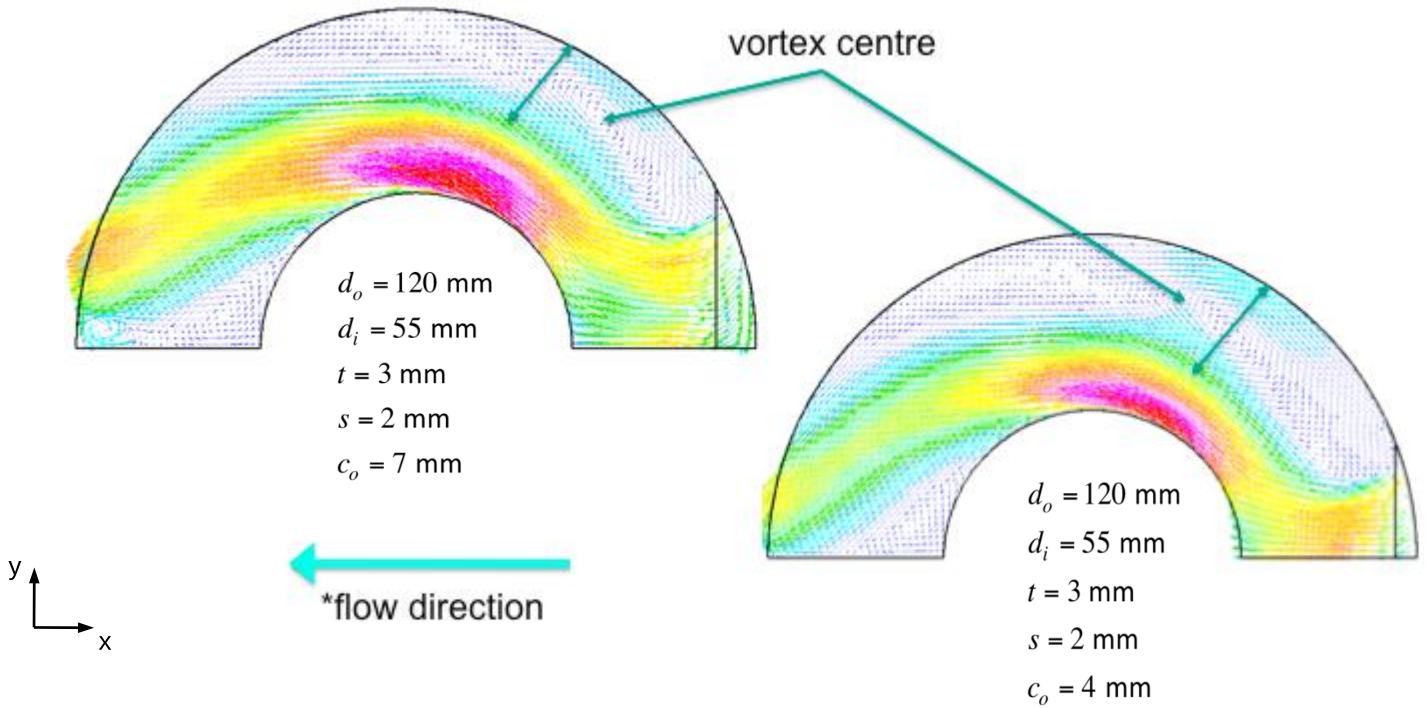
Flow field analysis – Flow on the plates

- Investigation of the effect of the MF geometry parameters on the flow field
- Variation of the inner diameter (d_i)
    - Recirculation zone (vortex) width increases with smaller inner diameter (outer diameter and cut off are kept constant)



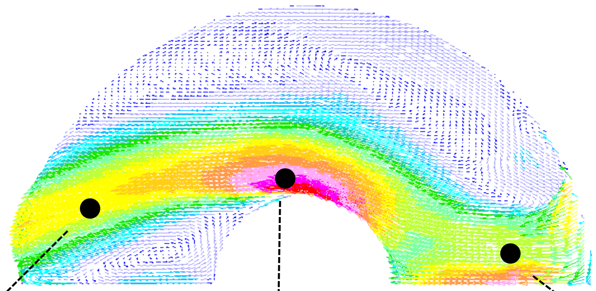
Flow field analysis – Flow on the plates

- Variation of the cut off (c_o)
  - Recirculation zone (vortex) width increases with smaller cut off (outer diameter and inner diameter are kept constant)



Flow field analysis – Axial flow on the plates

- Axial flow field analysis at different locations in the main stream

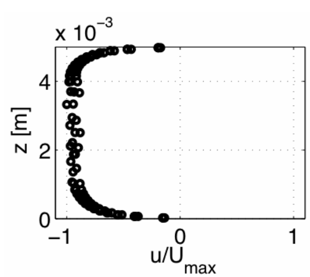


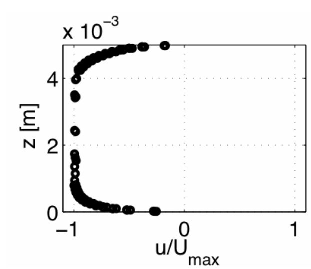
*flow direction

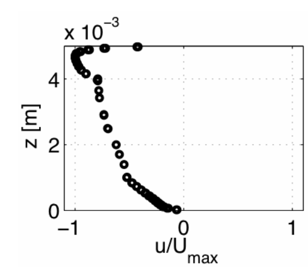
Outlet

Central bar

Inlet







Turbulent like flow profile

Perturbation of the flow field

Flow field analysis – Remarks

- Flow on the plates

  - The width of the vortex influences the main stream, depending on the inner and outer diameter and on the cut off
  - The velocity distribution shows characteristics similar to the classical turbulent velocity profile between parallel plates

