Session # 9

Keynote lectures

Chair: P. Schuurmans (SCK•CEN)
Strategy & Progress of ADS Reactor Development in China

Presented by Yican WU

Institute of Nuclear Energy Safety Technology (INESST)
Chinese Academy of Sciences
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I. Introduction
  Reactor, Accelerator, Target

II. Research Progress

III. Development Prospects

IV. Summary

China’s Plan on Nuclear Energy
(Plan up to 2020)

- Nuclear power plant currently in China
  - 18 reactors (~13.8GWe) in operation
  - 28 reactors (27.6GWe) under construction

- National plan of developing nuclear energy before 2020
  - 58 GWe in operation
  - 30 GWe under construction

- National plan for nuclear and radiation safety before 2020
  - More R&D are required to enhance nuclear safety, especially in the basic research of nuclear safety
  - ~79.8 billion RMB investment plan (~13.3 billion US dollars)

The strategy of sustainable fission energy in China were suggested by Chinese Experts of Academician: The Fast Reactor is better used for Nuclear fuel breeding and the ADS is better used for transmutation.
China Lead-based Reactor Development Plan

- Chinese Academy of Sciences (CAS) has launched the ADS Project, and plan to construct demonstration ADS transmutation system ~ 2030s through three stages.
- China LEAd-based Reactor (CLEAR) is selected as the reference reactor for ADS project and for Lead cooled Fast Reactor (LFR) technology development.

ADS Program Organization

**ADS main components**

<table>
<thead>
<tr>
<th>Implementing Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear Proton Accelerator</td>
</tr>
<tr>
<td>Spallation Target (Liquid LBE/ Granular flow)</td>
</tr>
<tr>
<td>LBE cooled Reactor (CLEAR Project)</td>
</tr>
</tbody>
</table>

**Chinese Academy of Sciences**

- IHEP: Institute of High Energy Physics
- IMP: Institute of Modern Physics

INEST: Institute of Nuclear Energy Safety Technology
CLEAR-I Implementation Plan

CLEAR-I (Stage A)
Subcritical operation for ADS integration technology test

CLEAR-I (Stage B)
Critical operation for fast reactor technology test

CLEAR-S
Integrated Test Platform for China Lead-based Reactor

CLEAR-0
Lead-based Zero Power Reactor for neutronics test

Accelerator Development Progress

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
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<tbody>
<tr>
<td>Particle</td>
<td>Proton</td>
<td></td>
</tr>
<tr>
<td>Energy</td>
<td>~250</td>
<td>MeV</td>
</tr>
<tr>
<td>Max. Flux</td>
<td>~10</td>
<td>mA</td>
</tr>
<tr>
<td>Max. Beam Power</td>
<td>~2.5</td>
<td>MW</td>
</tr>
<tr>
<td>Void Fraction</td>
<td>100</td>
<td>%</td>
</tr>
<tr>
<td>Beam Loss</td>
<td>&lt;1</td>
<td>W/m</td>
</tr>
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</table>

- Prototypes of high flux ion source, LEBT, high current RFQ, Spoke and HWR cavity have been manufactured
- Two 10MeV RFQ accelerators was tested, and continuously 10mA proton beam has been realized
Spallation Target Development Progress

—— Liquid LBE window target

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Structure material</td>
<td>T91</td>
</tr>
<tr>
<td>Heat deposition (window/flow) /MW</td>
<td>0.57/0.153</td>
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<tr>
<td>Inlet/outlet temperature /°C</td>
<td>300/385</td>
</tr>
<tr>
<td>Operation pressure /MPa</td>
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✓ Conceptual design and prototype manufacture of liquid LBE window targets has been finished
✓ Out-pile test under LBE environment has been carried out

Spallation Target Development Progress

—— Granular flow target

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat transfer power</td>
<td>&gt;2 MW</td>
</tr>
<tr>
<td>W granular mass flow rate</td>
<td>&lt;200 kg/s</td>
</tr>
<tr>
<td>W granular inlet temp.</td>
<td>&gt;380 °C</td>
</tr>
<tr>
<td>W granular outlet temp.</td>
<td>&lt;250 °C</td>
</tr>
</tbody>
</table>

✓ Innovative concept of granular flow target has been proposed
✓ Related R&D is underway
Contents

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II. Research Progress
   1. Reactor Design
   2. Key Technology R&D
   3. Safety Assessment

III. Development Prospects

IV. Summary

Reactor Design
CLEAR-I Main Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
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<tbody>
<tr>
<td>Core</td>
<td></td>
</tr>
<tr>
<td>Thermal power (MW)</td>
<td>10</td>
</tr>
<tr>
<td>Activity height (m)</td>
<td>0.8</td>
</tr>
<tr>
<td>Activity diameter (m)</td>
<td>1.05</td>
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<tr>
<td>Fuel (enrichment)</td>
<td>UO$_2$(19.75%) at first</td>
</tr>
<tr>
<td>Cooling System</td>
<td></td>
</tr>
<tr>
<td>Primary coolant</td>
<td>LBE</td>
</tr>
<tr>
<td>Inlet/Outlet temperature (°C)</td>
<td>~300/385</td>
</tr>
<tr>
<td>Primary coolant mass flow rate (kg/s)</td>
<td>529.5</td>
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<td>Coolant drive type</td>
<td>Forced Circulation</td>
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<td>Heat exchanger</td>
<td>4</td>
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<td>Second coolant</td>
<td>Water</td>
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<tr>
<td>Heat sink</td>
<td>Air cooler</td>
</tr>
<tr>
<td>Material</td>
<td></td>
</tr>
<tr>
<td>Cladding</td>
<td>15-15Ti/316Ti</td>
</tr>
<tr>
<td>Structure</td>
<td>316L</td>
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</table>

Overview of CLEAR-I Structure

- Heat exchanger
- Cover
- RVACS
- Vessel
- Core
- Core shroud
- Refueling and control rod driven system
- Structure support
CLEAR-I System Design Status

- The detailed conceptual design has been done (more than 20 Systems)
- Preliminary engineering design is underway

1. Nuclear Design
2. Thermo-hydraulic Design
3. Coolant System
4. Reactor Structure
5. Reactivity Control System
6. Refueling System
7. LBE Process System
8. Fuel Assembly
9. Safety System
10. I&C System
11. Application System
12. Radiation Protection System
13. Auxiliary System
14. ...

Key Technology R&D
Key Technology for Lead-based Reactor

I. Coolant technology
- PbBi Loop Engineering
- Preparation and purification
- Thermal-hydraulics validation

II. Key components
- Pump
- Heat exchanger
- Rotating plug system

III. Reactor materials and fuel
- Structural materials
- Fuel cladding materials
- Nuclear fuel

IV. Instrumentation and control
- Reactor Simulator
- Control rod driving machine
- Remote refueling system

Two integrated testing platforms, four types of key technologies

Material testing area and thermal-hydraulics testing area have been finished constructed in 2013, and the loop is stably operating at 500°C.
Key Technologies I: Coolant Materials Technology

◆ Preparation of lead alloy
  ✓ 12.5 tons of high purity ingots
  ✓ Homogeneous
  ✓ Purity: 99.9999%

Industrial scale of high purity LBE has been prepared.

◆ Oxygen measurement and control
  ✓ Pt/air and Bi/Bi$_2$O$_3$ developed by INEST
  ✓ Gas phase control and solid phase control technology

Oxygen control system has been operated for more than 5000hrs.

Key Technologies II: Key Components Development

◆ Pumping technology
  ✓ EMP (5m$^3$/h, 0.75MPa) has been operated for more than 3000hrs
  ✓ Mechanical pump (50m$^3$/h, 2MPa) with anti-corrosion coating has been developed
  ✓ Gas lift technology

◆ Heat exchanger technology
  ✓ Double wall HX
  ✓ Heat-exchanger for LBE with different coolant materials (air, oil, etc.)

Different types of pump and heat-exchanger have been developed.
Key Technologies III: Structural Materials and Nuclear Fuel

◆ R&D of nuclear-class structural materials
  ✓ Development technology of nuclear-class structural material
  ✓ Platform of non-nuclear performance tests and data accumulation of out-of-pile performance
  ✓ Development of neutron irradiated experiment and in-pile service performance

R&D and verification test system of material has already implemented.

◆ R&D of nuclear fuel
  ✓ Scheme design and preliminary engineering design of fuel assembly
  ✓ Preparation of full-scale simulated FAs and thermodynamic experiments

Experiments of full-scale simulated FAs has already been done, and experimental data has been given.

Key Technology IV: Instrumentation and Control

- **1:2.5 Scaling Verification platform for Fuel Handling System**
  - Double rotating plugs design Verification
  - Assembly interfaces and fixed way verification, etc..

- **1:1 Scope Verification platform for Control Rod Drive Mechanisms**
  - Validation on the Impact of LBE (High Density / Lead Vapor)
  - Verifying the design of Control Rod Drive Mechanisms, etc..

- **CLEAR Full Scope Simulator**
  - Reactor safety analysis and serious accident simulation
  - Reactor operator training, etc..

- **LBE target prototype**
  - Provide test data of pressure drop of LBE target, and plot property curve
  - Validate CFD simulation of LBE target, etc..

The fabrication of verification platform have been accomplished, and the experimental testing are under way.
**Key Components Integrated Test Platform**

(CLEAR-S)

- Validation platform of non-nuclear technologies and prototype components.
- Research platform for thermal-hydraulics properties and safety features.

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameter</th>
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<tbody>
<tr>
<td>Diameter</td>
<td>2.5 m</td>
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<tr>
<td>Height</td>
<td>7 m</td>
</tr>
<tr>
<td>Temperature</td>
<td>200-500°C</td>
</tr>
<tr>
<td>Power</td>
<td>2 MW</td>
</tr>
<tr>
<td>Coolant</td>
<td>Lead-bismuth</td>
</tr>
<tr>
<td>LBE mass</td>
<td>300 tons</td>
</tr>
<tr>
<td>Heater</td>
<td>Electrical</td>
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</table>

- Conceptual design has been done, the preliminary design is underway.
- Construction will be done by the end of 2015, and commissioning in the middle of 2016

**Highly Intensified Neutron Generator (HINEG)**

- Neutron with different energy
  - D+D → $^3\text{He} + n (2.5 \text{MeV})$
  - D+T → $^4\text{He} + n (14.1 \text{MeV})$

- Steady/pulse dual-moding
  - Steady intensity: $10^{13} \text{n/s}$
  - Pulsed width: 1.5 ns

- Test objectives
  - Reactor design verification
  - Materials radiation experiments
  - Radiation protection and environmental impact
  - Application of nuclear technology
  - ...

Engineering design has been finished, construction is underway.
Experimental Platform for Nuclear Technology
—— Lead-based Zero Power Reactor (CLEAR-0)

- Pre-research Facility of PbBi Cooled ADS
- Detailed conceptual design for CLEAR-0 has been finished
  Nuclear Design, Structure, Core and Standard Assemblies, Shielding,
  Reactivity Control System, Measuring System, I&C System, Plant and Auxiliary System
  (7 systems, 10 key equipments)

Requisite Platform for License Experiments:
V&V for Neutronics Software and Nuclear Design

Safety Assessment
Preliminary Safety Analysis

- **Accident Analysis**
  - Accident classify and initial events definition
  - Analysis code preparation
    - RELAP, MELCOR, NTC (self-developed), CFD (commercial)
  - Typical accident analysis
    - (U/P)LOHS, LOFA, Reactivity Insertion, SBO, etc.

- **Probability Safety Analysis**
  - The 1 class internal event PSA has been done
  - Quantify risk assessment and safety object study
  - Risk comparison between design options

Preliminarily analysis results shows that under the typical accident reactor core will not be damaged and the decay heat can be removed effectively.

Environmental Impact Assessment

- **Studies of Environmental Impact Assessment Report**
  - Radioactive inventory in reactor
  - Radioactive waste disposal system and reactor decommissioning
  - Environmental impact during normal operation / under accident
  - Character and safety of Lead-Bismuth
  - Environmental impact of construction
  - Monitoring both effluent and environment

Radioactive distribution in reactor

Dose distribution under an accident

Dose of public was far below the value in Chinese national standards (GB).
CLEAR-I design and analysis code V&V methodology and system has been established.

- **Code – code benchmark**
- **Verification Experiment**
  - More than 10 facilities
  - Self-developed & Cooperation (domestic / abroad institute)
- **Cooperation & communication**
  - Nuclear and Radiation Safety Center
  - State Nuclear Power Software Development Center

<table>
<thead>
<tr>
<th>Codes</th>
<th>Organization</th>
<th>Facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Nuclear Design / Nuclear Database</strong></td>
<td>NPIC</td>
<td>HFETR</td>
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<tr>
<td></td>
<td>North West Nuclear Technology Institute</td>
<td>Xi’an Pulsed Reactor</td>
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<tr>
<td></td>
<td>CIAE</td>
<td>CEFR</td>
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<td></td>
<td>Belgium SCK-CEN?</td>
<td>VENUS-F (Guinevere)</td>
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<td></td>
<td>Russia?</td>
<td>BOR-60/BFS-1/2</td>
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<td>NACIE</td>
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<tr>
<td><strong>Shielding Design</strong></td>
<td>CIAE</td>
<td>CPNG6</td>
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</tbody>
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Lead-Based Reactor Characteristics

❖ Lead-Based Coolant Technologies

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<tr>
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<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead Bismuth</td>
<td>Low operation temperature → Early application (CLEAR-I)</td>
</tr>
<tr>
<td>Lead</td>
<td>High power conversion coefficient → Long-term application</td>
</tr>
<tr>
<td>Lead Lithium</td>
<td>Tritium breeding → Fusion application</td>
</tr>
</tbody>
</table>

- Similar properties, key technologies shared with others
- Can be applied for both critical and sub-critical systems

Application Prospects of Lead-based Reactor

❖ Energy: Generation IV/Fusion/Hybrid Reactors
  - LFR-One of Generation IV reactors
  - Promote the development of fusion/hybrid reactors

❖ Isotopes Production
  - Tritium for fusion test reactor start-up
  - Other radioactive isotopes

❖ Hydrogen/Sea Water Desalination
  - Hydrogen is a clean energy and has great market potential
  - The world’s fresh water gap is 200 billion/year, per capita in China is only a quarter of world average
China ADS & Lead-Based Reactor Development Roadmap (Proposal)

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Summary

- Design and relevant R&D on China LEAd-based Rector (CLEAR) as the Chinese ADS reference reactor has been carried out, with current emphasis on:
  - Preliminary engineering design of CLEAR-I PbBi reactor
  - Enhancement of KYLIN series PbBi loops and relevant testing
  - Design & construction of integrated PbBi reactor component testing platform CLEAR-S
  - Design & construction of zero-power experimental facility CLEAR-0 as well as Highly Intensified Neutron Generator HINEG.

