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Karlsruhe Institute of Technology

Test section design for heat transfer measurements in a turbulent molten salt HITEC pipe flow

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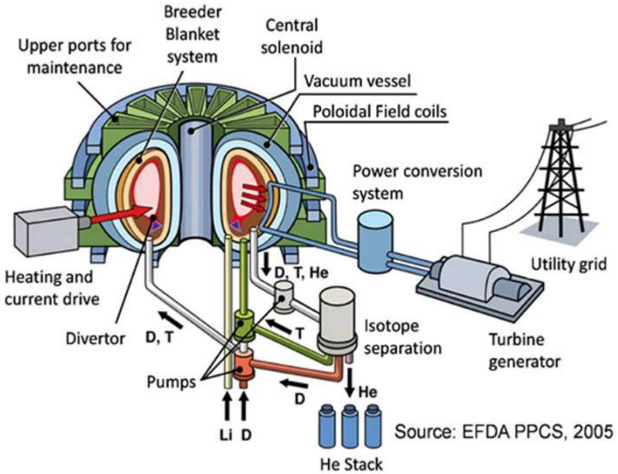
EU-DEMO Helium-cooled (HCPB) power plant

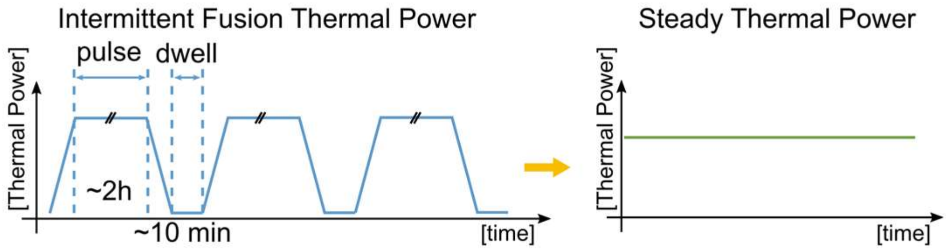
- DEMOnstration fusion power plant

$$D_2 + T_3 \rightarrow He_4 + n + (17.6\ \mathrm{MeV})$$

- Operates in pulsed mode (plasma current)
  - 2h pulse time ($\sim 2\ \mathrm{GW_{th}}$)
  - ~10 min dwell time (~1-3% nominal power)
- Stable operating conditions needed at the steam turbine