Definition of the hydraulic diameter (d_h) and the He cross section (A_{He}) for the MF geometry is possible

Correlations – MF turbulent heat transfer

- Combining of *Re*, *Nu* and other MF geometrical dimensionless quantities (e.g. t/d_i, d_i/d_o)

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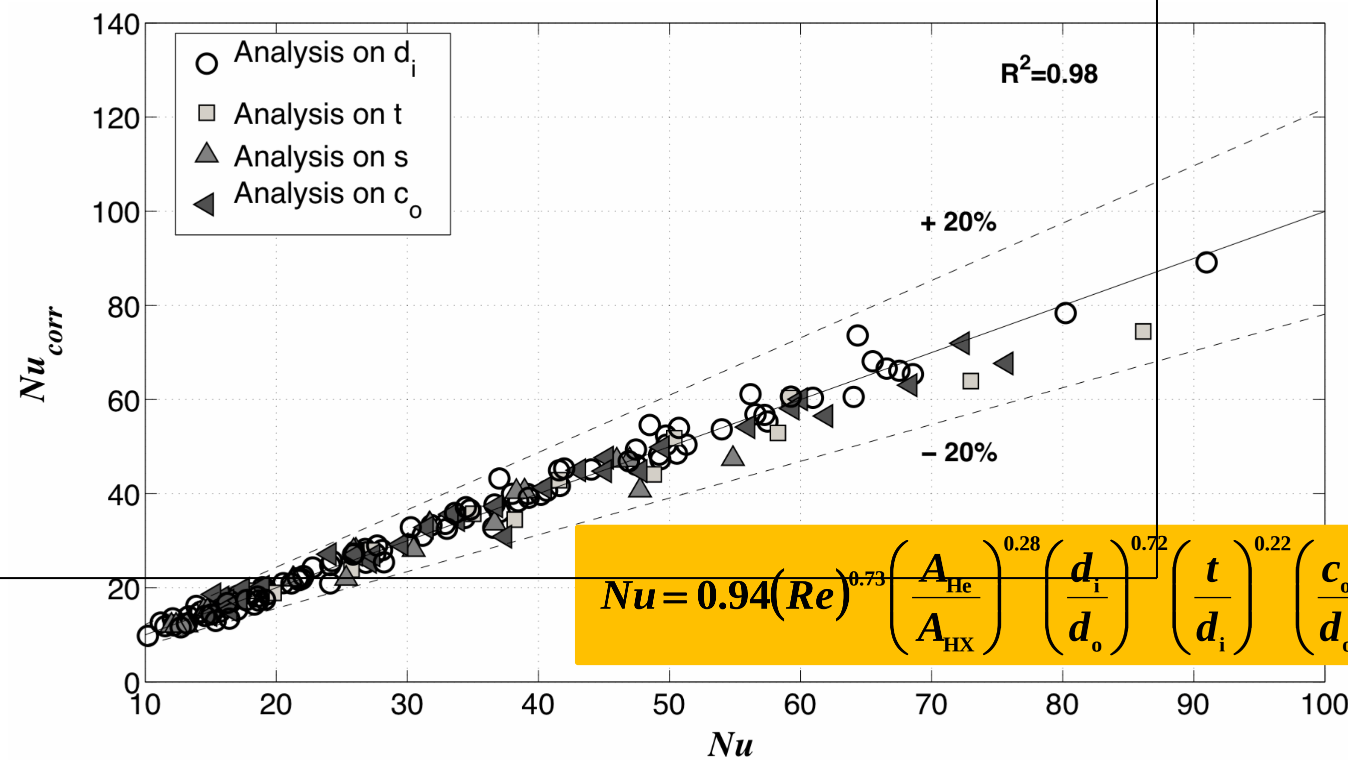
- Correlation derived with a multivariate linear regression analysis (accuracy +/- 20 %!)

Re	2000-30000
d_o	80 - 200 mm
d_i	35 – 120 mm
t	2 – 8 mm
s	2 – 6 mm
c_o	4 - 20 mm



$$Nu = 0.94 (Re)^{0.73} \left(\frac{A_{He}}{A_{HX}}\right)^{0.28} \left(\frac{d_i}{d_o}\right)^{0.72} \left(\frac{t}{d_i}\right)^{0.22} \left(\frac{c_o}{d_o}\right)^{0.10}$$

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Conclusions and perspectives

- A parametric analysis on the pressure drop and the heat transfer in the MF geometry has been performed with a computational periodic model
- An example of correlation for the MF has been shown (MF turbulent heat transfer)
- In perspective, finalize the derivation of the correlation for the turbulent friction factor and the correlations for the laminar region

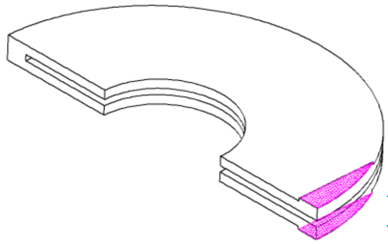
Thank you for your attention

Back -up

Periodic modelling constraints

- Partially cyclic boundary conditions

Available for cyclic pairs matched in Cartesian coordinates [3] → *double layer* domain instead of *single layer* domain



- Helium density

Partially cyclic boundary conditions require the density to be constant [3] → $\Delta\rho$ due to ΔT and Δp is limited to 5% with respect to the He inlet density

(condition always fulfilled)