- Development of concepts, relevant technology R&D and strategy of lead-based reactor are being performed to exploit broader applications for GIF-IV, fusion and others.

- Widely international cooperation on lead-based reactor design and technology R&D is welcome.

Website: www.fds.org.cn
E-mail: contact@fds.org.cn
Characterization of structural materials exposed to liquid lead bismuth eutectic. Results of specimens evaluated in US programs.

P. Hosemann, David Frazer; Cristian Cionea; Alan Bolind; Stephen Parker; Chloe Rose; Miroslav Popovic; University of California Berkeley

M. De Caro, S.A. Maloy, F. Rubio; Los Alamos National Laboratory

K. Lambrinou, E. Stergar; SCK-CEN; Belgium

OUTLINE

• Motivation and current status of LBE in the US

• General introduction in corrosion Issues of steels in heavy LM

• Results on stainless steel in flowing LM at medium temperature

• Results of Fe-Cr-Al steels exposed to static LM at medium and high temperature

• Less common characterization techniques deployed on oxide layers

• Irradiation and corrosion experiment

• Evaluating the bound strengths of passive films on steels.

• Summary
MOTIVATION FOR LBE COOLED POWER SYSTEMS

NUCLEAR POWER

The nuclear based LBE research is scaled to 0 in the US. No funds are spent on research on issues. One last experiment was conducted at the DELTA loop for MaRIE based materials evaluation (LANL internal funding). However, as a University UCB has more flexibility to continue nuclear based LBE research.

SOLAR CONCENTRATING POWER (CSP)

The CSP community is searching for better heat transport fluids. Metal coolants are an option. However, the requirements are different from the nuclear based work. Higher temperature and thermal cycling are necessary. Currently DOE-renewable energy is funding some LBE based research.

CORROSION ISSUES IN LEAD BISMUTH EUTECTIC (LBE)

Loop saturated with corrosion products cannot work due to the temperature gradient in the loop!

LBE Fully Saturated

Not sufficient oxygen to form a passive layer
Results of flowing LBE corrosion experiments
IPPE Loop

PREVIOUS EXPERIENCE WITH AUSTENITICS STAINLESS STEEL
3000h AT 550C (FLOWING) IN LBE (SEM) (IPPE LOOP)

Composition: Cr 13.5-14.5 %, Ni:14.5-15.5%, Mo 2%, Mn 1.65-2.35%, Si:0.5 -0.75%, C 0.035 -0.05%

P. Hosemann, R Dickerson, P Dickerson, N Li, SA Maloy, Transmission Electron Microscopy (TEM) on Oxide Layers formed on D9 stainless steel in Lead Bismuth Eutectic (LBE), Corr Scie. 66, (2013), 196–202
AFM MFM MEASUREMENTS ON D9 3000h, 550°C, 10^{-6} wt% O₂

S-TEM AND APT ON D9 OXIDE LAYERS

Yellow = oxygen
Red = Chromium
Blue is Nickel

N. Bailey, A. Reichard, P. Hosemann

SEM/EDX of HT-9 (0.1C, 8.3Cr, 0.43Si, 0.95Mo) 3000h 550°C, 10⁻⁶wt% (IPPE LOOP)

Back scattered SEM image (a) and EDX mapping of the same location on HT-9 exposed to 550°C LBE for 3000h.
AFM/MFM on HT-9

Outer layer
Inner layer
HT-9 bulk
Pores
Crack
Interface

-20 nm
8.5 V

-20 nm
8.5 V

C-AFM

Crack → Outer layer
Pores → Inner layer
Interface
HT-9 bulk

Cr₂O₃ lower electrical conductivity
than Fe₃O₃

Current line profile
through the boundaries
identified
Results of flowing LBE corrosion experiments

Delta Loop
**HIGH VELOCITY FLOW EXPERIMENT AT LANL (LBE)**

Flow conditions

<table>
<thead>
<tr>
<th></th>
<th>T [°C]</th>
<th>Velocity [m/s]</th>
<th>Oxygen concentration [wt%]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>488</td>
<td>3.5</td>
<td>3.2 x 10^{-5}</td>
</tr>
</tbody>
</table>

**Alloy**

<table>
<thead>
<tr>
<th></th>
<th>Cr</th>
<th>Al</th>
<th>Si</th>
<th>Mo</th>
<th>Mn</th>
<th>Ni</th>
<th>W</th>
<th>Y_{2}O_{3}</th>
<th>Ti</th>
<th>C</th>
<th>Fe</th>
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<tr>
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<tr>
<td>Alloy 4</td>
<td>12</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>Alloy 8</td>
<td>12</td>
<td></td>
<td>0.5</td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>Si-Fe “A”</td>
<td>0.09</td>
<td>1.24</td>
<td>0.0</td>
<td>0.04</td>
<td>0.08</td>
<td>0.03</td>
<td></td>
<td></td>
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<tr>
<td>Si-Fe “B”</td>
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<td>2.55</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>316L</td>
<td>17.5</td>
<td>0.46</td>
<td>2.3</td>
<td>1.8</td>
<td>12.3</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

**RESULTS OF HIGH VELOCITY TESTING OF VARIOUS STEELS LBE 535C 1000h**

**The DELTA Loop**

**Proceedings of the SEARCH/MAXSIMA 2014 International Workshop, Karlsruhe, Germany, October 7-10, 2014**
The Al-alloyed ODS steel (5.5wt%Al; 20wt%Cr; 0.5wt%Y2O3) did not show any kind of oxide layer when analyzed in cross section using SEM. Therefore a Sputter Depth Profiling (SDP) using X Ray Photoelectron Spectroscopy (XPS) was performed to determine the composition of the very thin oxide layer on the surface of this material.

Based on the published electron binding energy of each element, XPS allows the determination of the oxidation state of the element. Here the measured oxygen in the layer is compared with the calculated oxygen for the material.
Static corrosion testing at high temperature

CORROSION TESTING OF CANDIDATE MATERIALS AT HIGH TEMPERATURE

Materials selected for corrosion testing

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cr</th>
<th>Al</th>
<th>Fe</th>
<th>Ni</th>
</tr>
</thead>
<tbody>
<tr>
<td>316l</td>
<td>16-18</td>
<td>-</td>
<td>Bal</td>
<td>10-14</td>
</tr>
<tr>
<td>ALK</td>
<td>14-16</td>
<td>4.3</td>
<td>Bal</td>
<td>-</td>
</tr>
<tr>
<td>APM</td>
<td>20-23</td>
<td>5.8</td>
<td>Bal</td>
<td>5.8</td>
</tr>
</tbody>
</table>
Oxidation is preferential at GB. LBE penetration follows the oxide penetration.
INCONEL 693 AT 700°C FOR 300h AT $10^{-5}$ wt% OXYGEN CONCENTRATION

Al CONTAINING STEELS (Kanthal APM and APMT) EXPOSED TO LBE AT 800°C AND $10^{-6}$ wt% O
Less common characterization on oxide layers.

FIB PROCESSING ON LBE PENETRATED SAMPE; SCK SAMPLE

Standard FIB based lift out and slice and dice can be deployed in order to obtain the best location for a TEM sample.

316l, 450C, 1000h ≪ 10^{-8} wt%
At leaching paths bcc phase is found.

Twins are detected in the fcc area

In collaboration with K. Lambrinou SCK-CEN

Phase map (red fcc, blue bcc)

Legend for fcc

IPF Z for FCC Fe

Phase map (red fcc, blue bcc)
The irradiation and corrosion experiment (ICE)
Beam: 5 MeV protons, 0.5 µA current, 80 hour run
Target: Concaved HT-9 foil, 40 um at the center, 350 ºC
Damage level: 0.3 to 1.4 dpa
LBE chemistry control: no oxygen sensor
Corrosion rate change due to irradiation is not important/noticeable

**SPECIMEN DESIGN AND FACILITY**

Specimen concave shape allows to hold the pressure of the corrosive medium.

Dose profile shows maximum value at the edges of the specimen (T. Wynn, 2011)

Schematic machining:
INITIAL INVESTIGATION OF ICE SAMPLE

LBE Side on HT-9

~60 hours
430C, 2.5dpa

STEM ON ICE SPECIMEN (HT-9)

Out of the beam spot

In the beam spot
Investigating the strengths of the passive layers.

MECHANICAL STABILITY OF PASSIVE LAYERS FORMED IN LBE

Additional questions raised:

Mechanical strength of the oxide layers?

Interface strength between steel and passive layers?

Fracture surface and fracture mode of the passive layers?

Initial experiments were designed to evaluate the questions above.

In-situ testing in the SEM using a Hysitron PI85 picoindenter
INVESTIGATING MECHANICAL STABILITY OF PASSIVE FILMS, BRITTLE FRACTURE

Micro Cantilevers milled at the University of California, Berkeley

Milled using a FEI Quanta 3D FEG Focused Ion beam instrument

Ferritic/martensitic steel HCM12A after exposure to LBE. Sample provided by K. Kikuchi

IN-SITU FRACTURE TEST

$\sigma_{c\text{ cantilever 1}} = 1423$ MPa

$\sigma_{c\text{ cantilever 3}} = 1046$ MPa

Inner Oxide
- inner oxide # 4
- inner oxide # 3
- inner oxide # 2

Cross Section
- cross section # 7
- Cross section # 6
- Cross section # 5

Stress [MPa] vs Strain [-]
SUMMARY

• Introduced less common techniques to investigate passivation films formed in LBE on various steels.

• Evaluate physical properties of passivation films (strength, electrical conductivity and magnetic structure)

• We found enhanced corrosion and a less dense oxide on ICE samples.

• Examination of corrosion rates on Al-Alloyed steels under flowing and static condition.

• Increased the flow to of 3.5m/sec and no significant erosion has been found except on PM2000 and a 12Cr alloy (experimental heat)
Thank you for your attention!
## Recent Developments in (H)LM Measurement Techniques

Thomas Wondrak, Sven Eckert, Sven Franke, Natalia Shevchenko, Dominique Buchenau, Frank Stefani, Gunter Gerbeth

Helmholtz-Zentrum Dresden-Rossendorf

9th October 2014

### Measurement quantities

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Sensor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>Fiber optical sensor</td>
</tr>
<tr>
<td>Flow rate</td>
<td>Inductive Flowmeter</td>
</tr>
<tr>
<td></td>
<td>Lorentz Force Velocimetry</td>
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<tr>
<td>Local velocity</td>
<td>Mechanical devices</td>
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<td>Local Lorentz Force Velocimetry (near to the wall)</td>
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<tr>
<td></td>
<td>Potential probe (turbulent spectra)</td>
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<tr>
<td>Flow field</td>
<td>Ultrasound Doppler Velocimetry (UDV)</td>
</tr>
<tr>
<td>(1D/2D/3D)</td>
<td>Contactless Inductive Flow Tomography</td>
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<tr>
<td>Two phase</td>
<td>Resistance probes</td>
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<td></td>
<td>X-ray radioscopy</td>
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<tr>
<td></td>
<td>Ultrasound Transit Time Technique</td>
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<td>Mutual Inductance Tomography</td>
</tr>
<tr>
<td>Free surface</td>
<td>Ultrasound &amp; optical methods</td>
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</tbody>
</table>
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</table>

...non-invasive but contact needed...


Outline

1 Introduction

2 Non-invasive, but contact needed
   - Ultrasound Doppler Velocimetry (UDV)
   - Ultrasound Transit Time Technique (UTTT)

3 Contactless, x-ray radioscopy

4 Contactless, inductive methods
   - Inductive Flow Meter
   - Lorentz Force Velocimetry
   - Contactless Inductive Flow Tomography (CIFT)

Ultrasound Doppler Velocimetry (UDV)

- Scattering particles
- Repetitive ultrasound bursts
  - Time of flight (depth)
  - Phase shift (velocity)
- Instantaneous velocity profile
  - mm/s . . . 10 m/s
  - 20 . . . 30 Hz
- Can operate through wall
- Temperature: approx. 200 °C
- Higher temperatures: wave guide
  - Stainless steel foil: up to 700 °C
  - Ceramic: liquid steel ≈ 1600 °C
  - Wetting of the front!
Measuring concept for ESCAPE (SCK-CEN, Mol)

Flow mapping: continuous casting

Without brake  With brake (300 mT)
**UDV sensor arrays**

<table>
<thead>
<tr>
<th>State of the Art</th>
<th>Novel Development</th>
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<tbody>
<tr>
<td>Imaging dimensions:</td>
<td>2D-1C</td>
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<tr>
<td>Measuring lines:</td>
<td>≤ 21</td>
</tr>
<tr>
<td>Meas. line sampling:</td>
<td>sequential</td>
</tr>
<tr>
<td>Measurement rate:</td>
<td>5 fps</td>
</tr>
<tr>
<td>Measuring line pitch:</td>
<td>≥ 8 mm</td>
</tr>
</tbody>
</table>

- Two linear transducer arrays
- Measuring plane: 67 × 67 mm²
- Measuring grid: 24 × 24 vectors
- Grid pitch: 2.7 mm
- Spatial resolution: ≈ 3 mm

S. Franke et al., Ultrasonics (2013)
Two phase flow: bubble entrainment

Experimental setup

Free surface

ultrasonic signal during spin-up
formation of the funnel
detachment of particular gas bubbles

Ultrasound Transit Time Technique (UTTT)

Time of flight (transit time) \( t_B \) of the echo of the bubble gives the position \( x_B \):  
\[
x_B = \frac{1}{2} \cdot c \cdot t_B
\]

- c sound velocity
- Spatial distribution of bubbles
- Velocity of bubbles
- Bubble diameter

A. Andruszkiewicz et al., The European Physical Journal Special Topics (2013)
X-ray radioscopy

- Attenuation of the X-ray depends on the density of the material
- Visualization of bubbles
  - bubble size and shape
  - bubble trajectory
- Visualization of solidification
- High density of liquid metals: only thin layer of liquid is possible
- \( \gamma \)-ray, neutron radiography
- With GaInSn about 15 mm thickness possible

Comparison water - liquid metal (GaInSn)

- gas flow rate at each nozzle was \( \approx 1500 \text{ mm}^3 \text{ min}^{-1} \)
Inductive Flow Meter

- An applied magnetic field will be modified by the flow
- Amplitude / Phase shift is proportional to the flow rate
- Phase shift not sensitive to geometric changes
- Temperature drift compensation can be implemented
- High temporal resolution
- Can be applied at high temperatures
- Ceramic material ($T_{\text{max}} = 800 \, ^{\circ}\text{C}$)

