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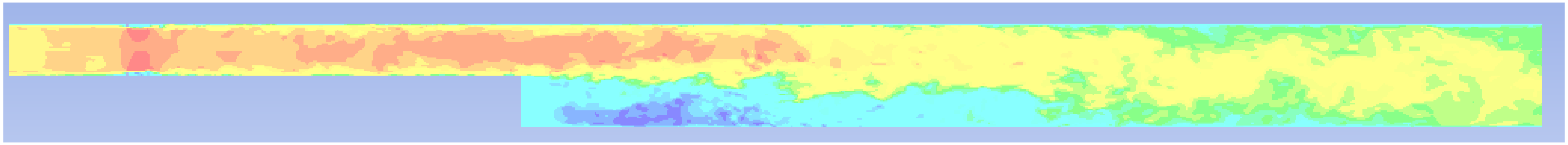
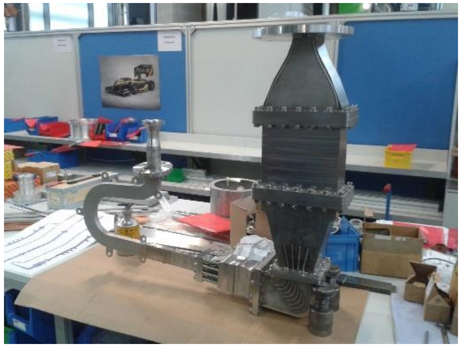
Design process of a vertical backward facing step experiment for forced- and mixed-convection low Prandtl number flows

Thomas Schaub (INR-KIT), Kevin Krauth (TEC-KIT) & Joachim Konrad (TEC-KIT)
Presented by Christine Steiner

INSTITUTE for NEUTRON PHYSICS and REACTOR TECHNOLOGY (INR)





Structure of this presentation

- Motivation and problems of liquid metal thermal-hydraulics: theory and experiments
- Presentation of a confined liquid metal vertical backward facing step experiment
- Design process of the experiment
- Perspectives on what to expect from the experiment

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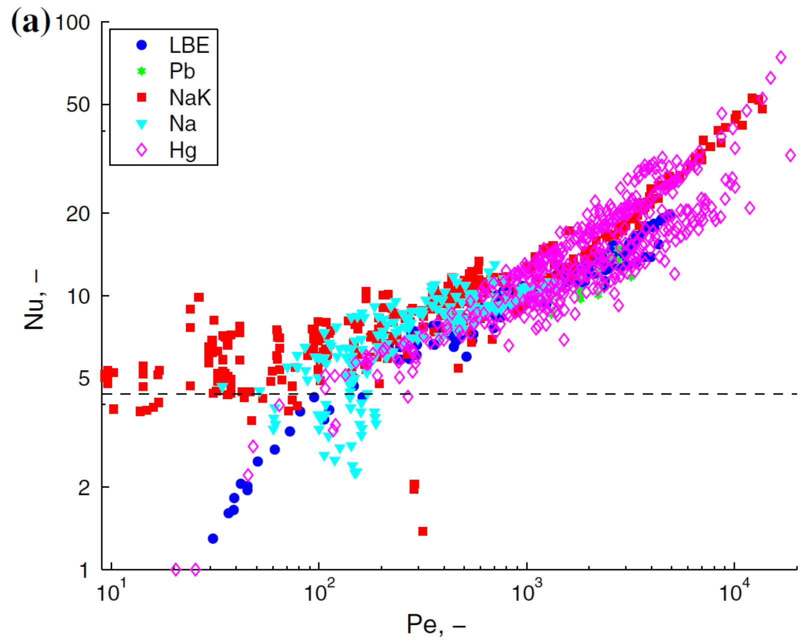
Motivation and problems: theory & experiments

- Liquid metal thermal-hydraulics „renaissance“: CSP + H_2 + C
- Industry: accurate calculation tools for various convective regimes
- Problem: viscous and thermal scale dissimilarity
- $\langle u_i' u_j' \rangle$ and ~~or~~ $\langle u_i' T' \rangle$:
  - minimum: algebraic models
  - ideal: transport equations

Motivation and problems: theory & experiments

- Highly scattered data
- Reasons:
  - Instrumentation?
  - Boundary conditions
    - No-slip?
    - Inlet?
    - Outlet?
  - Equations
    - Buoyancy?
    - Constant properties?
- Literature: data available for „canonic“ turbulence cases – mix?



J. Pacio · L. Marocco · Th. Wetzel
Heat Mass Transfer (2015) 51:153–164

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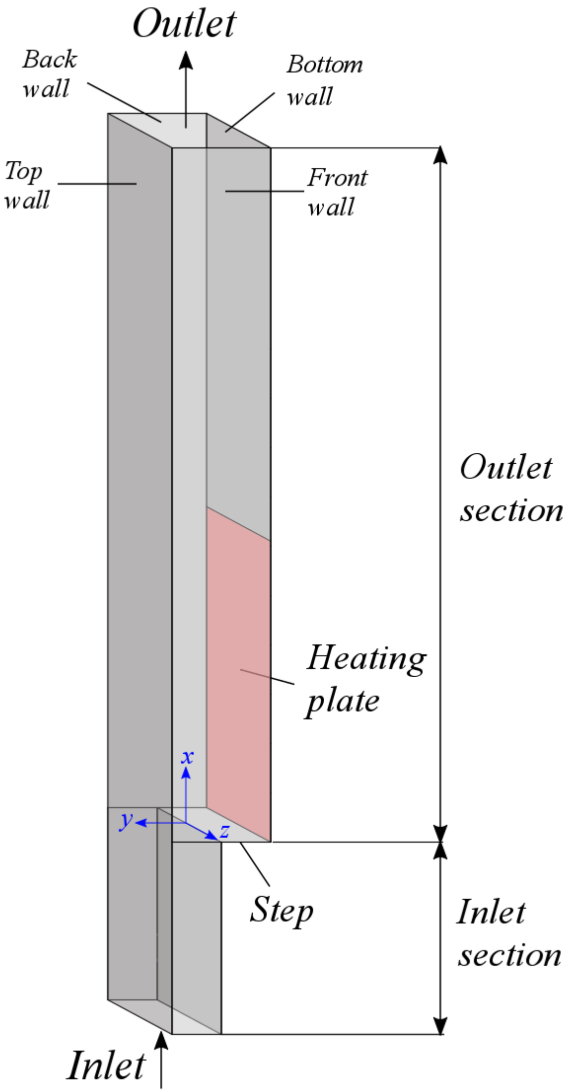
Presentation of the experiment



- Expansion factor: 2
- Aspect ratio: 2 → technical constraints!

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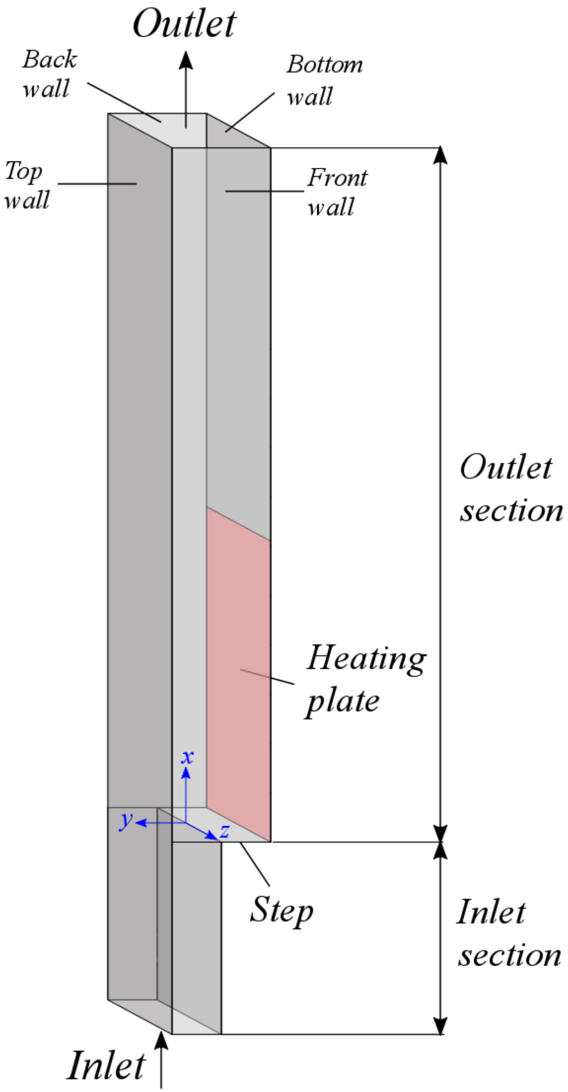
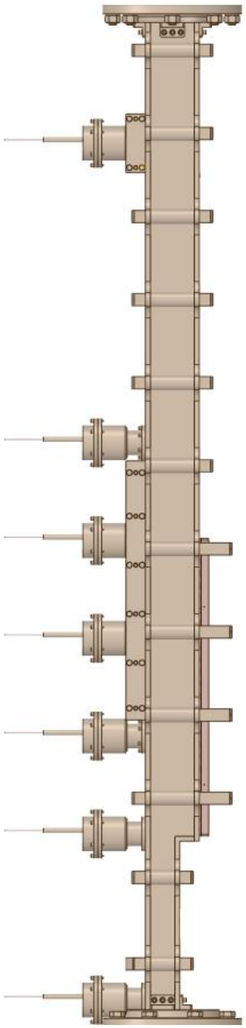
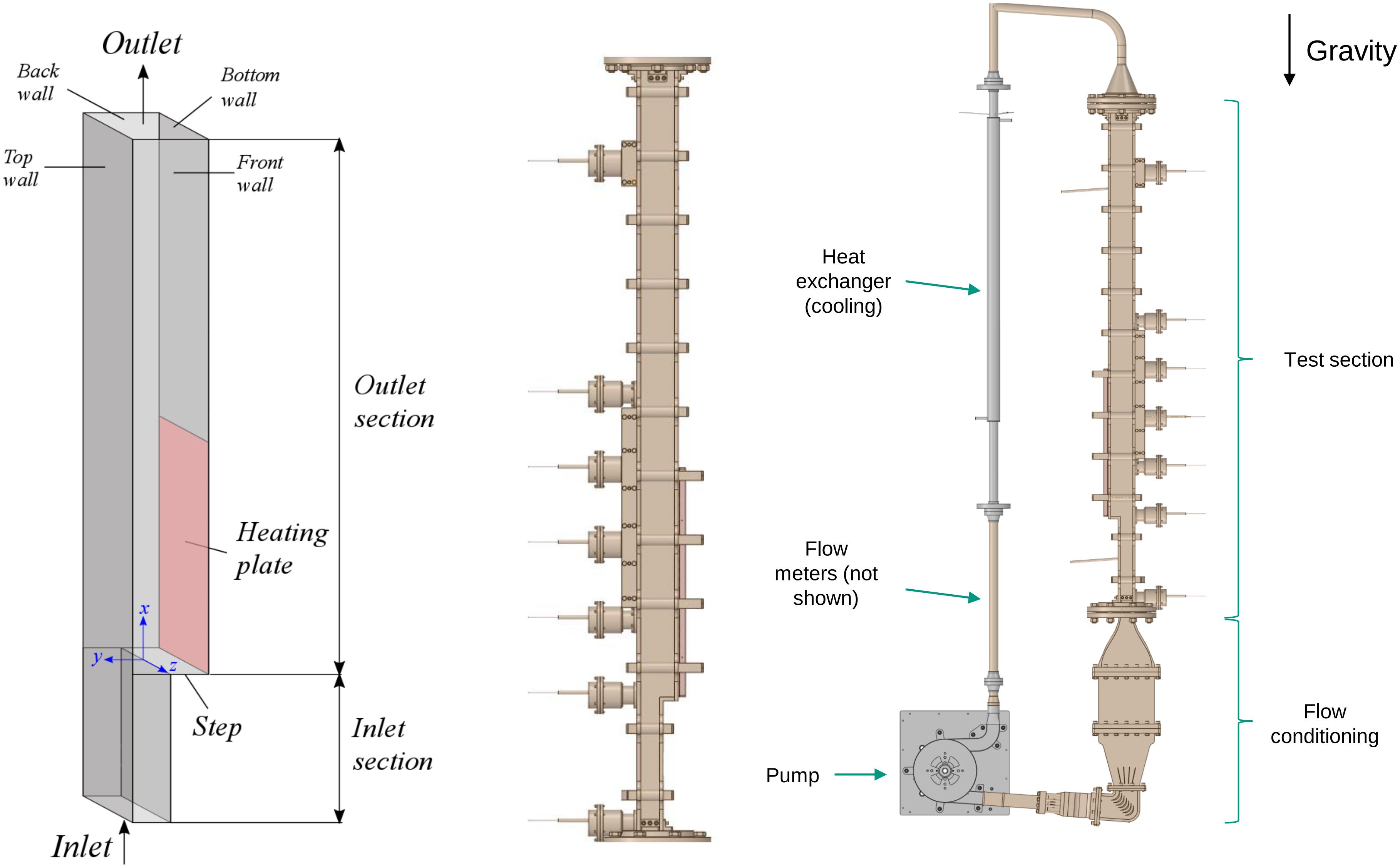
Presentation of the experiment