➡ Intermediate Heat Transfer System

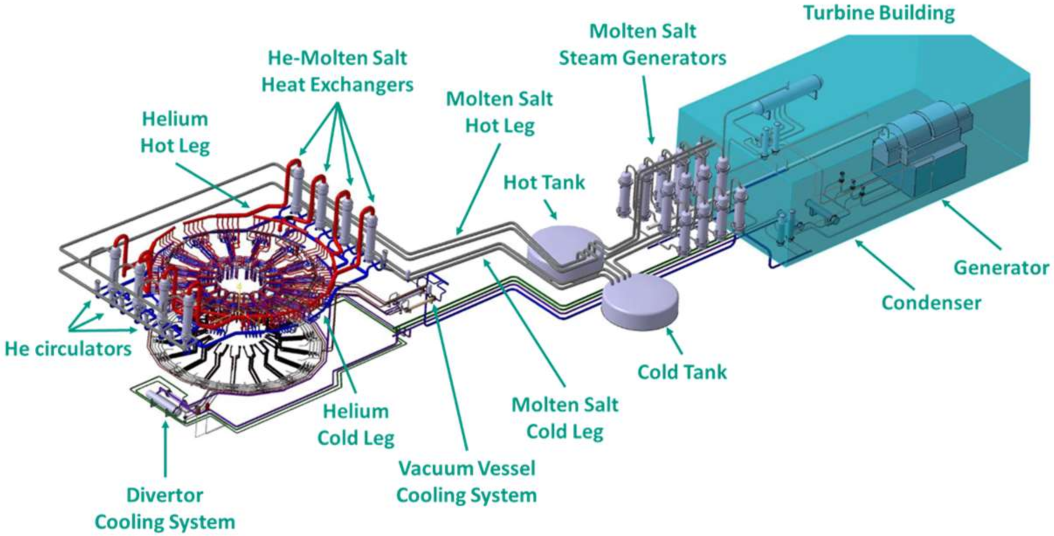


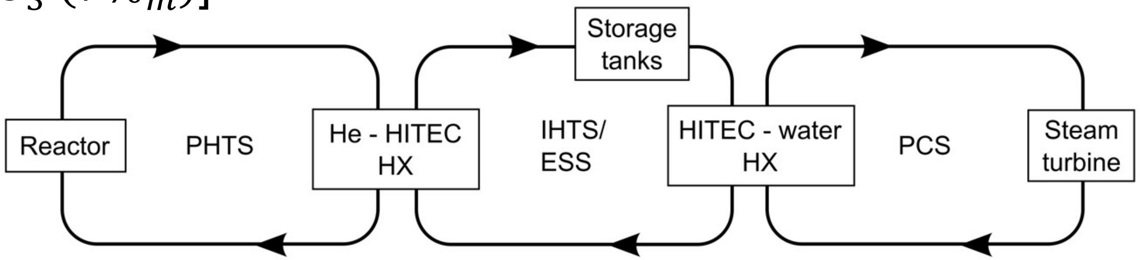


EU-DEMO Helium-cooled (HCPB) power plant

- Primary Heat Transfer System (PHTS)
  - Helium, 80 bar, $520 - 300°\mathrm{C}$,
  - 8x $\sim 260\ \mathrm{MW}$
- Power Conversion System (PCS)
  - Water / steam
- Intermediate Heat Transfer System / Energy Storage System (IHTS/ESS)
  - Similar to Concentrated Solar Power
  - Molten salt (HITEC) $[\mathrm{KNO_3}\ (53\%_m)$, $NaNO_2\ (40\%_m)$ and $\mathrm{NaNO_3}\ (7\%_m)]$
  - Temperature range $240 - 465°\mathrm{C}$

➡ HELOKA-Upgrade Storage facility





HELOKA-US

- HElium LOop Karslruhe – Upgrade Storage facility
- Design characteristic ($260\ \mathrm{kW_{th}}$):
  - High pressure Helium loop: $300-520°\mathrm{C}$, 80 bar
  - Molten salt (HITEC) loop with two tanks: $240-465°\mathrm{C}$, 6 bar
  - Water cooling system: $160-220°\mathrm{C}$, 35 bar
- Experimental research of the decoupling scheme
  - ➡ Heat transfer measurements
  - ➡ Investigate a He-HITEC heat exchanger prototype
  - ➡ He compressor prototype

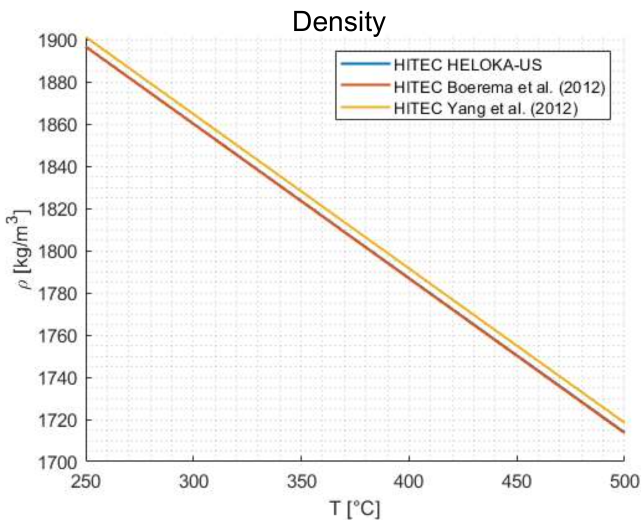
➡ Design a test section for heat transfer measurements

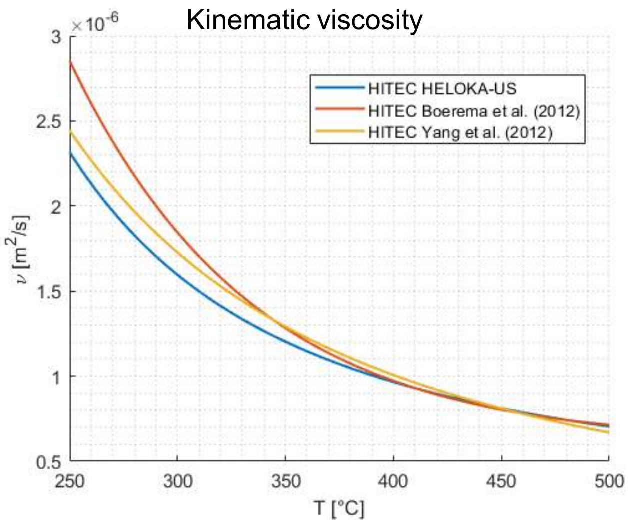
Test section - HITEC heat transfer measurements