Inductive Flow Meter

Development of a commercial prototype in cooperation with SAAS
**Lorentz Force Velocimetry (LFV) (TU Ilmenau)**

- Measurement of force or torque on outside magnet
  ⇒ Flow rate measurement
  ⇒ Extension to local measurements
- Applicable for glass melts, electrolytes


---

**Contactless Inductive Flow Tomography (CIFT)**
Contactless Inductive Flow Tomography (CIFT)

Exposing the flow $\mathbf{v}$ to an externally applied magnetic field $\mathbf{B}$

Induced current:

$$\mathbf{j} = \sigma (\mathbf{v} \times \mathbf{B} - \nabla \varphi)$$

Contactless Inductive Flow Tomography (CIFT)

1. Exposing the flow $v$ to an externally applied magnetic field $B$

2. Induced current:

$$ j = \sigma (v \times B - \nabla \phi) $$

3. Induced magnetic field:

$$ b(r) = \frac{\mu_0 \sigma}{4\pi} \int \frac{(v(r') \times B(r') - \nabla \phi(r'))(r - r')}{|r - r'|^3} dV' $$

4. Measurement of the magnetic field outside the melt
**Contactless Inductive Flow Tomography (CIFT)**

1. Exposing the flow $\mathbf{v}$ to an externally applied magnetic field $\mathbf{B}$
2. Induced current:
   \[ j = \sigma (\mathbf{v} \times \mathbf{B} - \nabla \phi) \]
3. Induced magnetic field:
   \[
   \mathbf{b}(\mathbf{r}) = \frac{\mu_0 \sigma}{4\pi} \int \left( \frac{\mathbf{v}(\mathbf{r}') \times \mathbf{B}(\mathbf{r}') - \nabla \phi(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} \right) dV'
   \]
4. Measurement of the magnetic field outside the melt
5. Reconstruction of the velocity field from the measured induced magnetic fields (linear inverse problem)


---

**CIFT demonstration facility**

- 2 orthogonal external magnetic fields of 4 mT
- 48 hall sensors
- Full 3D view of the velocity field
- Ratio: $b/\mathbf{B}_0 = 10^{-3}$
- Velocity $\approx 1$ m/s


---

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CIFT demonstration facility

![Diagram of CIFT demonstration facility]

CIFT demonstration facility

![Diagram of CIFT demonstration facility]
**CIFT 2D: continuous casting**

- Liquid steel flow structure in the mold effects the quality of the produced steel
- Slab casting: dominant flow structure is 2D
- 2D velocity reconstruction
- Sensors only at the middle of the narrow faces of the mold

**Mini-LIMMCAST: two-phase flow**

Experiments with Argon injection

Reference case: without Argon  
With Argon 500 sccm

Comparison with UDV
Towards robustness: noise

4 kA through one copper rod in a distance of 20 m

AC excitation field

Induction coil sensor system

- Advantage: no saturation effect applicable in the presence of strong static magnetic fields like an electromagnetic brake in continuous casting
- Low frequency < 10 Hz to avoid skin effect
- A lot of windings: reliable detection of magnetic fields in the order of 10 nT
- High dynamic range (5 orders of magnitude):
  - external magnetic field ± 5 V
  - induced magnetic field ± 600 µV
- 14 coils with
  - diameter: 28 mm
  - length: 29 mm
  - windings: 340 000
Electromagnetic brake

- Electromagnetic brake of ruler type
- Strength of the magnetic field: 310 mT
- Measurement using Ultrasonic Doppler Velocimetry (UDV)
- Jet is bend upward


SnBi model of a caster

T. Wondrak | Institute of Fluiddynamics | http://www.hzdr.de 
Member of the Helmholtz Association
Reconstructed velocity

![Reconstructed velocity diagram](image)

CIFT coil for cylindrical vessel (Si puller)

- Separable into two halves
- Coil inner diameter: 1100 mm
- Magnetic field: 2 mT at 30 A
Proposal for the application of CIFT to ESCAPE

Summary

- The availability of flow measurement techniques for liquid metals is crucial for
  - Thermal-hydraulic analysis and optimization of liquid metal cooled reactors
  - Monitoring of processes & safety issues
- New developments have been obtained during the last decade (ultrasonic and inductive techniques)
- First commercial prototypes are available
Session # 10

Steam generator tube rupture (SGTR)

Chair: J. Pacio (KIT)
SGTR large scale test section design implemented in CIRCE facility and pre-test analysis

A. Pesetti\textsuperscript{(a)}, M. Tarantino\textsuperscript{(b)}, N. Forgione\textsuperscript{(a)}

\textsuperscript{(a)} University of Pisa, Italy
\textsuperscript{(b)} ENEA, Italy

Abstract

In the frame of the MAXSIMA project (FP7 of the EC), work package 4, task 4.1, Large Scale Experiments (LSEs) in a Heavy Liquid Metal Pool (HLMP) will be performed, aiming to characterize the Steam Generator Tube Rupture (SGTR) event in a relevant configuration for MYRRHA reactor. Task 4.1 also foresees the assessment of the tube rupture propagation, damping effect of the surrounding structures, safety-guard devices, steam dragged into the main flow path and the investigation of the solid impurity formation and filter qualification, as a consequence of the SGTR phenomenon.

The experimental campaign involved in task 4.1 will be carried out in the CIRCE facility, the largest Lead-Bismuth Eutectic (LBE) alloy pool worldwide, set at ENEA research centre of Brasimone, Italy.

In order to properly take into account the not negligible above mentioned SGTR consequences, a proper test section (TS) will be designed, implemented and installed in the CIRCE pool. The test section will host a portion of a full scale bundle of the MYRRHA Primary Heat Exchanger (PHX).

This work reports the test section design, highlighting the MYRRHA geometrical and thermodynamic parameters that have been conserved against the performed necessary simplifications.

The test section is mainly composed by a pumping system (jet pump driven by centrifugal pump), and four SGTR-TSs. Each SGTR-TS consists of a tube bundle relevant for the MYRRHA PHX.

The central tube of any SGTR-TS is filled by evaporating water flowing upwards and will be broken, by an external hydraulic system, causing the SGTR event. Four experiments are foreseen, executed one at a time in the four SGTR-TSs.

The instrumentation planned to be installed in the TS is described. It is mainly composed by fast pressure transducers, bubble tubes, thermocouples, flow meters (Venturi nozzle), strain gauges, resistivity probes and oxygen sensors.

Preliminary pre-tests, performed by the SIMMER III code in a simplified CIRCE test section configuration, are reported. The results show that hazardous pressure peaks do not occur at the water injection start and that the cover gas pressurization could be maintained to a safe value (below 8 bar), by a 2 inch rupture disk set in the CIRCE dome.
MAXSIMA - WP4 – Task 4.1
Steam Generator & Cooling Safety

CIRCE test section design and SIMMER 3D model for SGTR investigation in a relevant configuration for MYRRHA

A. Pesetti, M. Tarantino, P. Gaggini
(alessio.pesetti@for.unipi.it)

SEARCH/MAXSIMA International Workshop
Karlsruhe, Germany, 7th – 10th October, 2014

List of contents

- Introductory remarks
- MYRRHA-PHX
- CIRCE facility (ENEA Brasimone RC)
- MAXSIMA Test Section design
- MAXSIMA Test Section instrumentation
- SIMMER IV model (3D)
- Future work
- Conclusive remarks
The SGTR scenario needs to be analysed, in the integrated pool type MYRRHA reactor configuration, aiming to predict the hazardous consequences of the PHX tube rupture taking place in the LBE pool (pressure wave propagation and cover gas pressurization, domino effect, steam dragged into the core, primary system pollution and slug formation).

In the frame of MAXSIMA task 4.1 a portion of a full scale bundle of the MYRRHA PHX will be installed in the CIRCE pool aiming to characterize the SGTR scenario in a relevant configuration for MYRRHA.

The design of the MAXSIMA-TS and the instrumentation foreseen to be implemented is modelled by SIMMER IV code (3D).

In the CIRCE facility a portion of a full scale bundle of the MYRRHA PHX will be host, with LBE inlet and outlet regions.

Two rupture positions will be experimentally investigated: **Middle** and **Bottom** positions.

In the table the main parameters of the MYRRHA PHX are shown.
CIRCE facility (ENEA Brasimone RC)

Main Vessel S100
- Outside Diameter: 1200 mm
- Wall Thickness: 15 mm
- Material: AISI 316L
- LBE Inventory (max): 90 tons
- Height: 8-10 m
- **Design Pressure**: 16 bar
- Design Temperature: 450°C

The largest LBE pool worldwide

MAXSIMA-TS design, objectives

- Tube rupture propagation into the HX-tube bundle
- Pressure waves propagation into the HX-tube bundle and damping effect of the HX-shell towards the surrounding structures
- Assessment and performance evaluation of the safety-guard devices (rupture disk and fast valves) aiming to mitigate the effects of the SGTR event
- Steam trapping in the main LBE flow path and dragging towards the core inlet region
- Investigation on the solid impurities formation after the SGTR event, accompanied by a quantitative qualification of filtering performance in the pool
MAXSIMA-TS design

<table>
<thead>
<tr>
<th>Operating conditions</th>
<th>Unit</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>LBE temperature</td>
<td>°C</td>
<td>350</td>
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<tr>
<td>LBE mass flow rate</td>
<td>kg/s</td>
<td>~80</td>
</tr>
<tr>
<td>H₂O inlet temperature</td>
<td>°C</td>
<td>200</td>
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<tr>
<td>H₂O outlet temperature</td>
<td>°C</td>
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<tr>
<td>H₂O pressure</td>
<td>bar</td>
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</tr>
<tr>
<td>H₂O mass flow rate</td>
<td>kg/s</td>
<td>~0.07</td>
</tr>
<tr>
<td>CIRCE cover gas pressure (abs)</td>
<td>bar</td>
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</tr>
<tr>
<td>CIRCE Ar cover gas volume</td>
<td>m³</td>
<td>~2.2</td>
</tr>
<tr>
<td>CIRCE LBE pool volume</td>
<td>m³</td>
<td>~7</td>
</tr>
<tr>
<td>Ar monitoring tubes pressure</td>
<td>bar</td>
<td>16</td>
</tr>
<tr>
<td>Tubes length</td>
<td>mm</td>
<td>~5200</td>
</tr>
</tbody>
</table>

MAXSIMA-TS instrumentation

~200 TCs
~50 in each SGTR-TS
6 TCs at level (two level below, one level at and 5-6 levels above the rupture position)
N 6 tubes 3x1 mm, 6” tube drilled
Vapour path propagation

5 fast Pressure Transducers (transient pressure)
12 Bubble Tubes (level, mass flow rate and stationary pressure)
**MAXSIMA-TS instrumentation**

8 Strain Gages in the **middle**
SGTR-TS rupture scenario

6 Strain Gages in the **bottom**
SGTR-TS rupture scenario

**SIMMER IV model MAXSIMA-TS (33x41x52cells)**

Horizontal section 33x41 – Level A (j 13)

Vertical structures modelled by virtual wall

Horizontal section 33x41 – Level B (j 15)

52 axial cells
Virtual walls are not shown in 3D views

- Flowing areas conserved
- Mass flow rates, temperatures, conserved

SGTR-TS

30 dummy tubes
1 water tube

Section A-A

Section B-B

SIMMER IV model MAXSIMA-TS, 2D view
Future work

- Pre-tests execution on the basis of the detailed SIMMER 3D model of the whole CIRCE vessel and implemented MAXSIMA Test Section presented
- Highly detailed SIMMER 3D model of the SGTR-TS region in which the ruptures occur
- RELAP5 model of the feed-water and two-phase discharge line

Conclusive remarks

- The design of the MAXSIMA-TS hosting 4 SGTR-TSs is completed
- The CIRCE cover procurement is completed
- The procurement of the MAXSIMA-TS and related instrumentations is ongoing
- The SIMMER 3D detailed model is realized
- MAXSIMA-TS is foreseen to be constructed, instrumented, and set into CIRCE facility by the first months of 2015
THANK YOU FOR YOUR ATTENTION

Conclusive remarks

- MS19 Test Matrix Definition → M3 (Jan. 2013)
- MS20 Test Section Design → M9 (July 2013)
- MS21 Start of the main component procurement → M12 (Oct. 2013)
- MS22 Test Section Implementation → M18 (April 2014)
- MS23 Experimental Campaign Accomplishment → M24 (Oct. 2014)
- MS24 Final Report Delivery → M36 (Oct. 2015)

MYRRHA PHX data received October 2013
Preliminary Experimental Study on HX Tube Rupture Accident for China Lead alloy-Cooled Reactor

R. Sa\(^{(a)}\), D. Zhou\(^{(a)}\), S. Gao\(^{(a)}\), Q. Huang\(^{(a)}\), FDS Team\(^{(a)}\)

\(^{(a)}\) Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei, Anhui, 230031, China

Abstract

Lead Bismuth Eutectic (LBE) has been proposed as the primary candidate spallation target and coolant materials for China LEAd alloy-cooled Reactors (CLEAR) with utilization high pressure water as secondary loop coolant. However, the risk of leakage of water into lead alloy due to Heat eXchanger (HX) tube rupture will provoke an intolerant pressure increasing and steam dragging in reactor core.