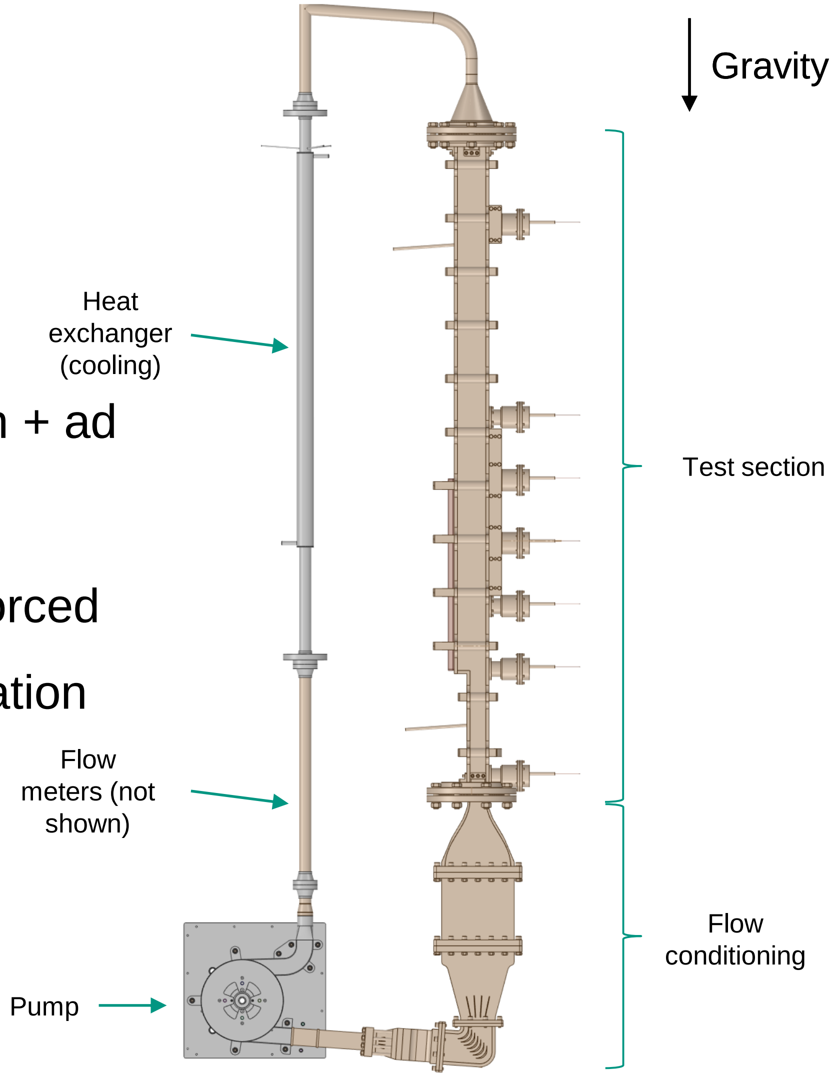


Presentation of the experiment



Presentation of the experiment

- Chosen liquid metal: GaInSn
- User friendly liquid metal
- **First step towards sodium BFS**
  - (Re-)Development of instrumentation + ad hoc data analysis methods
  - Data: study flow characteristics for forced and mixed convection + model validation
- DNS + LES already available
  - Niemann & Fröhlich (IJHMT + Dissertation, TU Dresden, 2016)
  - Oder et. al. (IJHMT, 2019)



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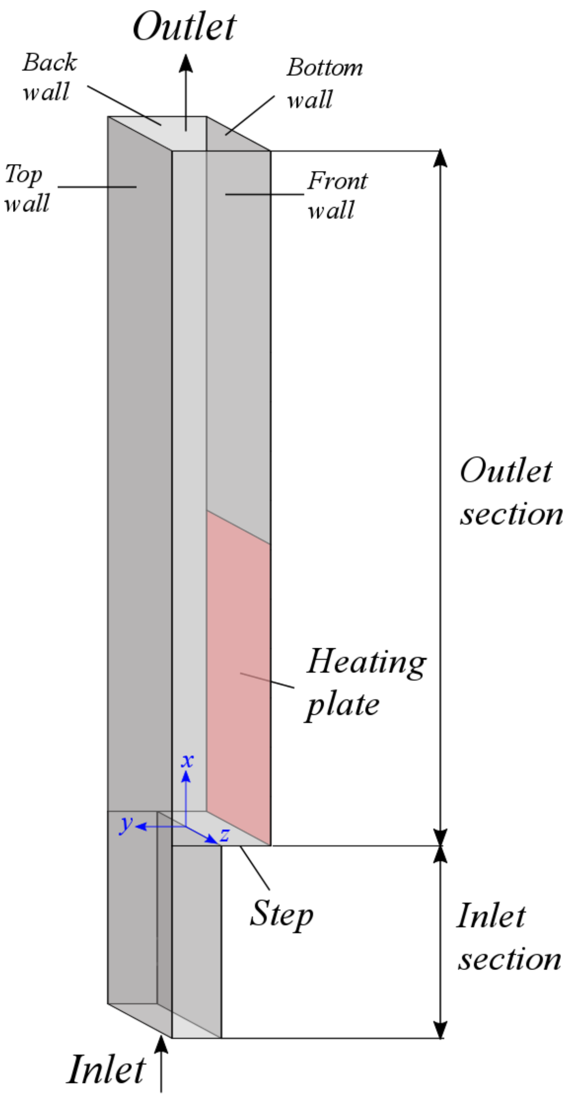

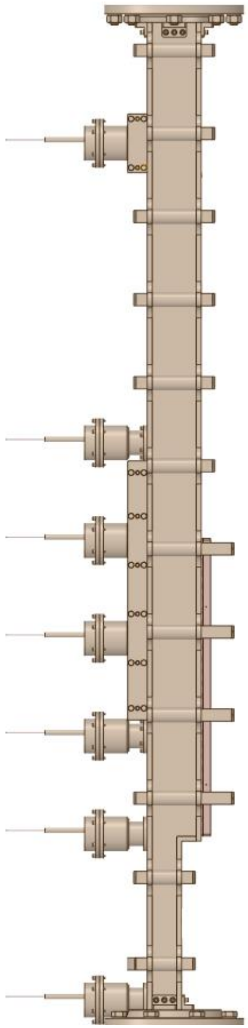

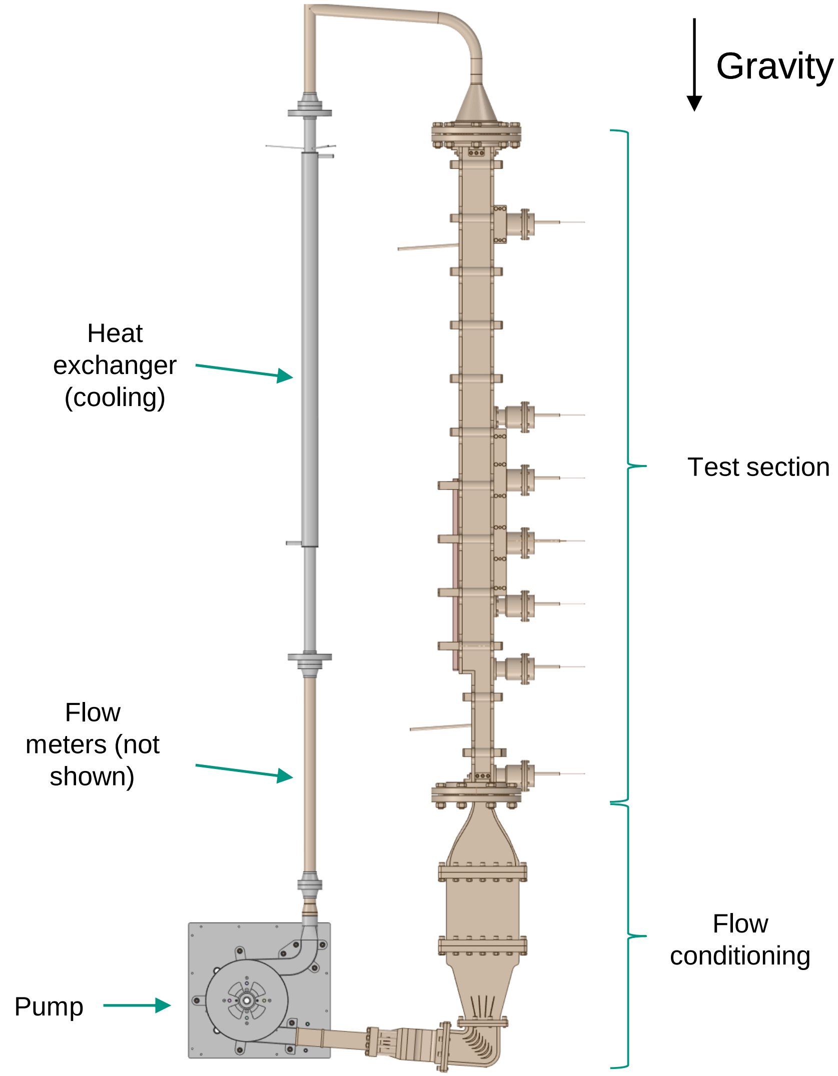

Design process

- W.K. George´s method
  - Why do an experiment?
  - Design steps

    Step 1: Isolate and identify the phenomena

    Step 2: Choose the right tool

    Step 3: Design backwards

Fluid dynamicist first, then, and only then, can you become an experimentalist

Design process

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    ~~Step 1: Isolate and identify the phenomena~~

    ~~Step 2: Choose the right tool~~

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Fluid dynamicist first, then, and only then, can you become an experimentalist

Design process – designing backwards

Ideal: backwards

Resolution < 2x scales of interest

BFS geometry + boundary conditions

Facility (+ liquid metal volume)

Components

Design process – designing backwards

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Facility (+ liquid metal volume)

Components

Our case...