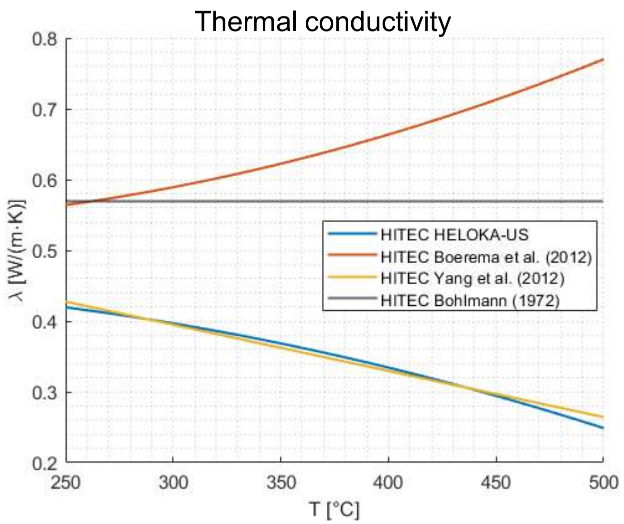
- Boundary conditions:
  - Mass flow: $\dot{m} = 0.9\ \mathrm{kg/s}$
  - Inlet temperature: $T_i = 240 - 465°\mathrm{C}$
- Design parameters:
  - Turbulent pipe flow with $Re_{max} \geq 10000$ for the full temperature range
    - ➡ Pipe diameter: $d_i = 28.5\ \mathrm{mm}$
  - Bulk temperature increase of 10K
    - ➡ Total heat flux $14\ \mathrm{kW}$
  - Heating wires within a copper block
    - ➡ Uniform angular temperature distribution
- Analytic description of the heat transfer
- Numerical simulation of the flow inlet and heated segment

HITEC fluid properties

- Heat capacity: constant $c_p = 1560\ \frac{\mathrm{J}}{\mathrm{kg \cdot K}}$
- Kinematic viscosity ν: Deviation of published values $< 25\%$
- Thermal conductivity λ: Deviation of published values up to 311%



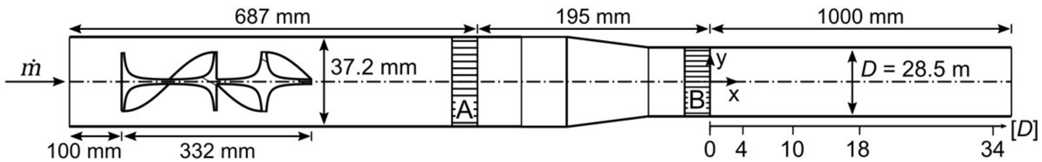




Flow straightener boundary conditions

- ANSYS Fluent meshing (poly-hexacore mesh)
- RANS simulation [ANSYS FLUENT 2022 R2]: $k - \omega\ SST$ model
- Fluid properties of HITEC: constant at $T = 305°C$
- Inlet velocity: $u_{in} = 0.446\ \mathrm{m}/s\ (Re = 14480)$
- Variation of the flow straightener components A and B
  - Honeycomb / perforated plate
  - Amount (none, one or two)

➡ Evaluation of the axial velocity profile and swirl angle



Flow straightener simulation results

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- Requirements:
  - Deviation of the axial velocity profile to fully developed pipe flow < 5%
  - Swirl angle $\Theta < 2°$

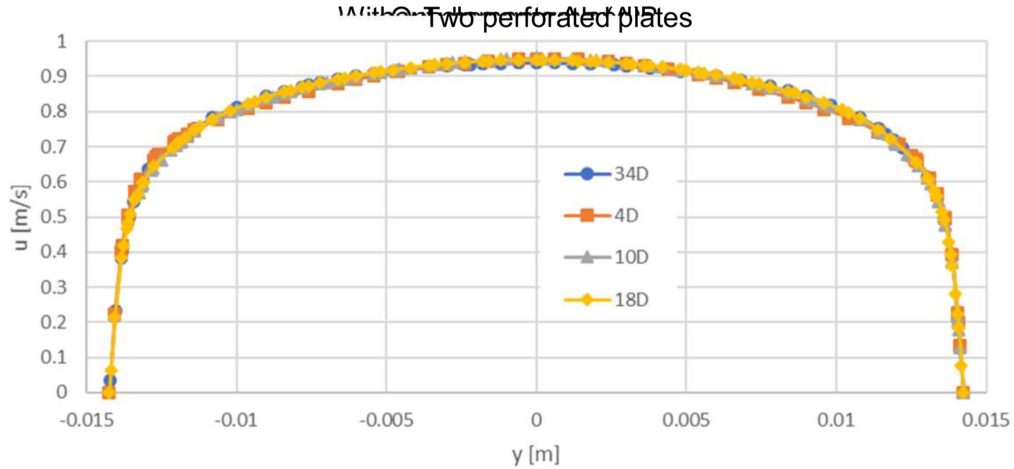
$$\tan(\Theta) = \left(\frac{u_t}{u}\right)$$