In order to validate the key safety assessment for CLEAR, corresponding research frame including scenario mechanism investigation, innovative measurement technique development and large scale safety facility design/construction was established and some preliminary results were obtained. One heavy liquid metal molten and releasing apparatus was designed and constructed to investigate the lead alloy/water interface phenomenon by releasing LBE droplet into a water pool. A two-phase flow apparatus equipped with patented void fraction probe was set up to investigate the bubble behavior by injecting gas into water. Experimental results, e.g. LBE fragmentation, two phase flow character and void probe validation, etc. were obtained in those experimental facilities. The recent progress of the studies related to HX Tube Rupture in CLEAR are summarized.
Preliminary experimental study on HX tube rupture accident for China Lead alloy-Cooled Reactor

Presented by Rongyuan SA

Contributed by FDS Team

Institute of Nuclear Energy Safety Technology
Chinese Academy of Sciences (INESST)
China Lead-based Reactor Development Plan

- Chinese Academy of Sciences (CAS) has launched the ADS Project, and plan to construct demonstration ADS transmutation system ~ 2030s through three stages.
- China LEAd-based Reactor (CLEAR) is selected as the reference reactor for ADS project and for Lead cooled Fast Reactor (LFR) technology development.
CLEAR-I Main Design Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Values</th>
</tr>
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<tbody>
<tr>
<td>Core</td>
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</tr>
<tr>
<td>Thermal power (MW)</td>
<td>10</td>
</tr>
<tr>
<td>Activity height (m)</td>
<td>0.8</td>
</tr>
<tr>
<td>Activity diameter (m)</td>
<td>1.05</td>
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<tr>
<td>Fuel (enrichment)</td>
<td>UO₂ (19.75%) at first</td>
</tr>
<tr>
<td>Cooling System</td>
<td></td>
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<tr>
<td>Primary coolant</td>
<td>LBE</td>
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<tr>
<td>Inlet/Outlet temp (°C)</td>
<td>~300/385</td>
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<tr>
<td>Primary coolant mass flow rate (kg/s)</td>
<td>529.5</td>
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<tr>
<td>Coolant drive type</td>
<td>Forcéd Circulation</td>
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<td>Heat exchanger</td>
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<td>Second coolant</td>
<td>Water</td>
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<td>Heat sink</td>
<td>Air cooler</td>
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<td>Material</td>
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</tr>
<tr>
<td>Cladding Structure</td>
<td>15-15Ti/316Ti</td>
</tr>
<tr>
<td>Structure</td>
<td>316L</td>
</tr>
</tbody>
</table>

China Liquid PbBi-Loop Technology Roadmap

"Three-steps" Strategy

- **CLEAR-I**
  - Materials and LBE technology test loop (2010-2012)
- **KYLIN-I**
  - Thermal-convection loop
  - Forced convection loop
  - Static/rotating Device
- **KYLIN-II**
  - Thermal-hydraulic and Safety validation loop (2010-2014)
- **CLEAR-S**

Series PbBi loops were built to develop the LBE technology and support the construction of CLEAR.
Contents

I. Background
II. Materials, thermal-hydraulic loop
III. SGTR related studies
IV. Summary

Materials and LBE technology test loop (KYLIN-I)

Design Objectives
- Thermal/Forced convection loop
- Corrosion behavior of SS316L/T91
- Pumping and instrumentation technology

Major parameters
- Loop size: 3m×3.5m
- Structural Material: SS316L
- Inner/out-diameter: 32/42mm
- Temperature: 500°C
- Volume of PbBi: ~50L
- Atmosphere: Ar (99.999%)
Multifunctional Lead-bismuth Loop (KYLIN-II)

Material testing area and thermal-hydraulics testing area have been finished constructed in 2013, and the loop is stably operating at 500°C.

- Max. Temperature / Velocity: 1100°C / 10m/s
- Max. Heat Power: 2000kW
- Oxygen control: 10⁻⁹~10⁻⁶wt%

Contents

I. Background
II. Materials, thermal-hydraulic loop
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Characteristics of heat exchanger (HX) in CLEAR-1:

- Primary coolant: Lead-Bismuth Eutectic (~0.1MPa, 300~380°C);
- Second coolant: Subcooled water or superheated steam (4MPa);
- No Intermediate heat exchanger (IHX);
- Immerse HX into primary coolant directly.

Potential risk:
SGTR includes high-pressurized water blasting into the lead pool introducing several risks:

1. Strong impact pressure due to severe direct contact boiling (challenge vessel integrity);
2. Positive void worth in core by dragged steam.
3. Pressurization of cover gas by accumulated steam, LBE sloshing...

SGTR related studies...

- Mechanism investigation: Vapor explosion, Sloshing...
- New instrument R&D: Void fraction probe, UDV...
- Mitigation tech. R&D: HX thermal hydraulic, New HX R&D...
- Integral test for SGTR: KYLIN-II-S
- Numerical code V&V

Integral test for SGTR

Full-scale test
CLEAR-S
Vapor explosion during SGTR

Visualization of water inject into lead bismuth eutectic (LBE) using neutron radiography [1]

•Vapor collapses and liquid-liquid contacts directly;
•Transient heat transfer occur leading intense evaporation, fragment the lead alloy and create potential for an energetic vapor explosion


LBE-water interaction test facility
LBE-water interaction results

LBE drop (773K) water (300K)
Vapor explosion

LBE drop (773K) water (350K)
No Vapor explosion (only deformation)

LBE-water interaction results

\[ T_I = \frac{T_H - T_C}{1 + \sqrt{\beta}} + T_C, \quad \beta = \frac{(\rho C_p \lambda)_C}{(\rho C_p \lambda)_H} \]

- the vapor explosion was apt to occur mainly when \( T_H \) and \( T_C \) satisfied the following conditions: \( T_I > T_{HN} = 586K \) (indicated by the red line), and subcooling temperature of water was higher than 40K.
LBE-water interaction results

- $T_{\text{LBE}} = 250^\circ C$, $T_{\text{water}} = 25^\circ C$
  - No explosion

- $T_{\text{LBE}} = 500^\circ C$, $T_{\text{water}} = 25^\circ C$
  - Violent explosion

Larger scale interaction (LBE jet & water) are still under investigating...

Steam ingress during SGTR

A nuclear power excursion could be triggered by steam ingress into the core which has a significant **positive void worth**!

**Assumption Failure point:** Bottom of elbow bend

- Higher residual stress;
- Higher potential energy and density of inside water (sub-cooled or saturated)

A downward water jet was proposed as the most severe condition for steam ingress during SGTR.
Steam ingress facility

- **Void fraction sensor (~200°C):**
  - Steel wire: ~0.3mm
  - Ceramic tube probe as support and sealed by waterproof plastic

- **High-speed camera:**
  - Resolution: 1920×1080
  - Speed: 90260fps

Preliminary test employed air gas penetration in water

Steam ingress results

Water: 25°C; Air: 4m³/h; D_j: 3.7mm

Future work was improvement of void fraction probe under high temp. and high pressure condition.
Fabrication of HX in KYLIN-II Thermal-hydraulic loop

Characteristic of HX

Double concentric tube with SS powder gap: High pressure water (Max. 6MPa) flows in the outer tube with a counter direction of LBE flowing in the inner tube.

- Tube material: 316L
- Cooling power: 80kW

The further experimental work will focus on the heat exchanger coefficient of double wall with SS powder gap.

New HX Manufacturing Technique-DW HX

- Dual boundaries between LBE/water (Double-walled tube)
  - Crack arresting at the interface;
  - Tube inspection for inner and outer tubes to ensure their integrity;

  Reduced possibility of LBE/water reaction

To prove rationality and feasibility of this project, building the model or specimen and initiated some tests are necessary.

Material: 316L
method: cold-drawing
Gap: ≤0.1mm
Out-of-roundness: ≤0.12
Tortuosity: ≤2.0

Roundness detection
Tortuosity detection
Gap detection
Heat Transfer Performance Tests

Three Steps
KYLIN-II Safety loop

Main Function:
- Vapor explosion of PbBi contacting with water
- Steam bubble transportation monitoring
- Hydrogen production investigation
- Heat-exchanger validation

Main parameters:
- Temperature: 200~550°C
- Pressure of water: ~25 MPa
- PbBi inventory: ~3t

Key issues:
- Innovation heat-exchanger development and testing
- Shock pressure measurement and evaluation
- LBE two-phase inspection and monitoring

Contents

I. Background
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III. SGTR related studies
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Summary

- **PbBi loops** were the necessary devices to investigate the key technologies for ADS.

- The **KYLIN-I loop** has been built operated for thousands of hours corrosion test, and the **large-scale multifunctional KYLIN-II loop** was built for the materials corrosion, thermal-hydraulic and safety tests in 2013.

- Related to **SGTR accident**, several mechanism experiments (e.g. vapor explosion, steam ingress), new instruments R&D and mitigation tech. (innovation HX heat transfer character investigation, new HX R&D) has been developed.

- A large integral test facility (**KYLIN-II-S**) was under construction, future work will focus on the integral test for SGTR.

**Thanks for Your Attention!**

Website: www.fds.org.cn
E-mail: contact@fds.org.cn
Velocity measurements of heavy liquid metal flows by the Ultrasound Doppler method

S. Franke\textsuperscript{(a)}, S. Eckert\textsuperscript{(a)}, T. Gundrum\textsuperscript{(a)}, G. Gerbeth\textsuperscript{(a)}

\textsuperscript{(a)} Helmholtz-Zentrum Dresden-Rossendorf, 01314 Dresden, Germany

Abstract

The application of heavy liquid metals as coolant or heat transfer medium in advanced reactor systems demands for a comprehensive knowledge of the flow characteristics. CFD simulations are the main tool to predict the flow behaviour, however, the numerical models have to be validated by experimental data. Flow measurements in hot liquid metals are challenging and the available choice of measuring techniques is rather limited. A great deal of work was done during the last decade to develop suitable measuring principles for applications in metallic melts. The Ultrasound Doppler method can be considered as an attractive technique to obtain real-time velocity profiles in liquid metal flows. Flow measurements in hot metallic melts involve several specific problems, especially the high temperature and the abrasive character of the melt. Furthermore, a sufficient input of acoustic energy into the melt to be measured requires favourable conditions concerning acoustic coupling, transmission and wetting. Moreover, the availability of seeding particles has to be guaranteed to obtain Doppler signals from the fluid. We will present a concept for velocity measurement in a liquid metal channel flow based on high temperature transducer probes in combination with a matched mechanical design of the probe seating. Specific measuring procedure enables us for reliable measurements in a temperature range up to 230°C. The measuring principles are successfully applied at experimental facilities operating with different metal alloys and geometric configurations: At the LIMMCAST (Liquid Metal Model for Continuous Casting) facility of Helmholtz-Zentrum Dresden-Rossendorf we studied the flow profile of a Sn60Bi40 alloy in a circular pipe. Furthermore, the LBE duct flow of the META: LIC loop (Megawatt Target: Lead Bi\textsubscript{3}smuth Cooled) at the Institute of Physics in Riga-Salaspils (University of Latvia) was measured. Parametric studies of the velocity profile measurements in the ducts will be presented here. Specific problems arising for the application of the Ultrasound Doppler method in the considered experimental configuration will be discussed.
Motivation

Liquid metal technologies

Metal industry
• Production of cast parts
• Continuous casting process
• Semiconductor crystal growth

Energy industry / R&D
• Solar power plants (CSP)
• Liquid metal cooled reactors (LFR)

Understanding of flow characteristics

Research methods

Numerical simulations (CFD)
Physical studies (Hot liquid metal model experiments)

Main challenge: Opacity of melts → Optical flow measuring methods inappropriate

Ultrasound Doppler method proved as efficient technique for non-invasive, spatial- and time-resolved flow velocity measurements at opaque liquids
**Ultrasound Doppler method: Operation principle**

- **Pulse-echo method:**
  - Transmission of multitude of ultrasonic bursts
  - Burst reflected at scattering particles → echo signal
  - Information about position: → time-of-flight
    \[ \chi = \frac{c \cdot t}{2} \]
  - Flow velocity component in beam direction
    → phase-shift between successive particle echoes in respect to the pulse repetition time
    \[ v_x = \frac{c \cdot \Delta \varphi}{4\pi \cdot f_0 \cdot T_{prf}} \]

- **Ultrasound Doppler method:**

**Ultrasound Doppler method: Specific issues in liquid metals**

**Ultrasound Doppler method is non-invasive but not contactless!**

**Challenging issues:**

- High temperatures of metal melts
- Chemical aggressiveness / corrosion
- Acoustic transmission through interfaces
  Reason: acoustic impedance mismatch
- Acoustic coupling at interfaces / wetting
  Reason: oxide layer / thin gas film
- Availability and distribution of scattering particles (Acoustic inhomogeneities)
  What are the natural scattering particles in liquid metals?
  – Oxides? Local temporal segregation of eutectic alloys? Other impurities?
High temperature measurements: Methodology & approaches

Approaches for the high temperature issue:

<table>
<thead>
<tr>
<th>Metal / metal alloy</th>
<th>( T_{\text{melt}} )</th>
<th>Probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ga68In20Sn12</td>
<td>10.5°C</td>
<td>Standard commercial ultrasonic probes</td>
</tr>
<tr>
<td>Na</td>
<td>98°C</td>
<td>Commercial high temperature ultrasonic probes (&lt; 230°C)</td>
</tr>
<tr>
<td>Pb44Bi56</td>
<td>125°C</td>
<td></td>
</tr>
<tr>
<td>Sn60Bi40</td>
<td>170°C</td>
<td></td>
</tr>
<tr>
<td>Sn63Pb37</td>
<td>183°C</td>
<td></td>
</tr>
<tr>
<td>Cu35Sn65</td>
<td>550°C</td>
<td>Ultrasonic probes with acoustic waveguides (&gt; 230°C)</td>
</tr>
<tr>
<td>Al</td>
<td>660°C</td>
<td></td>
</tr>
</tbody>
</table>

High temperature probes: Sensor probe setup

Probe seating:
- Housing allows simple probe exchange during operation
- Probe protection from chemical corrosion
- Advantages compared to direct coupling (safety reasons, better wetting)
- Removable for renewal of wetting
- Spring mechanism presses probe to front plate → acoustic coupling maintained despite thermal expansion

1. Transmission plate
2. Sensor adapter
3. Sensor fixing
4. Spring
5. Sleeve nut
6. Knurled nut
7. US sensor probe
High temperature probes: Acoustic signal transmission

Preparation of wetting:
- Transmission plate electroplated with nickel
- Wetting of adapter surface with BiSn for acoustic coupling from adapter into melt

Acoustic Coupling:
High temperature ultrasound couplant for acoustic coupling into transmission plate

Transmission:
- Thickness of steel plate optimized to maximum transmittance
- Maximum at \( d/\lambda = n/2 \) (\( n = 1, 2, 3 \ldots \))

\[
T = \frac{1}{\sqrt{1 + \frac{1}{4} \left( m - \frac{1}{m} \right)^2 \sin^2 \frac{2\pi d}{\lambda}}}
\]
\[m = \frac{Z_{\text{fluid}}}{Z_{\text{plate}}} \quad (Z = \rho c_{\text{sound}})\]

SnBi flow measurements: LIMMCAST facility

LIMMCAST experiment facility (HZDR):
- Liquid Metal Model for Continuous Casting
- Liquid metal Sn_{60}Bi_{40}
- Temperature range 200°C to 350°C

Measurement setup:
- Pipe circular cross section: \( d = 55 \text{ mm} \)
- Doppler angle: \( \theta = 45^\circ \)
- Operating temperature: 200°C
- Doppler Instrumentation: DOP 3000 from Signal Processing with 4MHz high temperature probe

Reference flow meter:
- Phase-shift sensor (Inductive flow rate sensor)
SnBi flow measurements: LIMMCAST measurement results

Flow profile and flow rate in dependence on rotation speed of electromagnetic pump