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Design process – designing backwards

Ideal: backwards

Resolution < 2x scales of interest

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Facility (+ liquid metal volume)

Components

Our case...

Design process – BFS geometry + b.c.

- GaInSn very expensive → limited volume
- From unconfined („2D“) to confined („3D“) + limited inlet and outlet lengths...
- Back to step 1: identify phenomenon
  - „2D“ physics +
    - Secondary motions of the second kind (Prandtl)
    - Obstacle (trip wire)
  - LES simulations are currently being performed
- Iterative process
  - Match probe´s resolution to volume
  - Match required Reynolds number to pump

Design process – BFS geometry + b.c.

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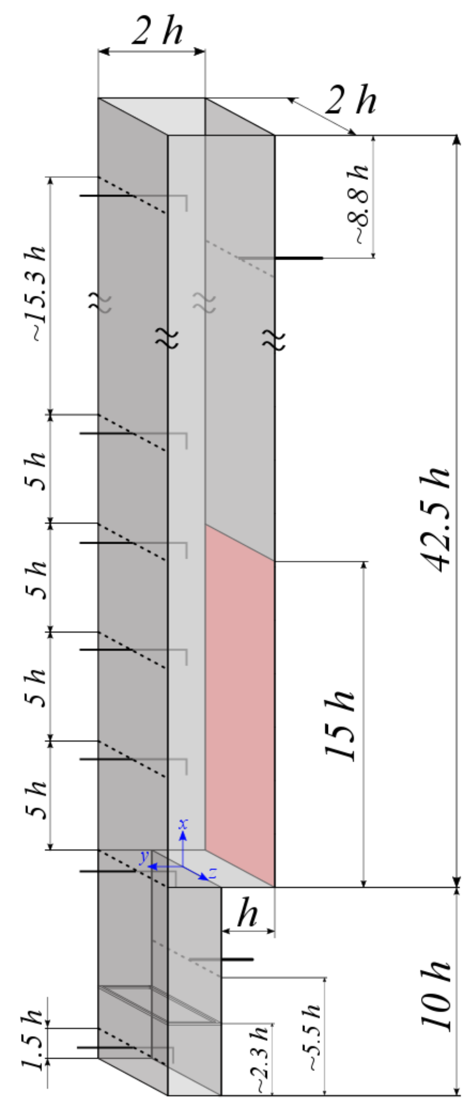


Design process – designing backwards

Ideal: backwards

Resolution < 2x scales of interest

BFS geometry + boundary conditions

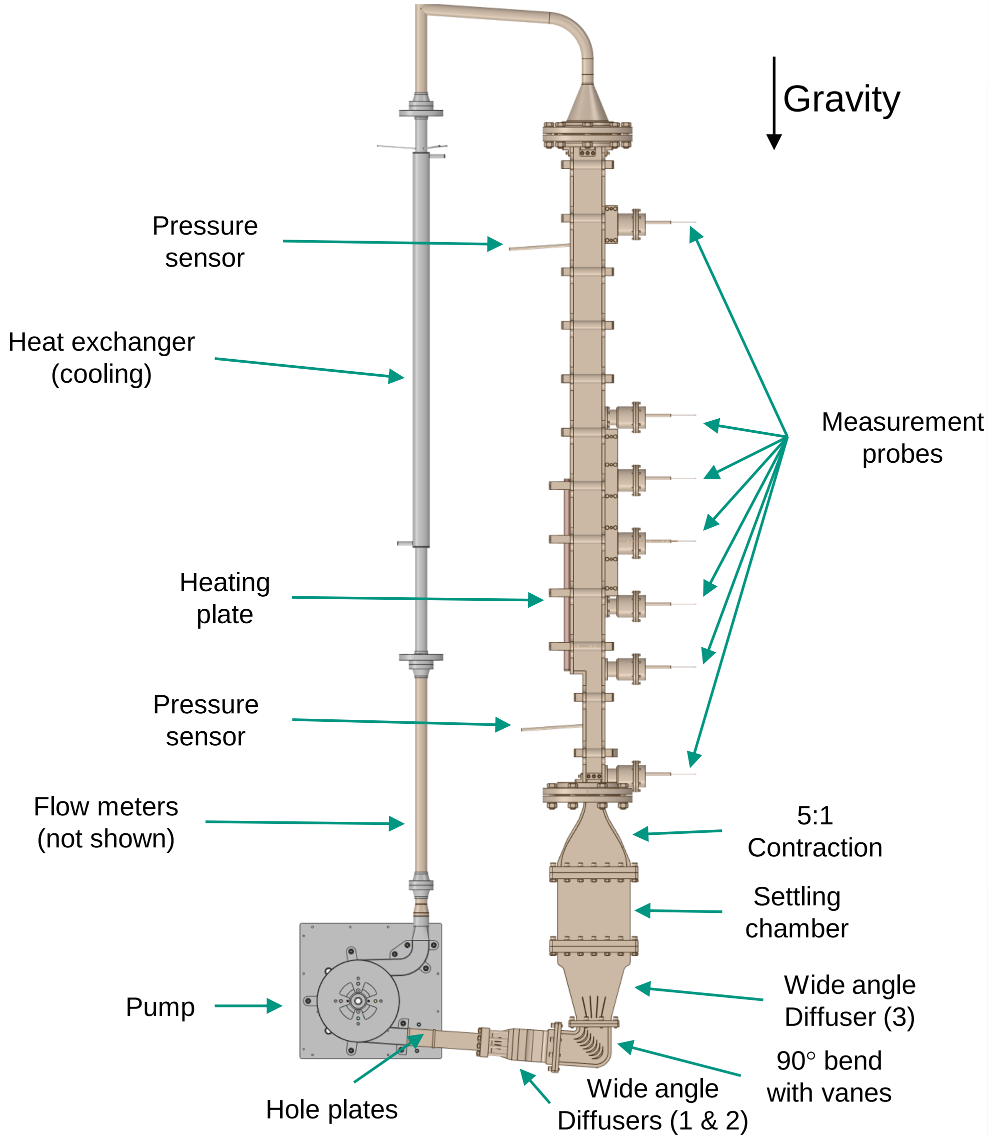
Facility (+ liquid metal volume)

Components

Our case...

Design process – BFS geometry + b.c.

- Boundary conditions (practice, still theory)
  - Flat velocity inlet with low Tu and laminar δ
    - Hydraulic design rules for air and water ~ liquid metals
    - Design based on classic literature on wind tunnel design: Bradshaw, Metha, Idel´chik, Barlow et.al. (and references therein)
    - GaInSn: oxide issues → mesh size > 2 mm



Design process – BFS geometry + b.c.

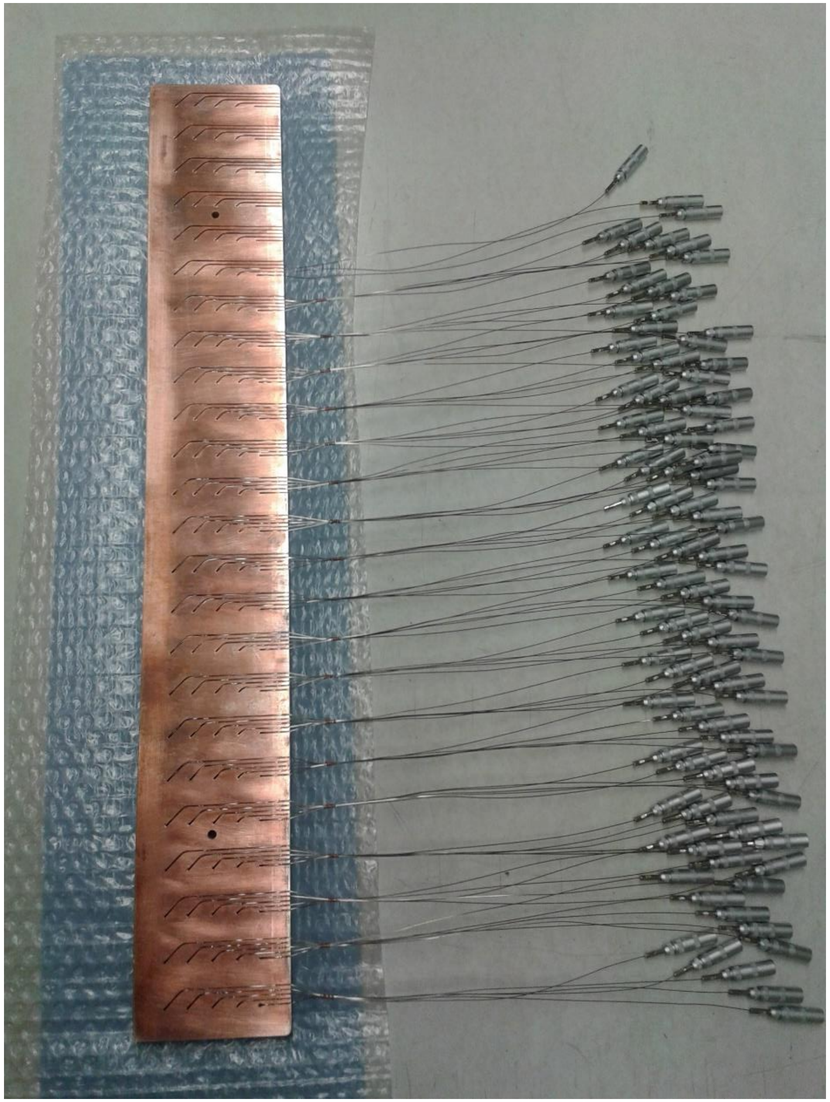
- Boundary conditions (practice, still theory)
  - Flat velocity inlet with low Tu and laminar δ
  - No slip + adiabatic walls

mechanically wet surfaces:
gallium-oxides

not easy!