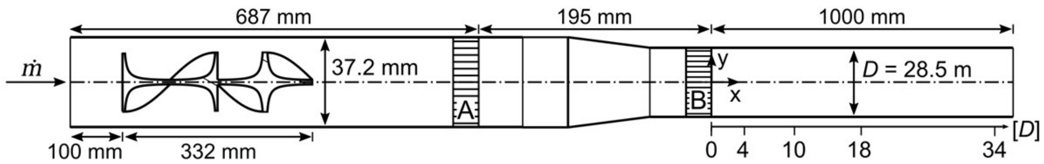
u_t - tangential velocity
u - axial velocity

- Entrance length:
  - Analytic: $L_{hyd}/D = 4.4 \cdot Re^{1/6} \approx 22$
  - Simulation: $\sim 34D$ ➔ $10D$

18D	Deviation vel. profile	Swirl angle
None	5%	$> 3°$
2 Honeycombs	$< 4\%$	$< 0.1°$
2 Perforated plates*	$< 1\%$	$< 0.5°$

*Laws (1990)





Analytic description heat transfer

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- Review of Nusselt number correlations:
  [Ghajar and Tam (1994); Hoffman and Cohen (1960); Kakac (1987)]
  ➡ Gnielinski correlation (for $2300 \leq Re \leq 5 \cdot 10^6$; $0.5 \leq Pr \leq 2000$):

$$f_P = (0.79 \cdot \ln(Re) - 1.64)^{-2}$$

$$Nu_G = \frac{\frac{f_P}{8} \cdot (Re - 1000) \cdot Pr}{1 + 12.7 \cdot \sqrt{\frac{f_P}{8}} \cdot (Pr^{2/3} - 1)}$$

$$Re = \frac{u \cdot d_h}{\nu}$$

$$Pr = \frac{\nu \cdot \rho \cdot c_p}{\lambda}$$

- Expected deviation of the Nusselt number
  - 5% due to the correlation [Kakac (1987)]
  - Up to 45% due to fluid property uncertainty

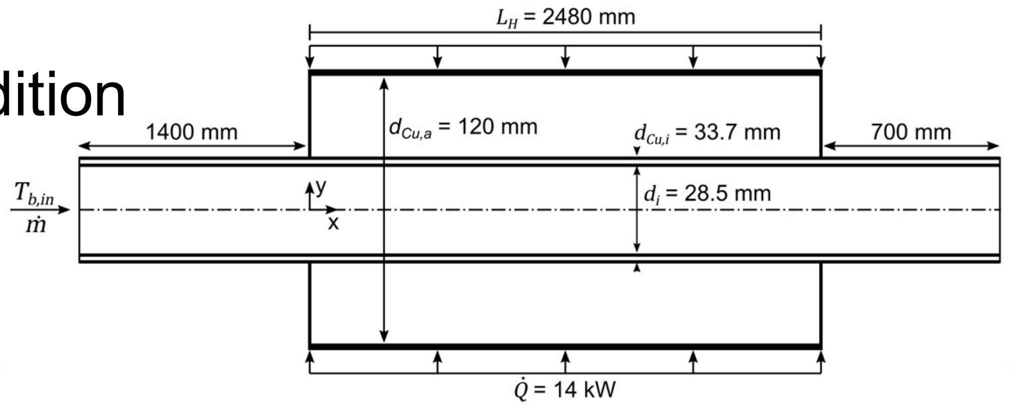
- Heated length of $L = 1.24$ m necessary
  ➡ Reduce wall temperature ➡ $L = 2.48$ m