Flow profile of normalized pipe diameter

Volume flow rate vs. Rotation speed of EM pump

Adapter surface after application:
- Deposition / fouling of impurities (oxides, intermetallic compounds etc.) after liquid metal is discharged ➔ wetting lost
- Wetting treatment must be renewed or adapter must be changed after each measurement series

➔ Ultrasound measurements implicates high effort

PbBi flow measurements: META:LIC loop

META:LIC loop facility (IPUL, Latvia):
- MEgawatt TArget:Lead bIismuth Cooled
- Comparative concept for a liquid metal target within the design phase of the European Spallation Source (ESS) project
- Target model of META:LIC concept at the Institute of Physics University of Latvia
- Liquid metal Pb\textsubscript{44}Bi\textsubscript{56} (LBE)
PbBi flow measurements: META:LIC measurement results

Measurement setup:
- Rectangular cross section: $H \times W = 80 \times 100$ mm$^2$
- Doppler angle: $\theta = 60^\circ$
- Operating temperature: 210$^\circ$C
- Flow rate instrumentation: Venturi tube

Flow profiles

E-SCAPE experiment facility (SCK-CEN):
- Thermal-hydraulic mockup of MYRRHA within the THINS (Thermal-Hydraulics of Innovative Nuclear Systems) project
- Large-scale model (ratio 1:6)
- Liquid metal PbBi (LBE)
- Temperature range 200$^\circ$C to 600$^\circ$C

CFD simulation of velocity field for flow pattern characterization (performed by NRG)

Source: SCK-CEN
PbBi flow measurements: E-SCAPE sensor concept

Flow field measurements in lower plenum section by up to 50 measuring points

Challenges:
- Complex geometry
- High penetration depth for US beam (0.6 m)

Acoustic waveguide probe

Working principles:
- Temperature gradient along slab
- Prevent unwanted propagation modes

Design:
- Wrapped metallic foil
- Foil thickness: ≈ 0.1 mm
- Material: stainless steel, molybdenum
- Length: 200 - 500 mm
- US frequency: 2 … 5 MHz
- Max. temperature: ≈ 700°C

Measurement in CuSn: swirling flow

Drawbacks of acoustic waveguides:
- Lower sensitivity than conventional sensor probes
- Waveguide length limits maximum measuring depth (multiple reflections from waveguide interface interfering the velocity profile)
Measuring issues: particle concentration and artifacts

Poor velocity profile

**Reason:** Low concentration of scattering particles at low flow velocities due to particle deposition at inner walls

**Approach:** Stir up settled particles by high flow rates (“mixing”) before starting measurement, especially at low flow rates

**Artifacts in profile**

**Reason:** Strong stationary echoes (multiple wall reflections from former US pulses)

**Approach:** Change of measuring parameters to shift away the stationary echoes out of measuring range; improvement of signal-to-noise-ratio

**No reliable velocity information near walls**

**Front wall:** Multiple reflections inside wall and ringing of transducer disturbs Doppler signal

**Back wall:** Velocity profile close to wall declines not to zero due to multiple reflection paths

Measuring issues: EMI

**Electromagnetic interference (EMI):**

- **Sources:** pumps, heaters, magnetic fields, power sources, …
- **Ways:** conductive (power line, conductive walls of facility), inductive, capacitive

**Approaches to reduce EMI and its effects:**

- Improved shielding of signal lines (e.g. permalloy against inductive EMI)
- High-frequency compliant grounding and high-frequency compliant connection between measuring point and instrumentation (e.g. specific high-frequency compliant, low-resistance wires)
- EMI filters (e.g. line filters before instrumentation and also EMI sources, toroidal core filters at ultrasonic sensors)
- Electrical isolated instrumentation (e.g. isolation transformer, battery operation, electrical isolators for data interfaces)
- Signal post-processing and signal reconstruction algorithms

No general formula for treatment of EMI, only individual solutions
Summary

- Two approaches for ultrasound Doppler measurements at high temperature melts:
  - High temperature ultrasonic transducers with probe seating (T ≤ 230°C)
  - Transducers with acoustic waveguides (T ≤ 700°C)
- Successful measurements with high temperature probes at PbBi and SnBi without drawbacks of waveguides
- Successful measurements with waveguides
- Adequate understanding of the measuring principle and its challenges as well as a correct evaluation of measuring results is crucial

Thank you for your attention!
Session # 11

Blockages

Chair: K. Litfin (KIT)
Water modelling for the thermal-hydraulic study of HLM reactors
Ch. Spaccapaniccia\textsuperscript{(a)}, Ph. Planquart\textsuperscript{(a)}, S. Buckingham\textsuperscript{(a)}, J.-M. Buchlin\textsuperscript{(a)}

\textsuperscript{(a)} von Karman Institute, Chaussée de Waterloo 72, B-1640 Rhode-St-Genèse, Belgium

Abstract
The thermal-hydraulics challenges in the design of new nuclear reactor are still numerous. The attendance and the number of publications of the bi-annual NURETH conferences show that it remains an important topic. It is obvious that thermal-hydraulics is a key point for the design and safety of reactors. The use of numerical simulation with CFD codes or the use of System codes can address a lot of the different challenges but nevertheless, the use of water modelling for the study and validation of the thermal-hydraulic behaviour of the primary circuit remains a valuable tool.

During the presentation, the experience of the von Karman Institute (VKI) in the use of water modelling to simulate the flow of liquid steel will be presented. First, we will review shortly the main scaling criteria when dealing with water modelling of heavy liquid metal (HLM). Afterwards, two water models used at VKI with their specificity will be described:

- The first model, AQUARIUM, is used for a parametric study of the natural convection flow pattern in a quasi-2D configuration representative of a typical Upper Plenum configuration.
- The second model, named MYRRHABELLE for MYRRHA Basic SEt-up For Liquid FLow Experiments, is a full Plexiglass model at a scale 1/5 of the design version 1.2 of MYRRHA.

Thanks to the optical access of both models, the velocity field is measured using the PIV technique and the temperature field is measured either with thermocouples or with the LIF (Laser-Induced Fluorescence) technique. The experimental results obtained on both models are presented and discussed.

The water models are used for the validation of CFD codes. Therefore, the thermal-hydraulic behaviour of MYRRHABELLE has been studied with CFD and the comparison with the water model results will be presented.
WATER MODELLING FOR THE THERMAL-HYDRAULIC STUDY OF HLM REACTORS

Ph. Planquart, Ch. Spaccapaniccia, S. Buckingham, J.M. Buchlin
von Karman Institute

OBJECTIVES OF WATER MODELING

1. Provide experimental data for the validation of CFD codes

2. Investigate the influence of parameters on the Thermo Hydraulic behavior of the primary circuit of the reactor

3. Extrapolate water model Thermo Hydraulic data to the HLM reactor
OUTLINE

1. Introduction
2. Water model of a HLM reactor – scaling criteria
   - Major scaling requirements
   - Dimensionless numbers
3. “2D” Water model to study Natural Convection – Aquarium
   - Results: influence of blockage in the velocity field
4. Water model of a HLM reactor – MYRRHABelle
   - Results: Nominal Conditions and Natural convection velocity fields
5. Conclusions

WATER MODELING OF LIQUID METAL

- Challenges in the upper plenum that will be addressed by water modeling:
  - UPPER Plenum:
    - Global velocity field and temperature distribution
    - Flow unsteadiness
    - Thermal stratification
    - Free surface behavior
    - Vortex formation at the free surface
    - Behavior of bubbles and particles escaping from the core of the reactor
    - Flow pattern in non-symmetric and accidental scenarios
WATER MODELING OF A HLM REACTOR - SCALING CRITERIA

The major scaling requirements are the following:

- The overall behavior in the prototype plant should be preserved
- The major thermal-behavior phenomena should be reproduced
- The scale of the water model must be sufficiently high to be able to represent the detailed features on the reactor
- The balance between buoyancy force and pressure losses must be preserved when studying natural convection
- The balance between heat generation and heat cooling must be preserved
- The water model should be built at a reasonable cost.

Two modes of operation have been considered for the water model:

- Physical simulation of the nominal condition (full power)
- Simulation of the natural convection in reduced power (decay heat removal after reactor shut-down)
Richardson number: \[ \frac{g \cdot \beta \cdot \Delta T \cdot L}{u^2} \]  
- buoyancy force
- inertia force
- MB!

Euler number: \[ \frac{\Delta P}{\rho \cdot u^2} \]  
- pressure force
- inertia force

Reynolds number: \[ \frac{\rho \cdot u \cdot L}{\mu} \]  
- inertia force
- viscous force

Grashof number: \[ \frac{\beta g \Delta T L^3}{\nu^2} \]  
- buoyancy force
- viscous force
- Aquarium!

Péclet number: \[ \frac{\rho \cdot C_p \cdot u \cdot L}{k} \]  
- heat transfer by convection
- heat transfer by conduction

Dimensionless numbers and scaling for the nominal condition:

\[ \frac{\rho}{\rho \cdot u^2} \]

\[ \frac{M}{L} \]

\[ \frac{Q}{M \cdot Cp} \]

\[ (\frac{g \cdot \beta \cdot \rho^2}{Cp}) \cdot (\frac{Q \cdot L^5}{M^3}) \]

x 1000

Two remarks have been taken into account in the design of the water model:

1. The maximum power density that can be tolerated in the water test is determined from the requirement that there is no boiling.
2. The velocities in the water experiment should be measurable within acceptable accuracy limits. Therefore, it is advisable to maximize the flow rate.
RESULTS ON AQUARIUM

DESCRIPTION OF AQUARIUM – “2D” NATURAL RECIRCULATION LOOP

- Core Heat and Pressure drop source
- Above core barrel (perforated cylinder): radial DP
- Heat Exchangers: Heat Sink

- Flow: develops as a consequence of the equilibrium between buoyancy and friction (Thermosyphon)

von Karman Institute for Fluid Dynamics
SEARCH/MAXSIMA Workshop, 9/10/2014 Karlsruhe
**MEASUREMENTS PERFORMED: VELOCITY FIELD AND TEMPERATURE PROFILE IN THE VESSEL**

**Optical techniques (PIV)**

- Argon Ion Laser (515 nm, P=2 W)
- SCMOS Camera + high pass filter
- Rotating Mirror
- Synchronizer
- Flat Mirror
- Water + Particles

**Thermocouples**

- Cooling loop is switched on!

**Configurations Tested**

**Case a**
- No Blockage!

**Case b**
- Barrel partially closed

**Case c**
- Barrel partially closed + SLOPE

**MEASUREMENTS PERFORMED:**

- **Velocity field**
- **Temperature Profile**

**VELOCITY FIELD**

**Temperature Profile**

**MEASUREMENTS PERFORMED:**

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**Configurations Tested**

**Case a**
- No Blockage!

**Case b**
- Barrel partially closed

**Case c**
- Barrel partially closed + SLOPE

**MEASUREMENTS PERFORMED:**

- Velocity field
- Temperature Profile
TEMPERATURE PROFILE COMPARISON: CASE A, B, C

VELOCITY FIELD COMPARISON: CASE A, B, C

Free Above Core area
Blockage in Barrel
No blockage

Velocity Magnitude (m/s)
JET STABILITY WITH TIME: CASE A

Case a

Jet inclination (degree)

0°

90°

Jet

0°

I hole

II hole

III hole

IV hole

V hole

VI hole

RESULTS ON MYRRHABELLE
DESCRIPTION OF MYRRHABELLE

The water model constructed at VKI is a full Plexiglass model at a scale 1/5 of Myrrha. MYRRHABELle = MYRRHA Basic SEt-up For Liquid FLow Experiments.

MEASUREMENTS PERFORMED: VELOCITY FIELD AND TEMPERATURE PROFILE IN THE VESSEL

No Blockage above the core!
Heating elements: 45 kW
Cooling elements 45 kW

Nd:YAG Double pulse Laser
Top View
RESULTS: NOMINAL CONDITIONS

Nominal conditions→Richardson similarity is respected

Jet stability in time:

RESULTS: NOMINAL CONDITIONS

Jet stability in time:
RESULTS: NATURAL CONVECTION

Stable Temperatures and temperature profiles after 1 hour

Velocities:
- t=3 min
- t=9 min
- t=15 min
- t=21 min
- t=27 min

Velocity Magnitude (m/s)

0.05
0.045
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0

RESULTS: NATURAL CONVECTION

The data allow further analysis:

Integration of velocity profile at every hole for the computation of the overall mass flow in natural convection.

CONCLUSIONS

- Aquarium is a simple natural convection model in which is possible to test different configurations (different blockages in the above core structure)

- Analogous behavior of the buoyant jets is observed in Myrrhabelle in natural convection regime

- Quantitative information has been provided by means of optical techniques (PIV) and thermocouples at the outlet of the above core barrel

- PIV measurements have been carried out at different locations of the upper plenum (heat exchanger entrance, free surface) and will continue…

- MYRRHABelle is providing a database for CFD codes validation.
ACKNOWLEDGMENTS

The development of the MYRRHABelle facility is performed in collaboration with SCK•CEN and is funded through the DEMOCRITOS research contract financed by BELSPO (Belgian Federal Science Policy).

THANK YOU FOR THE ATTENTION
The influence of blockages in wire-wrapped rod bundles

H.J. Doolaard\(^{(a)}\), V.R. Gopala\(^{(a)}\), H.A. Bijleveld\(^{(a)}\), F. Roelofs\(^{(a)}\)

\(^{(a)}\)NRG, Westerduinweg 3, 1755 LE Petten, Netherlands

Abstract

A preferred spacer design for fuel rods in a liquid-metal cooled fast reactor (LMFR) is wrapped wires. The helically coiled wire around each rod enhances mixing which reduces the peak temperatures in the fuel assemblies. Detailed Computational Fluid Dynamics (CFD) simulations are performed for a liquid metal flow through a wire-wrapped rod bundle to improve the understanding and prediction of the thermal-hydraulic behavior in wire-wrapped rod bundles. A detailed sensitivity study of the thermal-hydraulics of Lead-Bismuth Eutectic (LBE) flowing through a 19 pin wire-wrapped rod bundle is described in a previous publication.

A number of subjects will be addressed in the present analysis. Firstly, the influence of a blockage on the thermal-hydraulics in the 19 pin wire-wrapped rod bundle is examined. A mesh optimized wire shape from the previous sensitivity study is used in order to ease meshing and to reduce the computational power. Sensitivity studies of the blockage size, the blockage location and the conductivity of the blockage are carried out. The results are in support of the design of experiments which will be carried out in the KALLA lab in Karlsruhe.