Design process – BFS geometry + b.c.

- Boundary conditions (practice, still theory)
  - Flat velocity inlet with low Tu and laminar δ
  - No slip + adiabatic walls
  - Constant heat flux
    - No trace of heater
    - Isolated copper plate
    - 120 thermocouples
    - ... constant temperature?



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Design process – designing backwards

Ideal: backwards

Resolution < 2x scales of interest

BFS geometry + boundary conditions

Facility (+ liquid metal volume)

Components

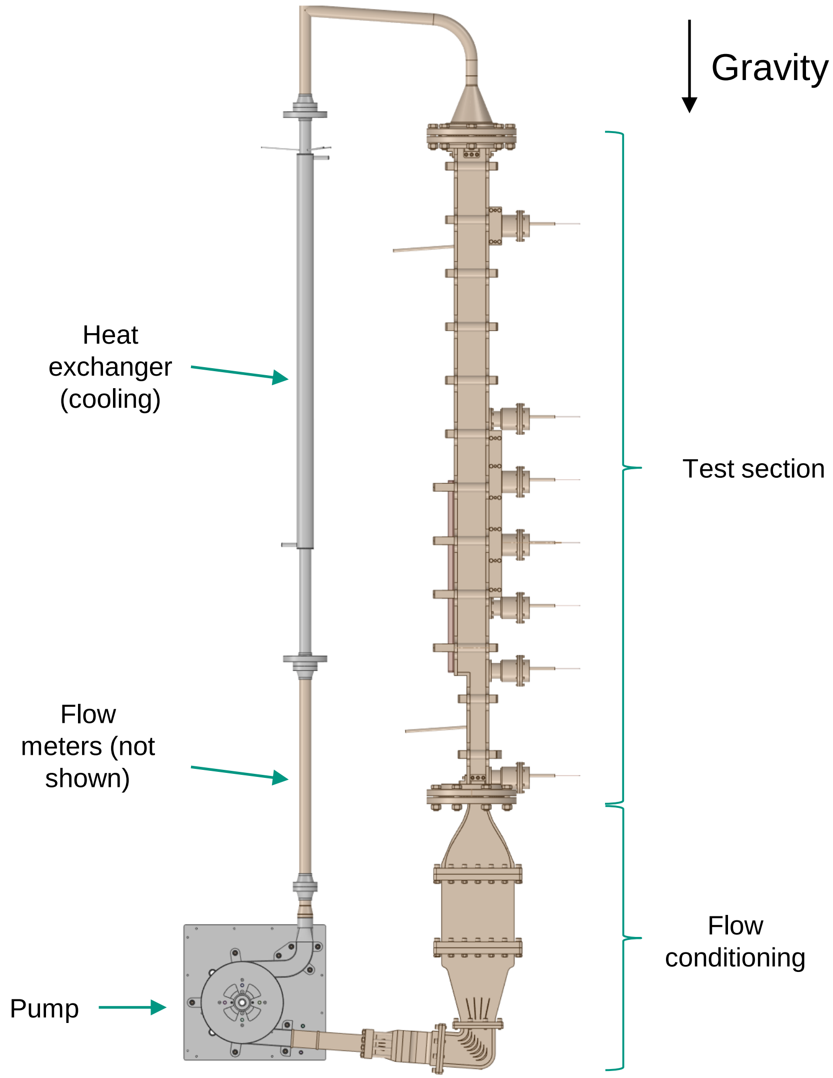
Our case...

- Unfortunately, not in this case
- Iterative process

Design process - facility

- Facility parameters

	Expected minimum value	Expected maximum value	Comments
T_{inlet}	$20°C$	$80°C$	$\Delta T_{max} = \frac{\dot{q}h}{k_{ref}} \sim 30\ [°C]$
Re_h	3 800	57 000	$Re_h = \frac{U_b h}{\nu}, \nu = \nu(T = 25°C)$
Pr	0.019	0.031	
Pe_h	128	1 900	$Pr = Pr(T = 25°C)$
Ri_h	0.007	1.6	$Ri_h = \frac{g\beta\Delta Th}{U_b^2}$, max. heat input



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- Current status: commissioning

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Perspectives on what to expect

- What we can measure
  - $u_i = \langle u_i \rangle + \boldsymbol{u'}$
  - $\mathrm{T} = \langle T \rangle + \boldsymbol{T'}$
  - $\langle \boldsymbol{u_i' T'} \rangle$
- Spectral characterization of convective regimes?
- Important!
  - When using and analysing data → viscosity must be assumed temperature-dependant
  - Result from similar analysis as Gray & Giorgini (1976) for air and water, but on GaInSn → sodium as well!

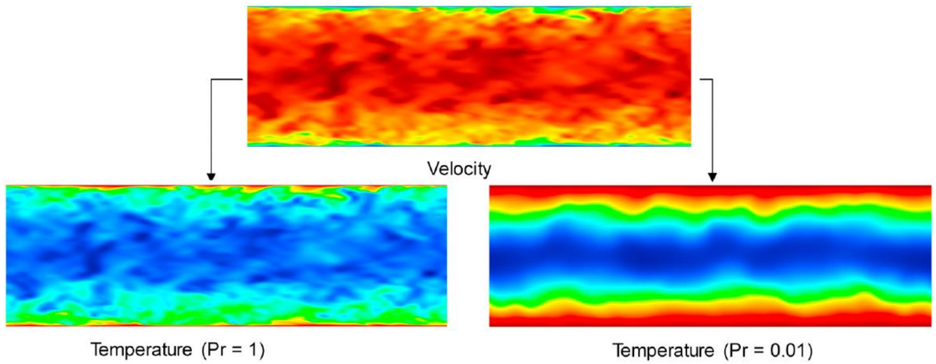
Summary: take away messages

- Liquid metal thermal-hydraulics: challenging in both theory and practice
- A confined vertical backward facing step experiment is going to be perfomed at KIT soon
- Design process based on W.K. George´s method + experience from past experiments
- Special efforts were put into generating reproducible and measurable boundary conditions: inlet, outlet, walls, heat input
- Preliminary results by winter 2019/2020 – final results expected for spring 2020

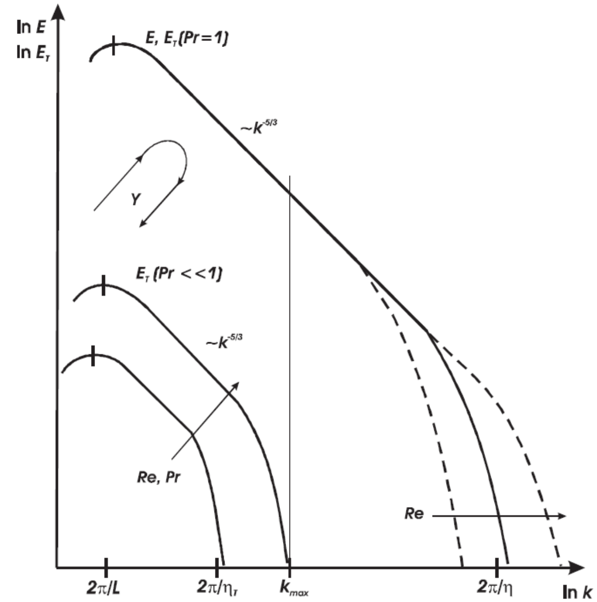
Appendix

Appendix

F. Roelofs et al. / Nuclear Engineering and Design 290 (2015) 99–106

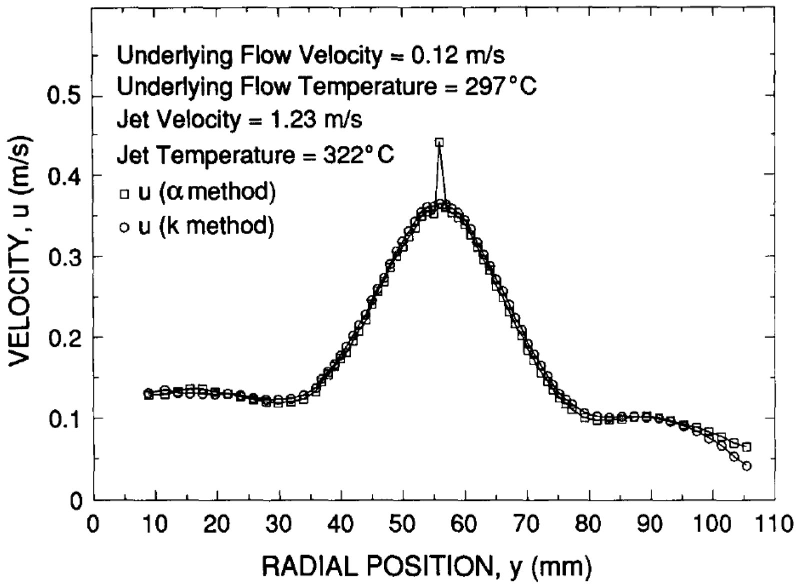


G. Grötzbach / Nuclear Engineering and Design 264 (2013) 41–55

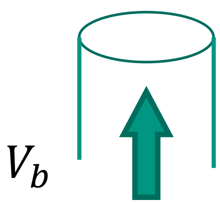


Appendix

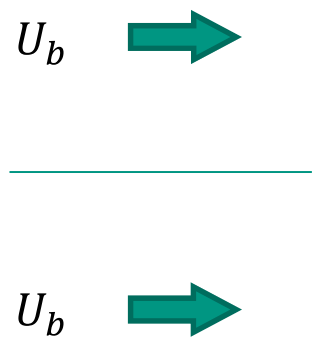
B. P. Axcell and A. Walton *Experimental Thermal and Fluid Science* 1993; 6:309–323

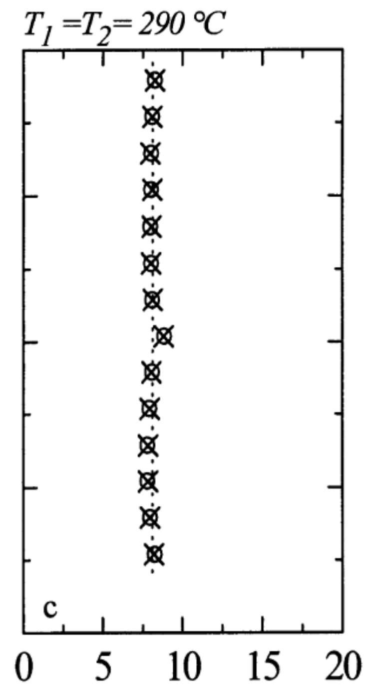


Jet flow



R. Kapulla et al. / Experimental Thermal and Fluid Science 20 (2000) 115–136





Plane mixing layer

- Instrumentation?

