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
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?

[Graph with data points and legend]
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Presentation of the experiment

- Expansion factor: 2
- Aspect ratio: 2 → technical constraints!
Presentation of the experiment

Outlet

Back wall
Bottom wall
Top wall
Front wall

Outlet section

Heating plate

Step

Inlet section

Inlet
Presentation of the experiment

Outlet

Back wall
Bottom wall
Top wall
Front wall

Outlet section

Heat plate

Step

Inlet

Inlet section

Heat exchanger (cooling)

Flow meters (not shown)

Flow conditioning

Gravity

Test section

Pump
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
  - Oder et. al. (IJHMT, 2019)
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Outlet section

Outlet

Inlet section

Inlet

Step

Heating plate

Bottom wall

Front wall

Top wall

Back wall

Outlet

Gravity
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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  - Why do an experiment?
  - Design steps
    - 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

Ideal: backwards

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Components

Our case...
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.

- 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 $\delta$
  - 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 $\delta$
  - No slip + adiabatic walls

mechanically wet surfaces: gallium-oxides

not easy!

$k_{GaInSn} \sim k_{SS}$
Boundary conditions (practice, still theory)

- Flat velocity inlet with low $Tu$
  and laminar $\delta$
- No slip + adiabatic walls
- Constant heat flux
  - No trace of heater
  - Isolated copper plate
  - 120 thermocouples
  - ... constant temperature?
Design process – designing backwards

- **Ideal: backwards**
  - Resolution < 2x scales of interest
  - BFS geometry + boundary conditions
  - Facility (+ liquid metal volume)
  - Components

- Unfortunately, not in this case
- Iterative process

Our case...
# Design process - facility

## Facility parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Expected minimum value</th>
<th>Expected maximum value</th>
<th>Comments</th>
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<tbody>
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<td>$T_{inlet}$</td>
<td>20°C</td>
<td>80°C</td>
<td>$\Delta T_{max} = \frac{\dot{q}<em>h}{h</em>{ref}} \sim 30$ [°C]</td>
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<tr>
<td>$Re_h$</td>
<td>3800</td>
<td>57000</td>
<td>$Re_h = \frac{u_h}{v}$, $v = v(T = 25°C)$</td>
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<tr>
<td>$Pr$</td>
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<td>0.031</td>
<td></td>
</tr>
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<td>$Pe_h$</td>
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<td>1900</td>
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<td>$Ri_h$</td>
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- **Heat exchanger (cooling)**
- **Test section**
- **Flow meters (not shown)**
- **Flow conditioning**
- **Gravity**
Design process - facility

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Current status: commissioning
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Perspectives on what to expect

- What we can measure

  - $u_i = \langle u_i \rangle + u'$
  - $T = \langle T \rangle + T'$
  - $\langle u'_iT' \rangle$

- 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 performed 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
Appendix


Underlying Flow Velocity = 0.12 m/s
Underlying Flow Temperature = 297°C
Jet Velocity = 1.23 m/s
Jet Temperature = 322°C
- u (α method)
- u (k method)

Jet flow

Instrumentation?
Appendix


No! Flow conditioning.

Appendix

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

Flow conditioning

Heat exchanger (cooling)

Test section

Gravity

Pump

Flow conditioning
Appendix

[Diagram showing a section of a flow system with labeled components: Pump, Heat exchanger (cooling), Test section, and Flow conditioning.]

Gravity
Appendix
Appendix

[Diagram showing a schematic of a fluid flow system with labeled components: Velocity Contour 2, Heat exchanger (cooling), Test section, Flow conditioning, Gravity, Pump]
Appendix
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