The influence of a different kind of blockage, namely at the inlet nozzle of a 127 pin MYRRHA fuel assembly, is also evaluated. For this purpose, the results of the unblocked 19 pin wire wrapped rod bundle are used to create a low resolution model of a full MYRRHA fuel assembly containing 127 wire-wrapped rods. The rods and wires are replaced by a porous medium to reduce the computational effort in order to be able to model multiple fuel assemblies. The obtained pressure drop compares well to the Rehme correlation. A set of seven porous fuel assemblies with headers in a hexagonal lattice is modelled. The inlet of the central fuel assembly is blocked with several blockage ratios. When the inlet is blocked, the side-entrances of the inlet header could function as bypass. The influences of the inlet blockage on the flow distribution between the fuel assemblies and on the temperature distribution are determined.
Introduction

Safety evaluations using CFD
1. Internal blockage
2. Inlet blockage
Outline

1. Objectives

2. Internal blockage
   – Sensitivity study blockage properties on maximum cladding temperature

3. Inlet blockage
   – Fuel assembly interaction

4. Conclusions

Objectives

Safety analyses MYRRHA

Internal blockage
• Determine feasibility of blockage experiments KALLA

Inlet blockage
• Assessment of functionality of side inlets inlet header
Internal Blockage

Rod Bundle

• 19 wire-wrapped rods
• Domain length: 2 wrapping pitches
• Experiments in THEADES bundle at KIT
• Mesh and wire shape optimization according to Gopala et al. 2014*
• 31 M cells

<table>
<thead>
<tr>
<th></th>
<th>KALLA Bundle</th>
<th>MYRRHA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pins</td>
<td>19</td>
<td>127</td>
</tr>
<tr>
<td>Pin diameter (d)</td>
<td>8.2 mm</td>
<td>6.55 mm</td>
</tr>
<tr>
<td>Pin pitch (P)</td>
<td>10.5 mm</td>
<td>8.4 mm</td>
</tr>
<tr>
<td>Wrapping pitch</td>
<td>328 mm</td>
<td>262 mm</td>
</tr>
<tr>
<td>Wire diameter</td>
<td>2.2 mm</td>
<td>1.75 mm</td>
</tr>
<tr>
<td>P/d</td>
<td>1.28</td>
<td>1.28</td>
</tr>
</tbody>
</table>

Blockage Properties

<table>
<thead>
<tr>
<th>Name</th>
<th>Blocked flow area (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>1.9</td>
</tr>
<tr>
<td>E1</td>
<td>2.6</td>
</tr>
<tr>
<td>C6</td>
<td>11.4</td>
</tr>
</tbody>
</table>

Sub-channels are blocked between $z = \frac{1}{2}$ and $\frac{3}{3}$ wrapping pitch

Computational Setup

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code</td>
<td>STAR-CCM+</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>SST k-ω *</td>
</tr>
<tr>
<td>Schemes</td>
<td>Segregated flow and segregated heat transfer</td>
</tr>
<tr>
<td></td>
<td>All second order</td>
</tr>
<tr>
<td>Time dependence</td>
<td>Steady state</td>
</tr>
<tr>
<td>Working fluid</td>
<td>Lead-Bismuth Eutectic (LBE)</td>
</tr>
<tr>
<td></td>
<td>Temperature dependent properties</td>
</tr>
<tr>
<td>Inlet</td>
<td>Re = 3.78 \cdot 10^4 (based on sub-channel)</td>
</tr>
<tr>
<td></td>
<td>$T_{\text{in}} = 270 , ^\circ \text{C}$</td>
</tr>
<tr>
<td>Outlet boundary condition</td>
<td>$P = 0 , \text{Pa}$</td>
</tr>
<tr>
<td>Wire and outer ring rod</td>
<td>Steel solid, no-slip walls</td>
</tr>
<tr>
<td>Inner ring rod</td>
<td>Boron-Nitride</td>
</tr>
<tr>
<td></td>
<td>Heat flux of 1.38 MW/m² applied at inner rod surface, resulting in a heat flux of 0.924 MW/m² at outer cladding</td>
</tr>
<tr>
<td>Total power</td>
<td>Total power 0.297 MW</td>
</tr>
<tr>
<td>Blockage</td>
<td>$\lambda = 2 , \text{Wm}^{-1}\text{K}^{-1}$</td>
</tr>
</tbody>
</table>

Cladding Temperature
Single Blocked Sub-Channel

- Unblocked reference case
- C1 or E1 blocked
- C1 and E1 blocked at the same axial position

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_{\text{max,clad}}$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>480</td>
</tr>
<tr>
<td>C1 blocked</td>
<td>520</td>
</tr>
<tr>
<td>E1 blocked</td>
<td>479</td>
</tr>
<tr>
<td>C1 &amp; E1 blocked</td>
<td>@C1: 519</td>
</tr>
<tr>
<td></td>
<td>@E1: 479</td>
</tr>
</tbody>
</table>

- These blockages are experimentally feasible.
- C1 and E1 barely influence each other if located at the same axial position.

Cladding Temperature
C1 and S1 blocked

Temperature

- Temperature K:
  - 773
  - 716
  - 659
  - 602
  - 546

- Temperature K:
  - 749
  - 698
  - 647
  - 596
  - 546


**Cladding Temperature**

**Six Blocked Sub-Channels**

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_{\text{max, clad}}$ (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>480</td>
</tr>
<tr>
<td>C6 blocked</td>
<td>1655</td>
</tr>
<tr>
<td>C6 Blocked, 50% nominal power</td>
<td>998</td>
</tr>
<tr>
<td>C6 Blocked, 20% nominal power</td>
<td>576</td>
</tr>
<tr>
<td>C6 Blocked, 10% nominal power</td>
<td>422</td>
</tr>
</tbody>
</table>

- Maximum cladding temperature at nominal power is too high
- 10% of nominal power results in smaller temperature differences than C1 or E1 at nominal power
- Maximum temperature difference approximately scales with the power input

**Power Variation**

**Six Blocked Sub-Channels**

- Maximum temperature increase as function of power input
- Linear fit useful for design of blockage experiments
- Fit useful for scaling results to MYRRHA using KALLA and NACIE experiments
Blockage Conductivity
Six Blocked Sub-Channels

- Thermal conductivity increased from 2 Wm\(^{-1}\)K\(^{-1}\) (oxides, worst case) to 12 Wm\(^{-1}\)K\(^{-1}\) (LBE)
- 6 blocked sub-channels with nominal MYRRHA power

<table>
<thead>
<tr>
<th>Case</th>
<th>Blockage Conductivity (Wm(^{-1})K(^{-1}))</th>
<th>(T_{max,cladding}) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>-</td>
<td>480</td>
</tr>
<tr>
<td>C6 blocked</td>
<td>2</td>
<td>1655</td>
</tr>
<tr>
<td>C6 blocked, high conductivity</td>
<td>12</td>
<td>903</td>
</tr>
</tbody>
</table>

- High conductivity significantly reduces the maximum cladding temperature
- Maximum cladding temperature is still experimentally unfeasible

Inlet Blockages
Domain

- Seven fuel assemblies with headers
- Central fuel assembly is blocked
- Rods and wires replaced by porous medium
  - Flow essence is modelled
  - Inlet and outlet not porous
  - Reduction computational effort
- 2.9 million cells

Computational Setup

<table>
<thead>
<tr>
<th>Property</th>
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</tr>
</thead>
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<tr>
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<tr>
<td>Time dependence</td>
<td>Steady state</td>
</tr>
<tr>
<td>Working fluid</td>
<td>Lead-Bismuth Eutectic (LBE)</td>
</tr>
<tr>
<td>Inlet</td>
<td>Temperature dependent properties</td>
</tr>
<tr>
<td>Total mass flow rate: 500 kg/s</td>
<td>T&lt;sub&gt;in&lt;/sub&gt; = 270 °C</td>
</tr>
<tr>
<td>Inlet headers</td>
<td>Steel, temperature dependent properties, no-slip walls</td>
</tr>
<tr>
<td>Outlet headers</td>
<td>Only fluid region modelled, no-slip walls, P = 0 Pa</td>
</tr>
<tr>
<td>Inter wrapper space</td>
<td>Solid, mixed properties of LBE and steel</td>
</tr>
<tr>
<td>Volumetric heat source</td>
<td>2.9·10&lt;sup&gt;8&lt;/sup&gt; W/m³</td>
</tr>
<tr>
<td>Porous medium</td>
<td>Same pressure drop as single fuel assembly with rods and wires</td>
</tr>
</tbody>
</table>
Velocity Magnitude

Unblocked 80% 100%

LBE enters central fuel assembly through side-inlets

Temperature Downstream
80% blocked

Outlets

Temperature (K)

684 656 628 600

684 681 677

Proceedings of the SEARCH/MAXSIMA 2014 International Workshop, Karlsruhe, Germany, October 7-10, 2014
Mass Flow Rate

100 % inlet blockage:
\[ \Delta m_{\text{central}} \approx -5 \% \]
\[ \Delta m_{\text{surrounding}} \approx +1 \% \]

Outlet Temperature

100 % inlet blockage:
\[ \Delta T_{\text{central}} \approx +6 \% \]
\[ \Delta T_{\text{surrounding}} \approx -1 \% \]
Conclusions

• Single sub-channel blockages are experimentally feasible
• Six blocked sub-channels are experimentally feasible applying lower power input
• Increased thermal conductivity highly reduces the maximum cladding temperature

• Side-inlets facilitate flow-redistribution in case of blockage inlet inlet-header
• 100 % blockage of the inlet of the inlet-header results in only 6 % temperature increase

Thank you for your attention!
Fuel assembly blockage phenomena in a LFR: modeling approaches, assumptions, and results

E. Bubelis\textsuperscript{(a)}, G. Bandini\textsuperscript{(b)}, X.-N. Chen\textsuperscript{(a)}, I. Di Piazza\textsuperscript{(c)}, H. Doolaard\textsuperscript{(d)}, R. Li\textsuperscript{(a)}

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\textsuperscript{(b)}ENEA, Via Martiri di Monte Sole 4, 40129 Bologna, Italy
\textsuperscript{(c)}ENEA UTIS-TCI, C.R. Brasimone, 40032 Camugnano(Bo), Italy
\textsuperscript{(d)}NRG, Westerduinweg 3, 1755 LE Petten, Netherlands

Abstract

The event which is analyzed and discussed in this presentation is the fuel sub-assembly (SA) blockage event in a heavy liquid metal cooled fast reactor, like ALFRED (lead cooled fast reactor (LFR) demo) and MYRRHA (LBE cooled fast reactor). A lot of investigations were performed up to now trying to estimate the consequences of such an event for the reactor operation. The maximal possible SA blockage, which still poses no danger to the normal reactor operation, was determined. Two types of SA blockages were investigated: external SA blockages and internal SA blockages. In case of an external SA blockage, coolant flow through the SA is reduced uniformly, thus all fuel pins see the same degree of coolant flow reduction. In case of internal SA blockage, fuel pins inside a fuel SA see rather different degree of coolant flow reduction (especially locally), thus the consequences of such an internal SA blockage might be rather different, when compared to an external SA blockage event. Moreover, for internal SA blockage studies, both wire-wrapped (MYRRHA) and grid-spaced (ALFRED) fuel sub-assemblies are considered. Codes used for such an analysis vary from system codes (SIM-LFR, RELAP5, SIMMER-III) to computational fluid dynamics (CFD) codes (ANSYS, STAR-CCM+). This presentation aims at discussing different modelling approaches, assumptions and results obtained using different codes when analyzing SA flow blockage phenomena in a LFR.
Fuel assembly blockage phenomena in LFR: modeling approaches, assumptions, and results

Outline

• Types of fuel SA blockages

• Fuel assembly blockage analysis with SIM-LFR

• Fuel assembly blockage analysis with RELAP5

• Fuel assembly blockage analysis with SIMMER-III

• Fuel assembly blockage CFD analysis with ANSYS

• Fuel assembly blockage CFD analysis with STAR-CCM+

• Conclusions
Types of fuel SA blockages

- **External**
  Central hole in SA foot part is blocked, coolant enters only through the side openings

- **Internal**
  Internal blockage inside fuel SA in a form of a thin plate (assumption)
  Internal blockage inside fuel SA in a form of a Pb oxide slug (assumption)

Outline

- Types of fuel SA blockages
- Fuel assembly blockage analysis with SIM-LFR
- Fuel assembly blockage analysis with RELAP5
- Fuel assembly blockage analysis with SIMMER-III
- Fuel assembly blockage CFD analysis with ANSYS
- Fuel assembly blockage CFD analysis with STAR-CCM+
- Conclusions
Fuel SA external blockage analysis with SIM-LFR (1)

- Hottest fuel SA of the MYRRHA reactor (design 1.4) was taken for the investigation (unprotected, constant power);
- It was assumed that the central hole in the foot part of the SA is blocked and thus LBE flow rate is being reduced;
- Fuel SA outlet temperature is assumed to be monitored, but the corresponding signal is assumed to fail in this transient;
- Several different cases were run at EOC conditions, varying the LBE flow blockage from 20% to 97.5% (20, 40, 60, 65, 70, 75, 80, 90, 95 and 97.5% cases).

Fuel SA external blockage analysis with SIM-LFR (2)

EOC conditions
Fuel SA external blockage analysis with SIM-LFR (3)

<table>
<thead>
<tr>
<th>Blockage (%)</th>
<th>Clad failure time* (sec)</th>
<th>Max. cool. SA outlet temp. (°C)</th>
<th>Max clad temp (peak pin) (°C)</th>
<th>Max fuel temp (peak pin) (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>3.9E+10</td>
<td>522</td>
<td>576</td>
<td>2080</td>
</tr>
<tr>
<td>40</td>
<td>1.1E+08</td>
<td>599</td>
<td>654</td>
<td>2124</td>
</tr>
<tr>
<td>60</td>
<td>7386</td>
<td>760</td>
<td>806</td>
<td>2210</td>
</tr>
<tr>
<td>65</td>
<td>266</td>
<td>829</td>
<td>874</td>
<td>2248</td>
</tr>
<tr>
<td>70</td>
<td>5.4</td>
<td>920</td>
<td>963</td>
<td>2299</td>
</tr>
<tr>
<td>75</td>
<td>0.0</td>
<td>1049</td>
<td>1086</td>
<td>2366</td>
</tr>
<tr>
<td>80</td>
<td>0.0</td>
<td>1244</td>
<td>1275</td>
<td>2466</td>
</tr>
<tr>
<td>90</td>
<td>0.0</td>
<td>1436</td>
<td>1455</td>
<td>2554</td>
</tr>
<tr>
<td>95</td>
<td>0.0</td>
<td>1460</td>
<td>1478</td>
<td>2565</td>
</tr>
<tr>
<td>97.5</td>
<td>0.0</td>
<td>1462</td>
<td>1481</td>
<td>2565</td>
</tr>
</tbody>
</table>

* - max fission gas pressure 5.5 bar

- The critical MYRRHA design will not experience any fuel pin failure for flow blockages of less than 70%, even under unprotected conditions;
- For flow blockages above 70%, clad failures should be expected;
- Clad melting (T_{clad} > 1320°C) should be expected for flow blockages above ~ 80%.