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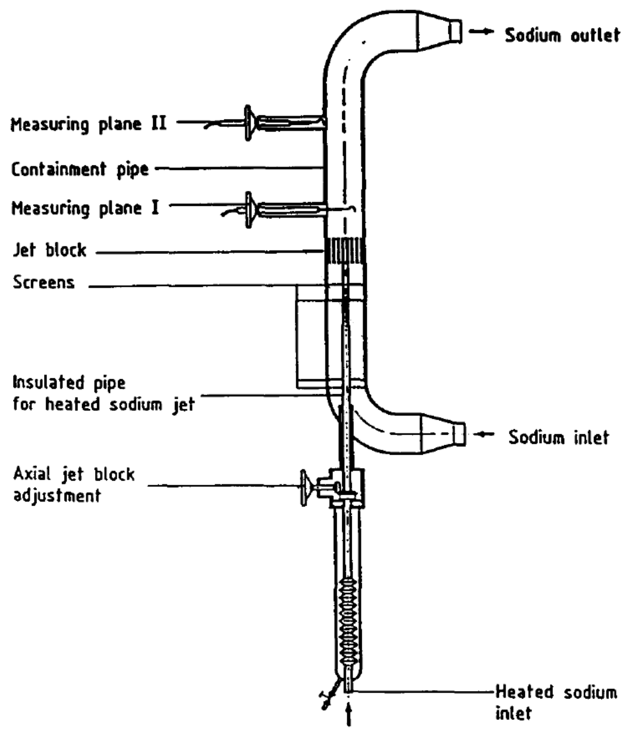

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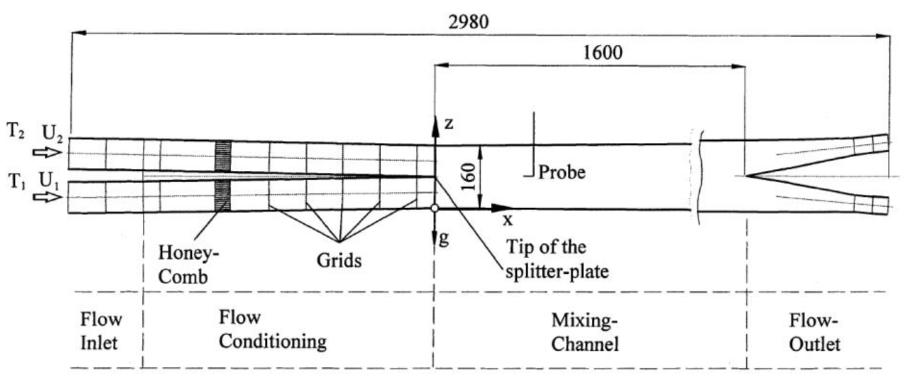
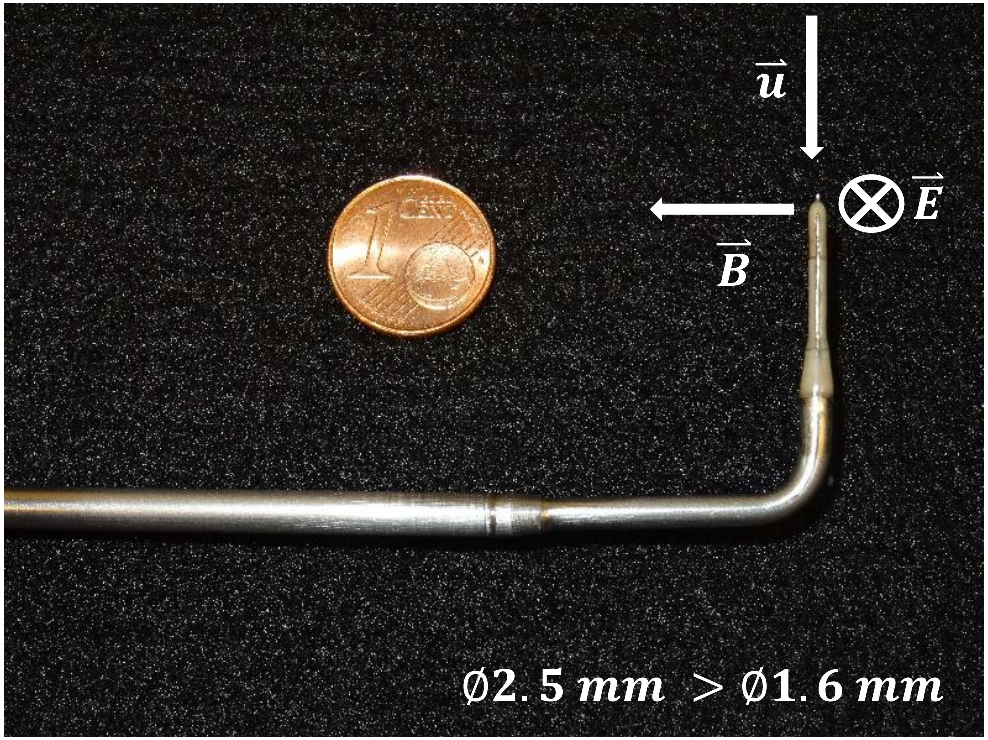


- No! Flow conditioning.

Appendix

- Permanent magnet probes
  - $u_i \rightarrow$ Faraday + Ohm (MHD)
  - $\mathrm{T} \rightarrow$ Seebeck
- What can measure?
  - $u = \langle u \rangle + \boldsymbol{u'}$
  - $\mathrm{T} = \langle T \rangle + \boldsymbol{T'}$
  - $\langle \boldsymbol{u'T'} \rangle$



- Very challenging measurement chain + few drawbacks
  - Highly sensitive devices (external noise)
  - Very low voltages (nanovolt range) $\rightarrow$ Peltier + Johnson + Thomson matter!
  - Invasive + miniaturization restricted BUT „perfect“ signal transfer function

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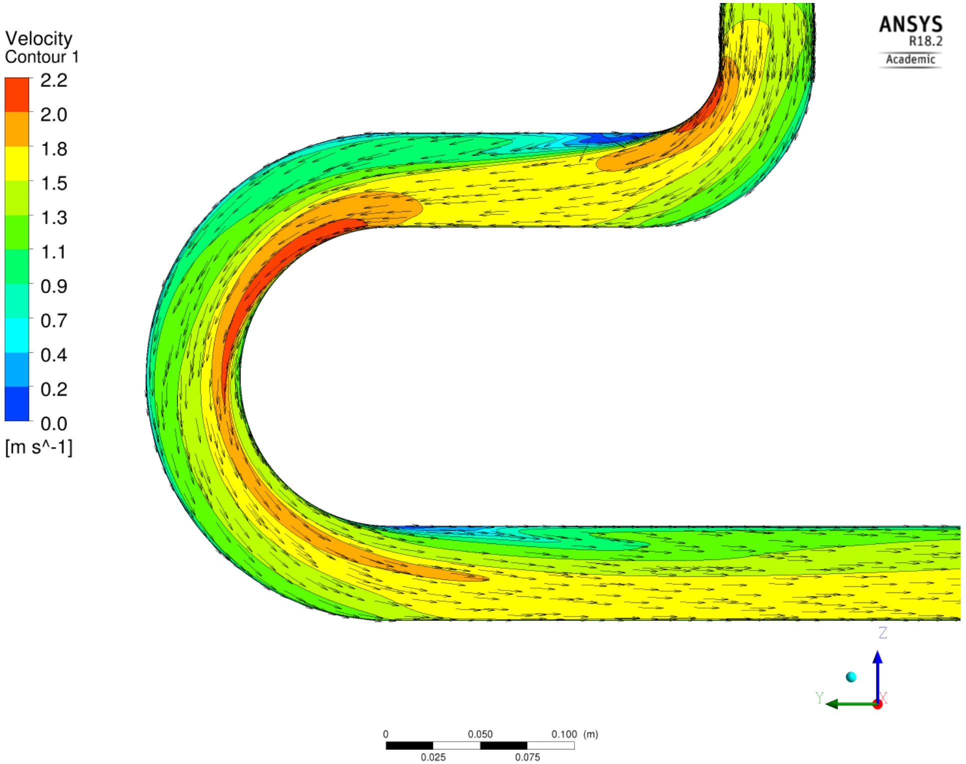
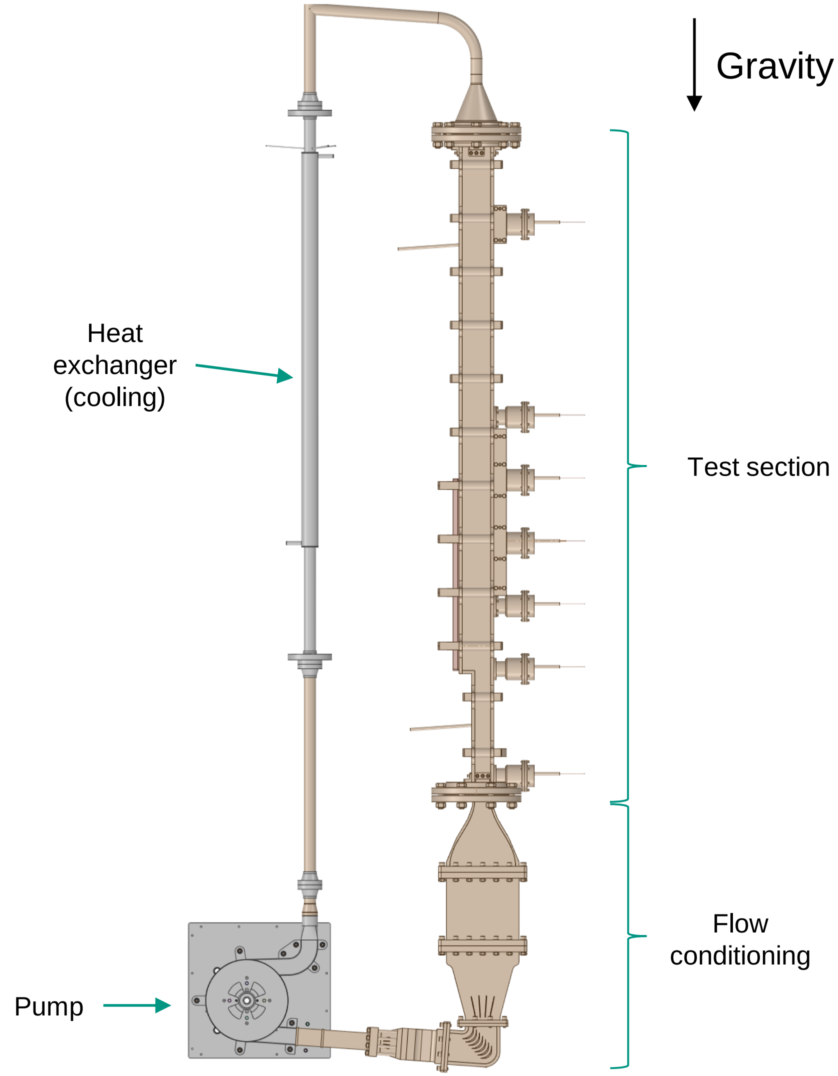