$T_{b,in}$[°C]	Re_{max}	Pr	Nu_G	$T_{w,1}$ [°C]	$T_{w,2}$ [°C]
260	10412	14.6	108.2	345.4	305.2
300	14012	11.4	129.9	375.2	340.1
350	18820	9.1	155.9	418.1	386.6
400	23797	8.0	182	464.7	434.9
450	28808	7.5	210	500*	484.5

for 10K temperature increase

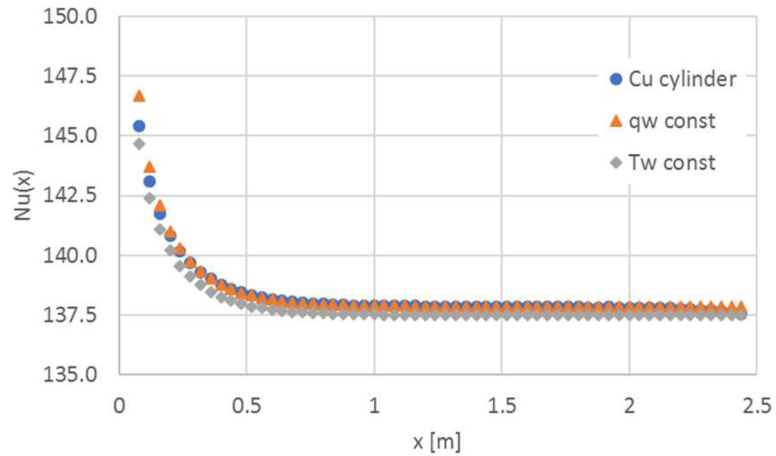
Heated segment boundary conditions

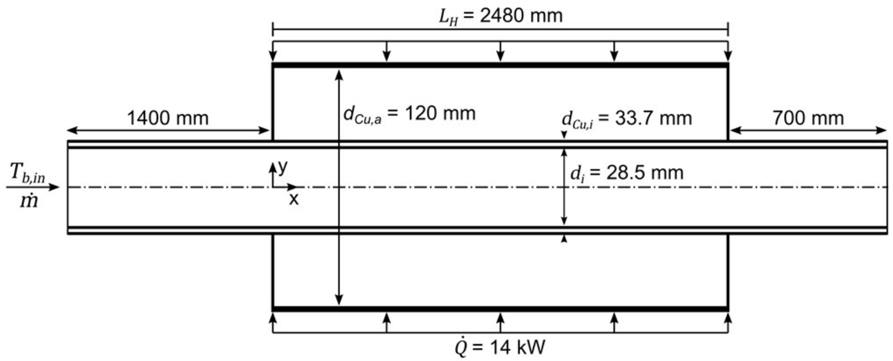
- Structured mesh [ICEM CFD 19.2]
  - $30 \cdot 10^6$ cells, cell size at the wall: $y^+ < 1$
- RANS simulation [ANSYS FLUENT 2022 R2]: $k - \omega\ SST$ model
- Fluid properties of HITEC: constant at $T = 305°\mathrm{C}$
- Inlet velocity: $u_{in} = 0.7599\ \mathrm{m/s}$ ($Re = 14480$)
- Inlet Temperature: $T_{b,in} = 300°\mathrm{C}$
- Temperature increase of $\Delta T_b = 10\mathrm{K}$
- Variation of the thermal boundary condition
  - 14 kW at the copper surface
  - Ideal constant heat flux
  - Ideal constant wall temperature



Heated segment simulation results

- Increase of the wall temperature 10K
  - Temperature difference $T_w - T_b < 40\mathrm{K}$
  - Matches the predicted wall temperature
- Thermal entrance length: $L_{th} = 0.64\ \mathrm{m}$
  - Deviation <1% for the fully developed temperature profile and Nusselt number
- Mean Nusselt number $Nu_m = 138$
  - Deviation to correlations 5%





Summary

- Necessity of an Intermediate Heat Transfer System for DEMO
- Boundary conditions of a HITEC test section
  - Mass flow $\dot{m} = 0.9\ \mathrm{kg/s},$ Inlet temperature $T_i = 240 - 465°\mathrm{C}$
- Design parameter:
  - Pipe diameter $d_i = 28.5\ \mathrm{mm}$ ➡ Reynolds number range $Re = 5000 - 28800$
  - Temperature increase 10K ➡ Heat flux $\dot{Q} = 14\ \mathrm{kW}$ ➡ Heated length 2.48 m
- Flow straightener of two perforated plates
- Deviation of the analytically and numerically calculated Nusselt number within 5% (constant fluid properties)
  - Impact of the heat transfer uncertainties up to 45%
  - Experiments to measure the impact of wall to bulk temperature difference