Fuel SA external blockage analysis with SIM-LFR (4)

- Hottest fuel SA of the ALFRED reactor was taken for this investigation (unprotected, constant power);
- It was assumed that the central hole in the foot part of the SA is blocked and the Pb flow rate is being reduced;
- Fuel SA outlet temperature is assumed to be monitored, but the corresponding signal is assumed to fail in this transient;
- Several different cases were run at BOC & EOC conditions, varying the Pb flow blockage from 20% to 97.5% (20, 40, 60, 65, 70, 75, 80, 90, 95 and 97.5% cases).
Fuel SA external blockage analysis with SIM-LFR (5)

![Graph showing Clad failure time vs. SA blockage percentage]

**Max coolant temp. (SA outlet)**

![Graph showing Max coolant temp. (SA outlet) vs. SA blockage percentage]

**Max clad temperature**

![Graph showing Max clad temperature vs. SA blockage percentage]

**Max fuel temperature**

![Graph showing Max fuel temperature vs. SA blockage percentage]

**EOC conditions**

* - max fission gas pressure ~18 bar

- The ALFRED reactor will not experience any fuel pin failure for flow blockages of less than 75%, even under unprotected conditions;
- For flow blockages above 75%, clad failures should be expected;
- Fuel melting is not an issue for ALFRED reactor. Fuel melting temperatures are not reached even in 97.5% SA flow blockage case.

### BOC Conditions

<table>
<thead>
<tr>
<th>Blockage (SA outlet)</th>
<th>Clad failure time* (sec)</th>
<th>Max. cool. temp. (SA outlet)</th>
<th>Max. clad temp. (peak pin)</th>
<th>Max. fuel temp. (peak pin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td></td>
<td>°C</td>
<td>°C</td>
<td>°C</td>
</tr>
<tr>
<td>20</td>
<td>4.00E+10</td>
<td>542</td>
<td>573</td>
<td>2052</td>
</tr>
<tr>
<td>40</td>
<td>2.20E+08</td>
<td>608</td>
<td>638</td>
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<tr>
<td>60</td>
<td>4.20E+04</td>
<td>742</td>
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<td>65</td>
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<td>97.5</td>
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<td>1158</td>
<td>1176</td>
<td>2359</td>
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</tbody>
</table>

* - max fission gas pressure ~18 bar

### EOC Conditions

<table>
<thead>
<tr>
<th>Blockage (SA outlet)</th>
<th>Clad failure time* (sec)</th>
<th>Max. cool. temp. (SA outlet)</th>
<th>Max. clad temp. (peak pin)</th>
<th>Max. fuel temp. (peak pin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>%</td>
<td></td>
<td>°C</td>
<td>°C</td>
<td>°C</td>
</tr>
<tr>
<td>20</td>
<td>2.70E+10</td>
<td>545</td>
<td>574</td>
<td>2089</td>
</tr>
<tr>
<td>40</td>
<td>1.50E+08</td>
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<tr>
<td>60</td>
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<td>745</td>
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<td>1661</td>
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<tr>
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<td>874</td>
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<td>75</td>
<td>0</td>
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<td>996</td>
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<tr>
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<tr>
<td>97.5</td>
<td>0</td>
<td>1148</td>
<td>1165</td>
<td>2350</td>
</tr>
</tbody>
</table>

* - max fission gas pressure ~25 bar

Proceedings of the SEARCH/MAXSIMA 2014 International Workshop, Karlsruhe, Germany, October 7-10, 2014
Outline

- Types of fuel SA blockages
- Fuel assembly blockage analysis with SIM-LFR
- Fuel assembly blockage analysis with RELAP5
- Fuel assembly blockage analysis with SIMMER-III
- Fuel assembly blockage CFD analysis with ANSYS
- Fuel assembly blockage CFD analysis with STAR-CCM+
- Conclusions

Fuel SA external blockage analysis with RELAP5 (1)

The active core (171 SAs) is represented by:

- 1 fuel SA (101) representing the hottest fuel SA
- 1 average fuel SA (102) representing 170 SAs of the core

Blockage simulation → Reduction of junction area
Fuel SA external blockage analysis with RELAP5 (2)

- Hottest fuel SA of the ALFRED reactor was taken for this investigation
- Partial blockage of the flow area at the fuel SA inlet was taken into account in this simulation by progressively reducing the inlet section area from 100% down to 2.5%
- Unprotected transient at EOC: no reactor scram on high coolant temperature detection at fuel SA outlet
- Constant core power → no reactivity feedback effects
- For conservative analysis the heat exchange with the six surrounding fuel SAs has been neglected

Fuel SA external blockage analysis with RELAP5 (3)

- Total pressure loss through the fuel SA is 1.0 bar
- Pressure loss at the fuel SA inlet (0.22 bar, if no blockage) is simulated by RELAP5 with a constant K factor at the inlet junction
- 80% area blockage results in flow rate reduced down to 40%
Fuel SA external blockage analysis with RELAP5 (4)

- T-clad limit of 700 °C is exceeded for area blockage > 85%

- No clad melting is calculated if area blockage is below 95%

- Fuel melting is calculated if area blockage is above 97.5%

- 50% area blockage could be detected by TCs at fuel SA outlet

Outline

- Types of fuel SA blockages
- Fuel assembly blockage analysis with SIM-LFR
- Fuel assembly blockage analysis with RELAP5
- Fuel assembly blockage analysis with SIMMER-III
- Fuel assembly blockage CFD analysis with ANSYS
- Fuel assembly blockage CFD analysis with STAR-CCM+
- Conclusions
Fuel assembly blockage analysis with SIMMER-III (1)

- Fuel assembly blockage and its consequent fuel pin failure have been studied extensively within SEARCH project for MYRRHA V1.4.

Ref: SEARCH D 5.5 by Li, Chen and Rineiski

- Further development of pin-bundle model for simulation of coolant sub-channel blockage was initiated and will be applied for the MAXSIMA project.

Ref: HLMC-2013 Conference Paper by Chen, Li and Rineiski

Fuel assembly blockage analysis with SIMMER-III (2)

- Parametric blockage studies
  - Blockage: pin bundle entrance and uniform blockage
  - Wrapper gap flow and heat transfer are considered
  - Flow rate blockage as variation parameter
Fuel assembly blockage analysis with SIMMER-III (3)

- Snap shots of material distribution in case of flow rate 88.2% blockage

Fuel assembly blockage analysis with SIMMER-III (4)

Pin bundle model development and its geometrical arrangement

This FA sub-channel model is only applied to the central FA in the current calculation.

Pins "smeared" in the flow rings, e.g. there is 1 steel pin and 1 fuel pin in the first ring.
Fuel assembly blockage analysis with SIMMER-III (5)

Pin bundle model development and its validation (steady state)

**SUBCHANFLOW**

- $T_{\text{av}} = 407.3^\circ\text{C}$
- $T_{\text{max}} = 426.08^\circ\text{C}$
- $T_{\text{min}} = 347.9^\circ\text{C}$

**SIMMER**

- $T_{\text{av}} = 410.8^\circ\text{C}$
- $T_{\text{max}} = 437.6^\circ\text{C}$
- $T_{\text{min}} = 347.4^\circ\text{C}$

Fuel assembly blockage analysis with SIMMER-III (6)

Preliminary results of the sub-channel blockage

Blockage position: bottom of the active zone, 1 (central) and 3 sub-channel rings blockage (2% and 18% of the flow area)

**1-Ring Blockage**

- Max. coolant temperature increase 62 °C

**3-Rings Blockage**

- Max. coolant temperature increase 369 °C
Fuel assembly blockage analysis with SIMMER-III (7)

Preliminary results of the sub-channel blockage

Blockage position: bottom of the active zone, 5 sub-channel rings blockage (50% flow area)

Clad melting takes place between 4 and 5 s after the blockage appears.

Fuel assembly blockage analysis with SIMMER-III (8)

- SIMMER-III results for uniform blockages (all rings of pins) in a MYRRHA fuel assembly: no pin failure until flow rate blockage of ~90%.

- New SIMMER-III model for partial blockages (few rings of sub-channels) in a fuel assembly: 18% flow area blockage may lead to pin clad failure, while 50% flow area blockage (only 25% flow rate reduction) may lead already to pin melting behind the blockage, but no pin failure (melting) propagation will take place.
Outline

• Types of fuel SA blockages
• Fuel assembly blockage analysis with SIM-LFR
• Fuel assembly blockage analysis with RELAP5
• Fuel assembly blockage analysis with SIMMER-III
• Fuel assembly blockage CFD analysis with ANSYS
• Fuel assembly blockage CFD analysis with STAR-CCM+
• Conclusions

Fuel SA Internal blockage analysis with CFD

A CFD study has been carried out on fluid flow and heat transfer in the HLM-cooled Fuel Pin Bundle of the ALFRED LFR DEMO.
Fuel SA Internal blockage analysis with CFD

Models and Methods

Blockage model:
thin non-conductive surface at the beginning of the active region

✓ ANSYS CFX 13
✓ SST $k-\omega$ Menter (1994)
✓ $y^+ \sim 1$ at the wall
✓ $N_{\text{nodes}} \sim 22 \cdot 10^6$ (160 axial)
✓ $\Delta t \sim 1$ ms (CFL $\sim 1$)
✓ $q_{\text{wall}} = 1$ MW/m$^2$

### Rod diameter $d$
| 10.5 mm |

### Pitch to diameter ratio $p/d$
| 1.32 |

### Number of fuel rods
| 127 |

### Mean Wall Heat Flux $q_{\text{wall}}$
| 0.7 MW/m$^2$ |

### Conservative Wall Heat Flux (for engineering computations)
| 1 MW/m$^2$ |

### Active Height $L$
| 0.6 m |

### Lead Inlet Temperature $T_{\text{inlet}}$
| 400 °C |

### Lead Outlet Temperature $T_{\text{outlet}}$
| 470 °C |

### Lead Bulk Velocity
| 1.4 m/s |

### Lead flow average FA
| 144.1 kg/s |

### Bypass flow average FA (3%)
| 2.76 kg/s |

### Clad Maximum Temperature (expected under nominal conditions)
| 550 °C |

### Nbblock = 19, $\beta$ (area blockage fraction) = 0.15, case 11, stationary

### Nbblock = 37, $\beta$ = 0.29, case 12, stationary
Fuel SA Internal blockage analysis with CFD

### Transient solutions

<table>
<thead>
<tr>
<th>CASE Number</th>
<th>TYPE</th>
<th>BlockTYPE</th>
<th>( N_{\text{block}} )</th>
<th>( \beta )</th>
<th>( \dot{m}_f/\dot{m}_g )</th>
</tr>
</thead>
<tbody>
<tr>
<td>28</td>
<td>TRANSIENT</td>
<td>CENTRAL</td>
<td>1</td>
<td>0.008</td>
<td>1</td>
</tr>
<tr>
<td>29</td>
<td>TRANSIENT</td>
<td>CENTRAL</td>
<td>7</td>
<td>0.055</td>
<td>1</td>
</tr>
<tr>
<td>30</td>
<td>TRANSIENT</td>
<td>CENTRAL</td>
<td>19</td>
<td>0.150</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Clad temperature contours for case 30 \((N_{\text{block}}=19)\):

\(\text{time} = 9 \text{ s}\).

---

Fuel SA Internal blockage analysis with CFD

### Comparison with RELAP simulation on external blockage

<table>
<thead>
<tr>
<th>CASE Number</th>
<th>TYPE</th>
<th>BlockTYPE</th>
<th>( \beta )</th>
<th>( \dot{m}_f/\dot{m}_g )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CFR80</td>
<td>STATIONARY</td>
<td>FOOT</td>
<td>0.8</td>
<td>66.788</td>
</tr>
<tr>
<td>CFR90</td>
<td>STATIONARY</td>
<td>FOOT</td>
<td>0.9</td>
<td>37.066</td>
</tr>
</tbody>
</table>

Overall results from CFD analysis of internal blockage: maximum clad temperature.
A CFD analysis by fully resolved RANS simulations has been carried on fluid flow and heat transfer in the case of flow blockage in heavy liquid metal cooled fuel assemblies. The hexagonal closed ALFRED FA have been considered for the study. The model includes the different FA regions (entry, active, follower, plenum), the conjugate heat transfer in the clad and the wrap, the bypass and power released by gamma. All the pins of the FA have been modeled and no special symmetry planes have been considered.

Two main effects can be distinguished in a flow blockage: a local effect in the wake/recirculation region downstream the blockage and a global effect due to the lower mass flow rate in the blocked subchannels; the former effect gives rise to a temperature peak behind the blockage and it is dominant for large blockages ($\beta > 0.1-0.2$), while the latter effect determines a temperature peak at the end of the active region and it is dominant for small blockages ($\beta < 0.1$).

The blockage area has been placed at the beginning of the active region, so that both overmentioned phenomena can fully take place. The mass flow rate at the different degree of blockage has been imposed from preliminary system code simulations (minor influence).

Results indicate that a blockage of ~15% (in terms of area) leads to a maximum clad temperature around 800 °C, and this condition is reached in a characteristic time of 3-4 s without overshoot. Local clad temperatures around 1000 °C can be reached for blockages of 30% or more.

CFD simulations indicate that Blockages >15% could be detected by putting thermocouples in the plenum region of the FA.

Outline

• Types of fuel SA blockages
• Fuel assembly blockage analysis with SIM-LFR
• Fuel assembly blockage analysis with RELAP5
• Fuel assembly blockage analysis with SIMMER-III
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• Fuel assembly blockage CFD analysis with STAR-CCM+
• Conclusions
Fuel SA blockage CFD analysis with STAR-CCM+
THEADES bundle

• 19-pin wire-wrapped rod bundle experiment at KIT
• Several internal blockages are implemented
• Numerical sensitivity analysis is performed to reduce the number of experiments
• Influence of the size, location and the conductivity of the blockage.