Velocity
Contour 1
2.2
2.0
1.8
1.5
1.3
1.1
0.9
0.7
0.4
0.2
0.0
[m s^-1]
ANSYS
R18.2
Academic
0
0.050
0.100 (m)
0.025
0.075


Gravity
Heat exchanger (cooling)
Test section
Flow conditioning
Pump

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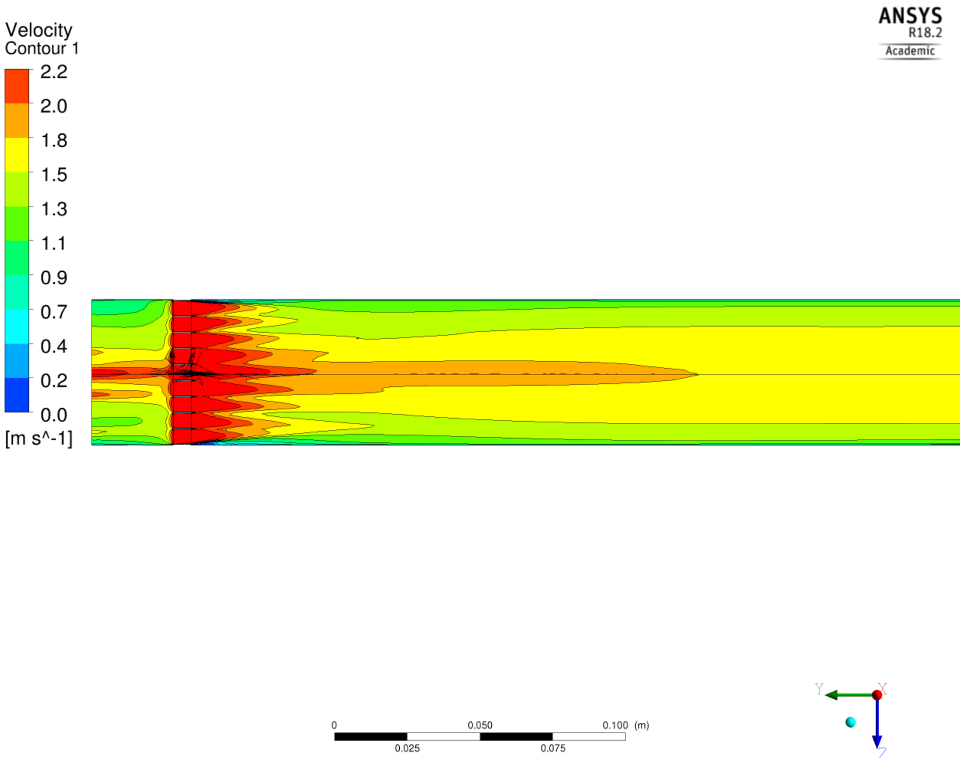

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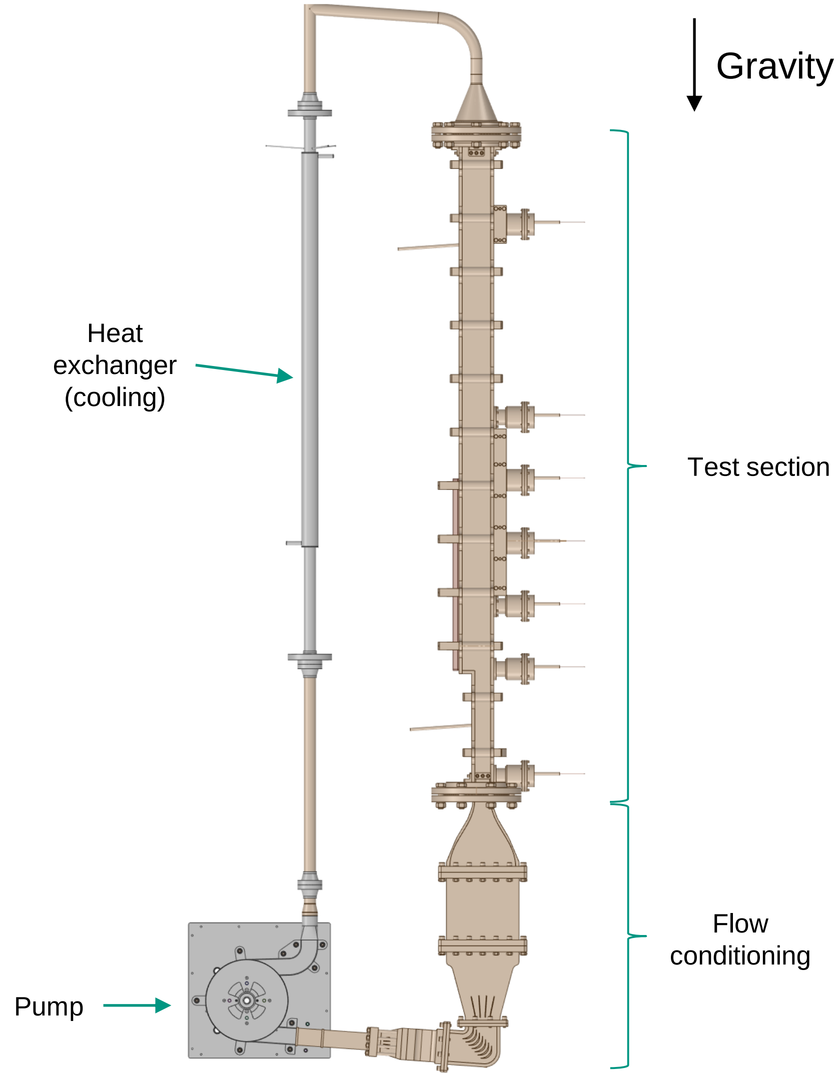

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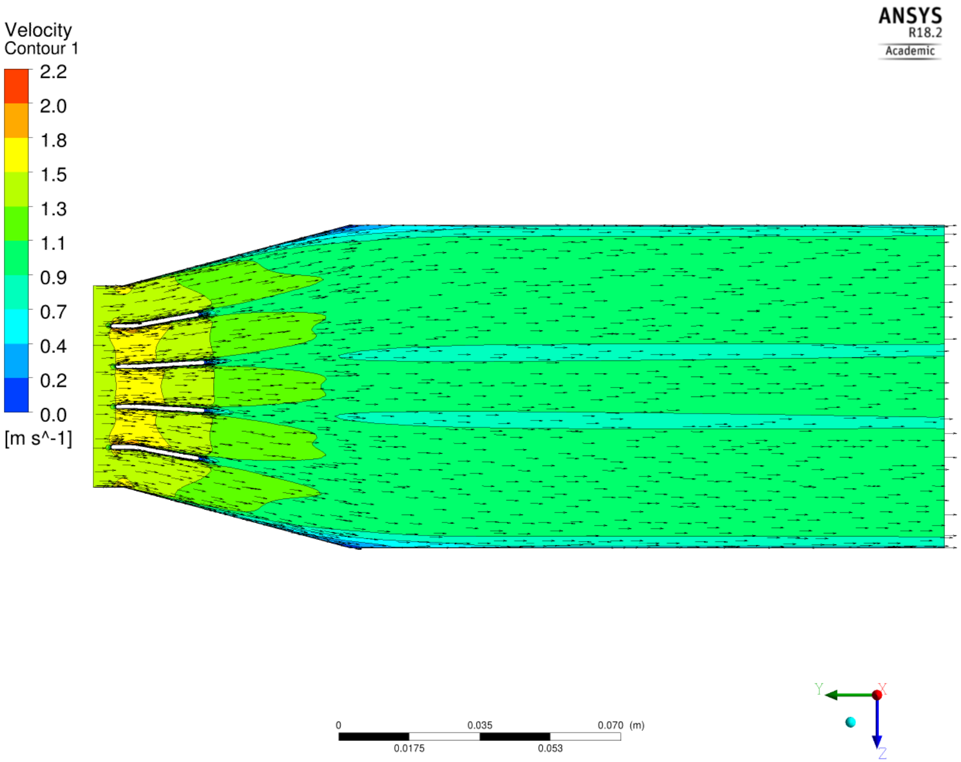
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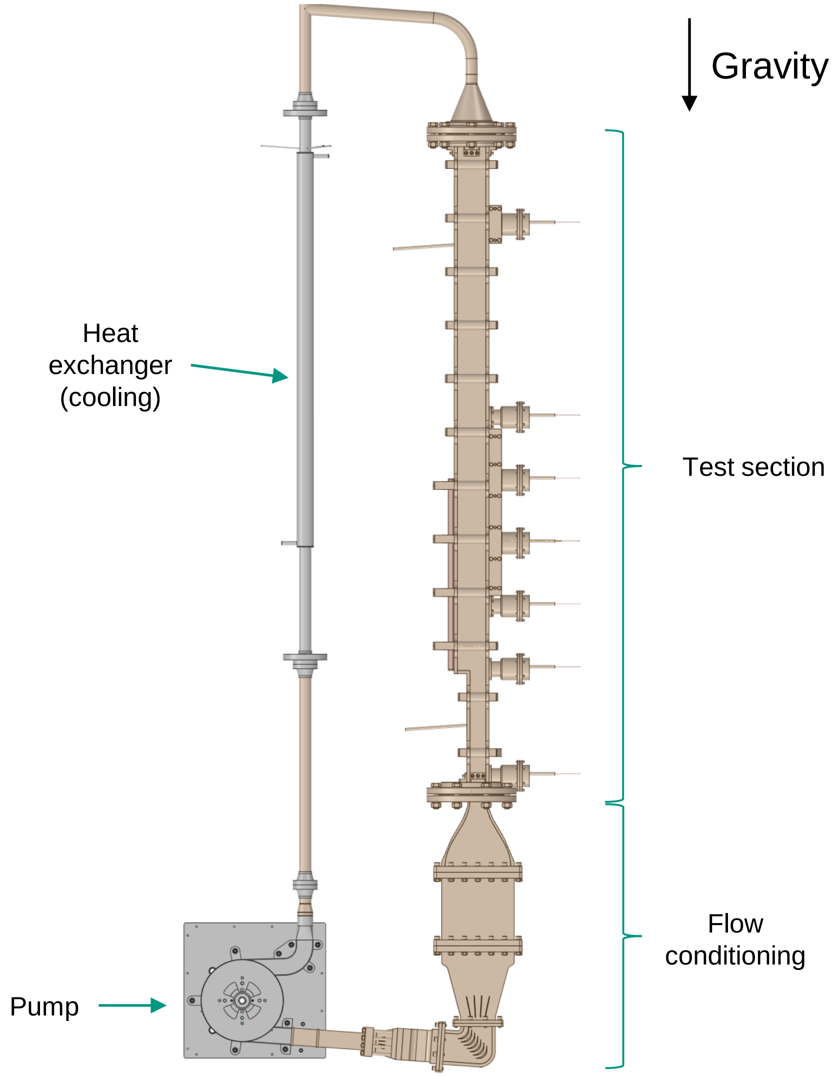
0.7
0.4
0.2
0.0
[m s^-1]
ANSYS
R18.2
Academic
0
0.035
0.070 (m)
0.0175
0.053
Y
X
Z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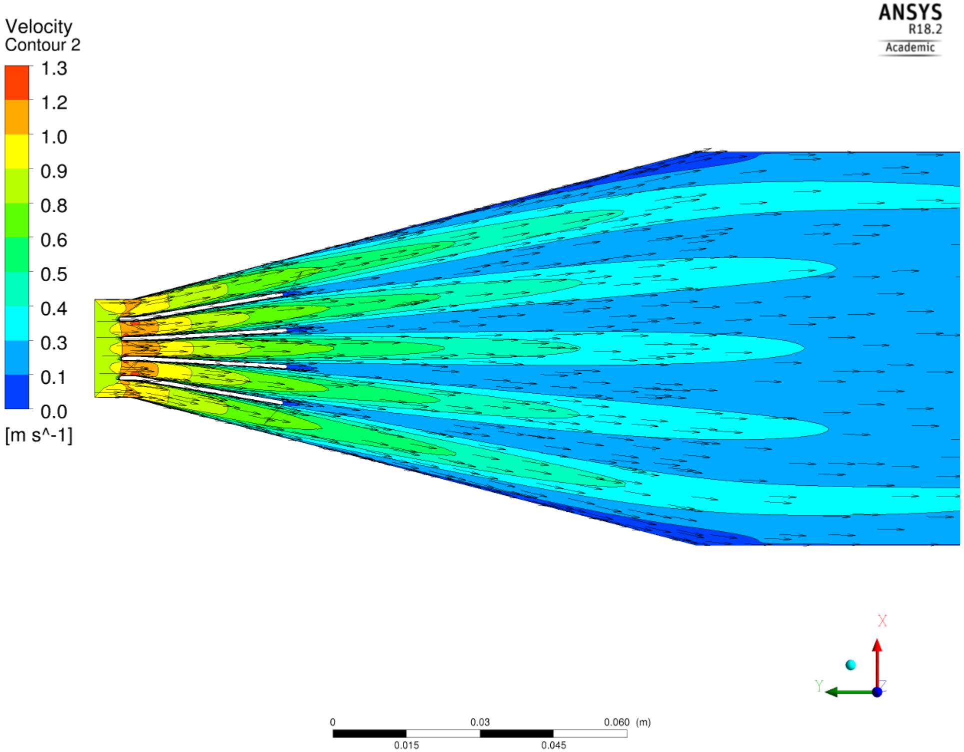
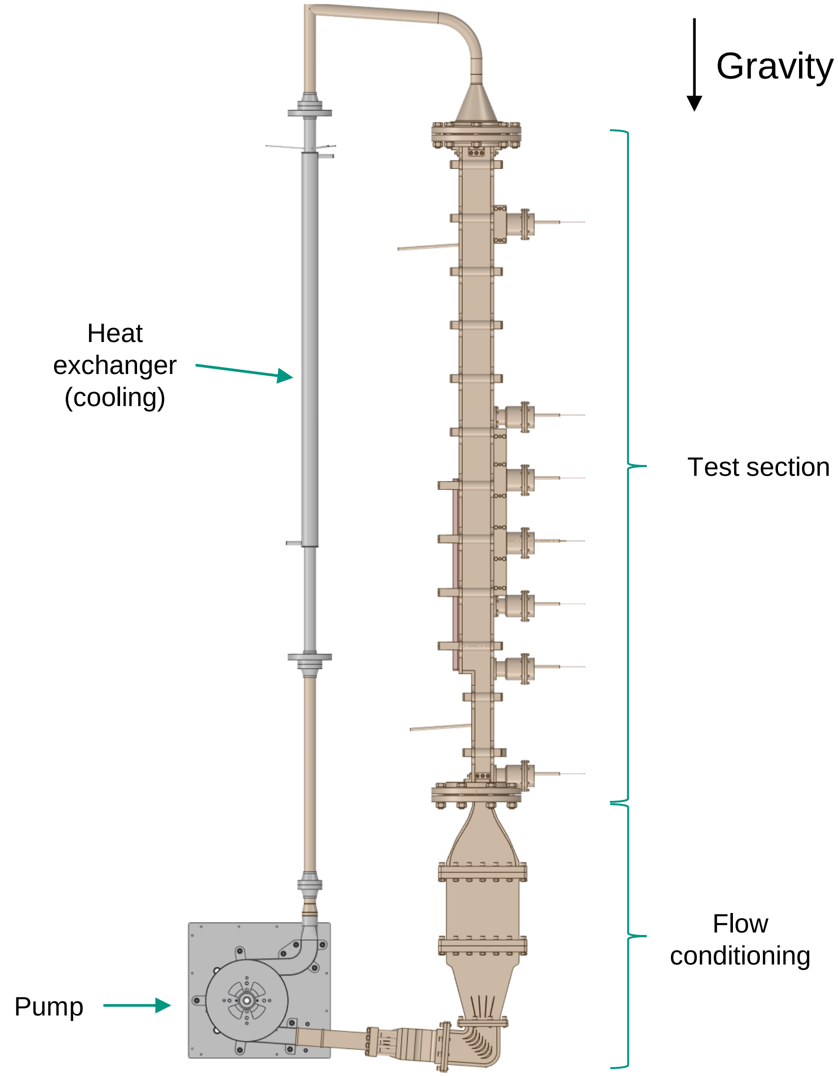

Velocity
Contour 2
1.3
1.2
1.0
0.9
0.8
0.6
0.5
0.4
0.3
0.1
0.0
[m s^-1]
ANSYS
R18.2
Academic
0
0.03
0.060 (m)
0.015
0.045
X
Y
Z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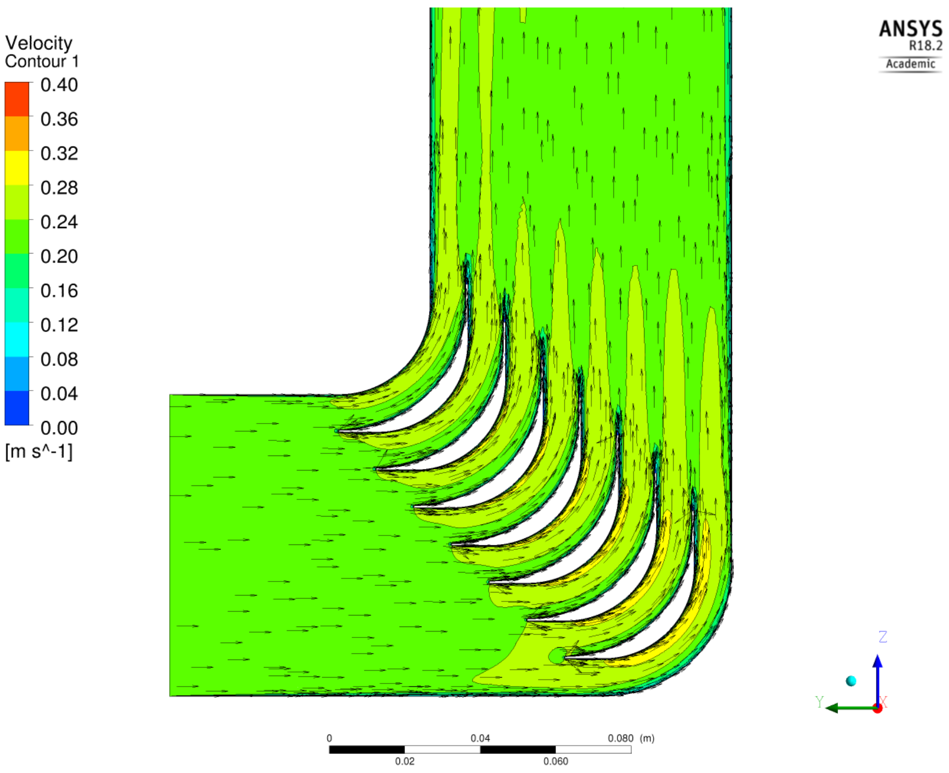

Velocity
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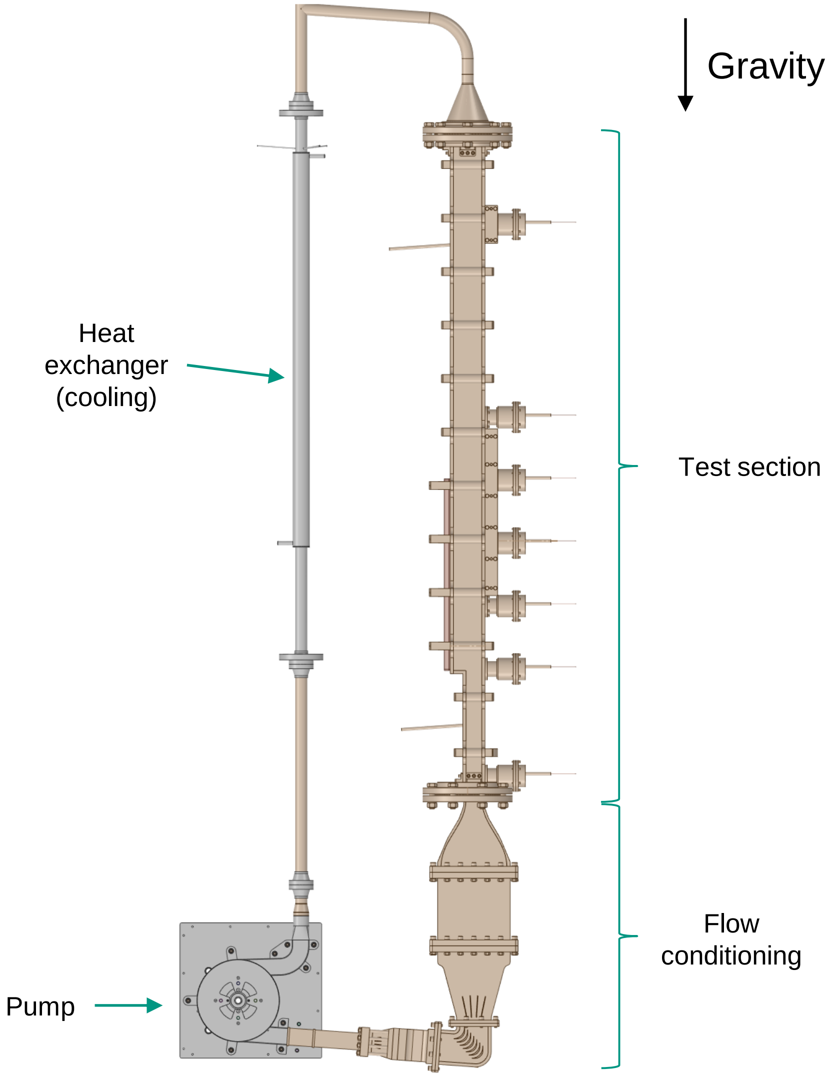
0.40
0.36
0.32
0.28
0.24
0.20
0.16
0.12
0.08
0.04
0.00
[m s^-1]
ANSYS
R18.2
Academic
0
0.04
0.080 (m)
0.02
0.060



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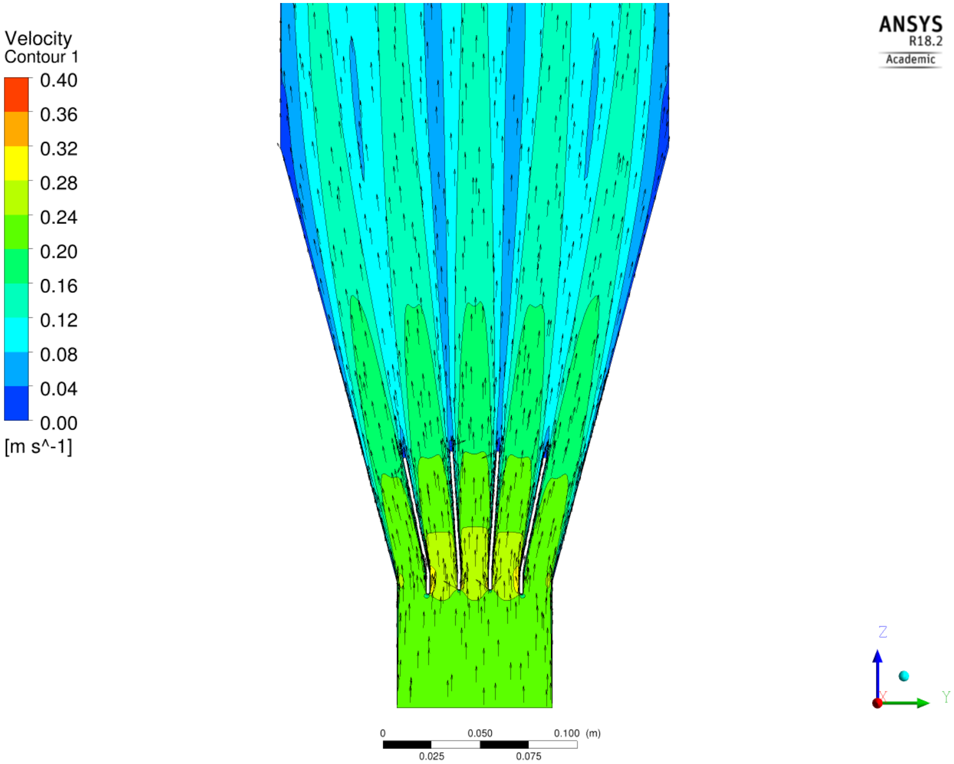
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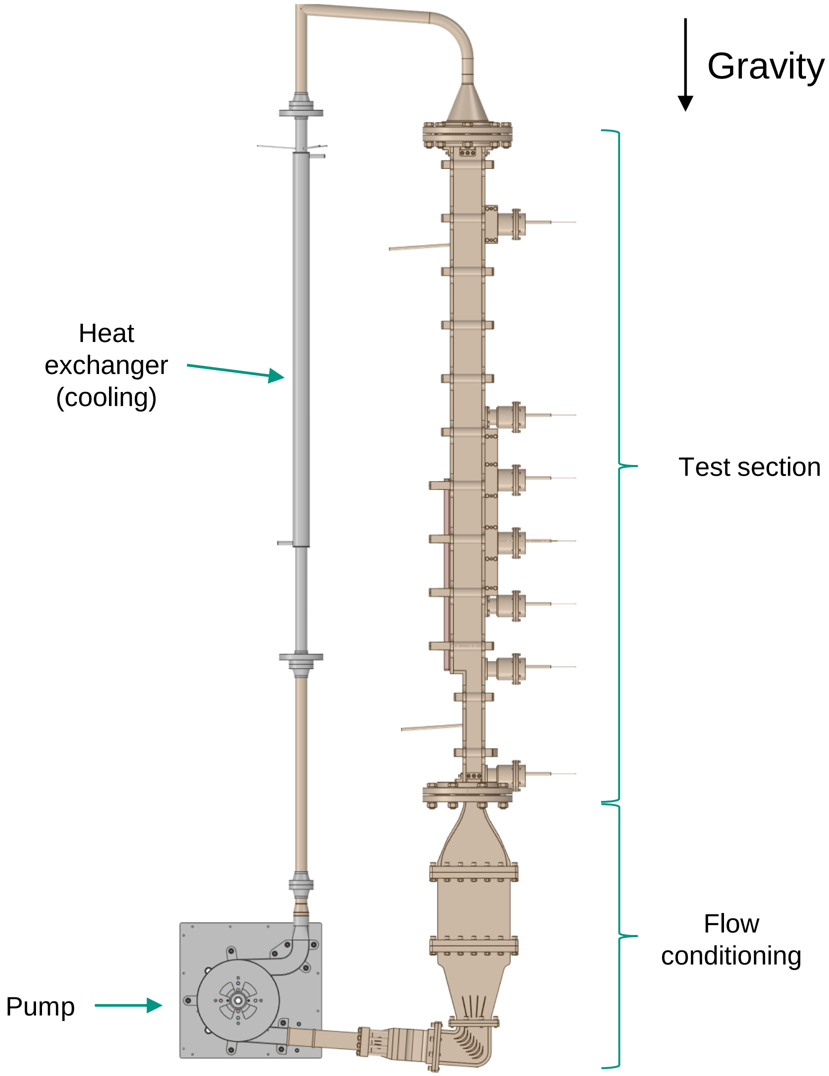
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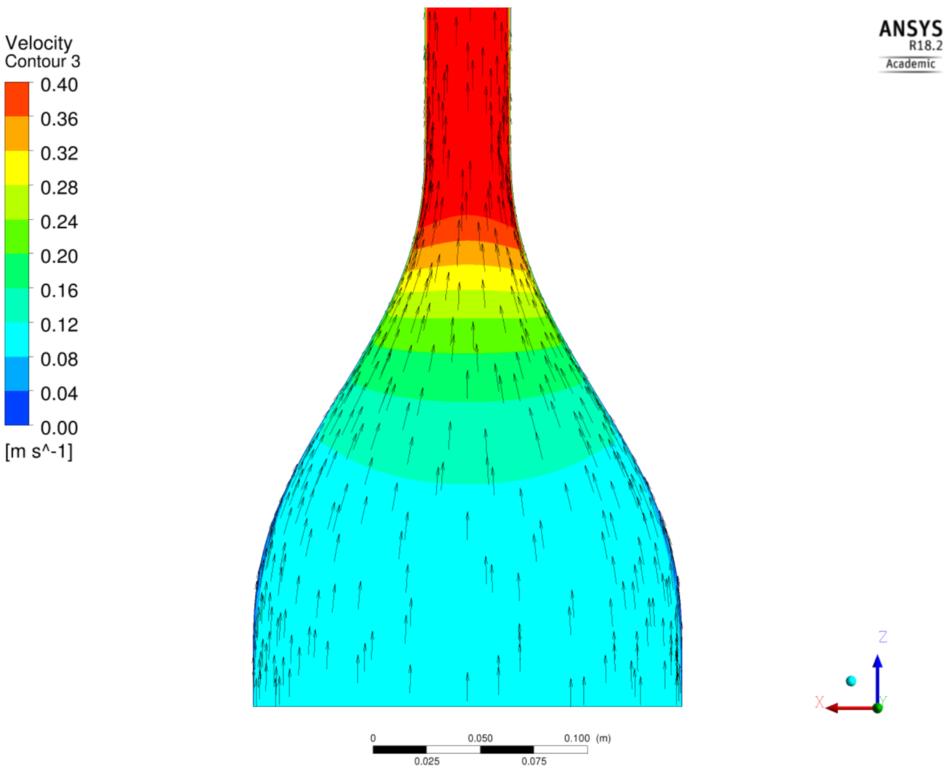

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Contour 3
0.40
0.36
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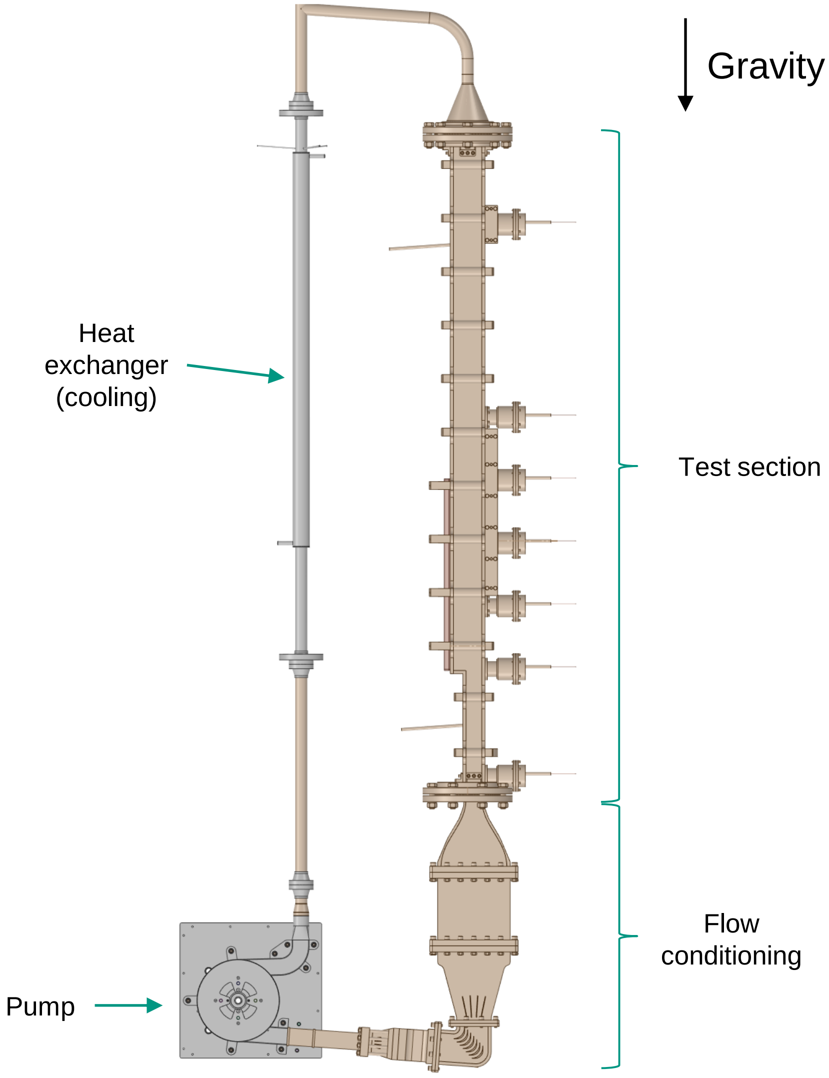

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