<table>
<thead>
<tr>
<th></th>
<th>KALLA Bundle</th>
<th>MYRRHA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of pins</td>
<td>19</td>
<td>127</td>
</tr>
<tr>
<td>Pin diameter</td>
<td>8.2 mm</td>
<td>6.55 mm</td>
</tr>
<tr>
<td>Pin pitch</td>
<td>10.5 mm</td>
<td>8.4 mm</td>
</tr>
<tr>
<td>Wrapping pitch</td>
<td>328 mm</td>
<td>262 mm</td>
</tr>
<tr>
<td>Wire diameter</td>
<td>2.2 mm</td>
<td>1.75 mm</td>
</tr>
<tr>
<td>Smallest gap</td>
<td>0.1 mm</td>
<td>0.1 mm</td>
</tr>
</tbody>
</table>

$P_w$ = wrapping pitch
$z$ = streamwise coordinate $z = [0, 2 \cdot P_w]$

Fuel SA blockage CFD analysis with STAR-CCM+
Blockages

<table>
<thead>
<tr>
<th>Name</th>
<th>Blocked flow area (%)</th>
<th>Conductivity (Wm$^{-1}$K$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>1.9</td>
<td>2</td>
</tr>
<tr>
<td>E1</td>
<td>2.6</td>
<td>2</td>
</tr>
<tr>
<td>C6</td>
<td>11.4</td>
<td>2</td>
</tr>
</tbody>
</table>

Sub-channels are blocked between $z = \frac{1}{2} P_w$ and $\frac{3}{2} P_w$
## Computational Setup

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code</td>
<td>STAR-CCM+</td>
</tr>
<tr>
<td>Turbulence model</td>
<td>SST k-ω</td>
</tr>
<tr>
<td>Schemes</td>
<td>Segregated flow</td>
</tr>
<tr>
<td></td>
<td>Segregated heat transfer</td>
</tr>
<tr>
<td></td>
<td>All second order</td>
</tr>
<tr>
<td>Time dependence</td>
<td>Steady state</td>
</tr>
<tr>
<td>Working fluid</td>
<td>Lead-Bismuth Eutectic (LBE)</td>
</tr>
<tr>
<td></td>
<td>Temperature dependent properties</td>
</tr>
<tr>
<td>Inlet</td>
<td>Re = 3.78 \times 10^4 (based on sub-channel)</td>
</tr>
<tr>
<td></td>
<td>T_{in} = 270 °C</td>
</tr>
<tr>
<td>Outlet boundary condition</td>
<td>P = 0 Pa</td>
</tr>
<tr>
<td>Wire and outer ring rod</td>
<td>Steel solid, no slip walls</td>
</tr>
<tr>
<td>Inner ring rod</td>
<td>Boron-Nitride</td>
</tr>
<tr>
<td></td>
<td>Heat flux of 1.38 MW/m² applied at inner rod surface,</td>
</tr>
<tr>
<td></td>
<td>resulting in a heat flux of 0.924 MW/m² at outer cladding</td>
</tr>
<tr>
<td>Total power</td>
<td>Total power 0.297 MW</td>
</tr>
</tbody>
</table>

### Case Results

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_{\text{max,cladding}} / T_{\text{bulk}}$</th>
<th>$z/P_w$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>87 / 480</td>
<td>2</td>
</tr>
<tr>
<td>C1 blocked</td>
<td>211 / 520</td>
<td>0.63</td>
</tr>
<tr>
<td>E1 blocked</td>
<td>170 / 479</td>
<td>0.63</td>
</tr>
<tr>
<td>C1 &amp; E1 blocked</td>
<td>@ C1: 210</td>
<td>@ E1: 170</td>
</tr>
</tbody>
</table>

- Temperatures are experimentally feasible.
- C1 and E1 barely influence each other if located at the same axial position. So in one experiment, both C1 and E1 can be blocked.
Fuel SA blockage CFD analysis with STAR-CCM+
Six blocked sub-channels

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_{\text{max,cladding}} - T_{\text{bulk}}$ ($^\circ$C)</th>
<th>$T_{\text{max,cladding}}$ ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>87</td>
<td>480</td>
</tr>
<tr>
<td>C6 blocked</td>
<td>1349</td>
<td>1655</td>
</tr>
<tr>
<td>C6 Blocked, 50% nominal power</td>
<td>710</td>
<td>998</td>
</tr>
<tr>
<td>C6 Blocked, 20% nominal power</td>
<td>299</td>
<td>576</td>
</tr>
<tr>
<td>C6 Blocked, 10% nominal power</td>
<td>148</td>
<td>422</td>
</tr>
</tbody>
</table>

- Maximum cladding temperature at nominal power is too high
- 10% of nominal power results in smaller temperature differences than C1 or E1 at nominal power
- Maximum temperature difference approximately scales with the power input.
- Linear fit useful for design of experiments

Fuel SA blockage CFD analysis with STAR-CCM+
Blockage conductivity

- 6 blocked sub-channels with nominal MYRRHA power
- Conductivity is increased from 2 Wm$^{-1}$K$^{-1}$ (oxides) to 12 Wm$^{-1}$K$^{-1}$ (LBE)

<table>
<thead>
<tr>
<th>Case</th>
<th>Blockage Conductivity (Wm$^{-1}$K$^{-1}$)</th>
<th>$T_{\text{max,cladding}} - T_{\text{bulk}}$ ($^\circ$C)</th>
<th>$T_{\text{max,cladding}}$ ($^\circ$C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>-</td>
<td>87</td>
<td>480</td>
</tr>
<tr>
<td>C6 blocked</td>
<td>2</td>
<td>1349</td>
<td>1655</td>
</tr>
<tr>
<td>C6 blocked, high conductivity</td>
<td>12</td>
<td>597</td>
<td>903</td>
</tr>
</tbody>
</table>

- High conductivity significantly reduces the maximum cladding temperature
Conclusions (1)

- Two types of SA flow blockages exist: external and internal;

- For **external** blockages case, all codes agree that fuel pin failure occurs when blockage exceeds ~85% of the flow area, while clad melting can be expected when blockage exceeds 90-95% of the flow area. Blockage effects can be detected already starting from ~25% of the flow blockage area;

- For **internal** blockages case, SIMMER-III and all CFD codes show that fuel pin failure occurs already when blockage exceeds ~15% of the flow area. Hot spot is located just behind or even within the blockage. This depends to a great extent on the blockage region thermal conductivity: the higher blockage conductivity, the lower fuel pin clad temperature and the risk for the pin to fail or for the clad to melt;
Conclusions (2)

➢ In order to re-confirm these predictions of the CFD codes, corresponding R&D activity should be foreseen, experimentally analyzing various possible internal flow blockages in a SA and their formation mechanisms;

➢ The paramount role when avoiding the SA flow blockages plays oxygen control in a LFR (avoiding formation of lead oxides). In this sense, coolant cleaning from possible oxides and other sorts of debris is a prerequisite preventing them from reaching the active core region.

Acknowledgements

➢ The work presented in this presentation was performed in the frame of the following FP7 EC projects: CDT, LEADER, SEARCH and MAXSIMA. The authors of the presentation really appreciate the financial support received from the above mentioned projects, that made it possible to perform these studies.

➢ We would like also to acknowledge the help and intellectual support of our colleagues, especially V. Gopala, W. Jäger, A. Rineiski, F. Roelofs, and M. Schikorr, who made it possible for us to present the results of our common work at this international workshop.
Macroscopic Pin Bundle Model and its Blockage Simulations

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Hermann-von-Helmholtz-Platz 1, D-76344 Eggenstein-Leopoldshafen, Germany

Abstract

In the seventh framework program (FP7) of European Commission, a project named Methodology, Analysis and eXperiments for the “Safety In MYRRHA Assessment” (MAXSIMA) has been launched. The LBE cooled accelerator driven system (ADS) MYRRHA should be investigated. The KIT-IKET Transmutation group with the main numerical analysis tool, the SIMMER-III code, is involved for studying severe core disruptive accidents of this reactor.

The SIMMER-III code is a neutronic thermal hydraulic coupled multiphase flow core severe accident analysis tool. Usually it is applied in a coarse mesh scale, i.e. in subassembly (SA) dimensions. On the other hand, the blockage accident is of importance in the LBE cooled reactor, because the solid oxide particles could block the subchannels. Such a flow blockage is initiated from one or several subchannels and developed from the subchannel scale to the subassembly scale. Therefore it is necessary to study the subchannel flow blockage within this code framework.

This paper proposes a macroscopic differential model of pin bundle flow for computational fluid dynamics (CFD) simulation. The pin bundle flow is treated in general as a flow in a porous medium with a certain coolant volume fraction and an associated wet area. In particular the effective pressure drops, as they appear in the momentum exchange terms, which are anisotropic, are treated in different ways in the axial and radial directions. Thus, the model can be used for both whole reactor vessel flow in a large scale and pin bundle subchannel flow in a small scale. In this paper, the set-up of the model and its implementation in the SIMMER-III code are described. This makes it possible to apply finer meshes and to simulate the pin bundle cross flow. A steady state of subchannel flow, which is approximately axially symmetric, but significantly non-uniform in the radial direction, is investigated and compared with a subchannel code. Satisfactory agreements are achieved. As a practical example the subchannel blockage originating from the central channels is considered and simulated. The scenario of pin failure and fuel swept-out is expected, but it can take place at only 50\% area blockage, if the active core entrance of the central subchannel rings is blocked, according to our current SIMMER pin bundle numerical simulation.
Introduction

Motivation:

EU FP7 Program, CDT, SEARCH and MAXSIMA Projects on MYRRHA reactor
CDT FASTEF design

Our previous investigations with SIMMER code concentrated on sub-assembly (SA) blockage transients, i.e. SA uniform blockage.

Sub-channel blockage is an important issue in LBE coolant

SIMMER code development and application for this problem

$D_{\text{max}}$ is only about 1 mm
Introduction

Background of SIMMER as a CFD code:

If you are doing whole reactor core simulation, the sub-assembly (SA) scale (10 cm) is a suitable choice for the mesh size, where each SA or SA ring is modeled as a channel. This is the original model (coarse mesh) in both SIMMER III and IV. In most cases it is sufficient and good enough. This is one of the reasons for the SIMMER success.

However, in certain cases it is not sufficient, e.g. sodium boiling in SFR and sub-channel blockage as considered here.

On the other hand it is still not possible to apply very fine meshes (about or less than 1 mm) to simulate pin bundle flow in the whole reactor core. The situation is similar in experiment.

What is the solution for this problem?

Macroscopic pin bundle model (sub-channel scale of about 10 mm)

What does it mean by the “macroscopic” modeling?

Continuum Mechanics Approach: discrete medium => continuum model (differential equation)

In this sense or with this approach (asymptotic method) the discrete pin bundle can be regarded as a continuum medium, in a large scale.

This continuum medium is actually “porous model” in any CFD code, which have been already applied consciously or unconsciously with the “macroscopic” approach.
SIMMER III: 2D fluid dynamics code coupled with a structure model and a space-, time- and energy-dependent neutron dynamics model.

Coolants: Sodium (initially), LBE, Lead, Water, Helium, Molten Salt

**Fluid Dynamics**
- 8 velocity fields (7 for liquid, 1 for gas)
- Multi-phase, multi-component flow
- Phase transitions
- Flow regime (pool-channel)
- Interfacial area tracking
- Elaborate EOS (various fuels, coolants and gases)
- Heat and mass and momentum transfer

**C^4P**
1968/560 Group Master Library
Basis: JEFF, JENDL, ENDF/B
Full Range Neutron Spectrum

**Neutronics**
- Neutron transport theory
- Improved quasi-static method
- Cross-section generation
- Heterogeneity treatment
- Decay heating
- External neutron source
- Precursor movement

**Structure model**
- General structure model
- Pin model
- Advanced fuels
- Loop model (IHX & pumps)
- Axial + radial heat transfer
- Virtual structure model
- Structure disintegration
- Freezing on structures

**Basic Equations**

\[
\frac{\partial (\alpha_q \rho_q)}{\partial t} + \nabla \cdot (\alpha_q \rho_q \mathbf{V}_q) = \Gamma_{q' \rightarrow q}
\]

\[
\frac{\partial (\alpha_q \rho_q \mathbf{V}_q)}{\partial t} + \nabla (\alpha_q \rho_q \mathbf{V}_q \cdot \mathbf{V}_q) + \alpha_q \nabla p - \alpha_q \rho_q \mathbf{e}_q \cdot \mathbf{K}_{q,s} \mathbf{V}_q - K_{q',q} (\mathbf{V}_{q'} - \mathbf{V}_q) = \nabla \cdot (\alpha_q \rho_q \mathbf{V}_q) - \mathbf{V} \mathbf{M}_q
\]

\[
\frac{\partial (\alpha_q \rho_q \mathbf{e}_q)}{\partial t} + \nabla \cdot (\alpha_q \rho_q \mathbf{e}_q \mathbf{V}_q) + p \left[ \frac{\partial \alpha_q}{\partial t} + \nabla \cdot (\alpha_q \mathbf{V}_q) \right] + \ldots
\]

\[
= Q_N + Q_T + Q_{HT}
\]

\[K_{k,s}\] Momentum eXchange Matrix (MXM) (fluid-structure) \(\text{N}\cdot\text{s/m}^4\)

Momentum eXchange Model (MXM)
MXM in the Rod Bundle Flow

The rod cylinder experiences the friction $\tau_w$ in the axial direction and the drag $f_D$ in the horizontal direction. The drag coefficients are defined as

$$ C_{D, \text{axial}} = \frac{\tau_w}{\frac{1}{2} \rho u^2} \quad C_{D, \text{radial}} = \frac{f_D}{\frac{1}{2} \rho u^2 d} $$

where $d$ is the pin diameter, $u$ and $v$ are coolant macroscopic average velocities and $f_D$ the drag force per unit length of the cylinder pin. The dynamical pressure drops (momentum losses) can be expressed and derived as

in axial direction

$$ \frac{\partial p}{\partial z} = -\frac{C_f}{D_H} \frac{1}{2} \rho v |v| $$

with $C_f = 4C_{D, \text{axial}}$, $D_H = \frac{4A_{\text{cool}}}{L_{\text{wet}}}$

in radial direction

$$ \frac{\partial p}{\partial r} = -C_{D, \text{radial}} \frac{1}{2} \rho u |u| \frac{4(1-\alpha_{\text{cool}})}{\alpha_{\text{cool}} \pi d} $$

MXM in SIMMER Code

SIMMER Anisotropic form:

$$ K_r = A_r + B_r \cdot |u| $$

$$ K_z = A_z + B_z \cdot |v| $$

Axial channel flow

$$ A_z = \begin{cases} \frac{2a^2 \mu_c}{\alpha_r} & \text{for } Re \leq Re_0 \ , \ \frac{2a^2 \mu_c}{\alpha_r} & \text{for } Re \geq Re_0 \end{cases} $$

$$ B_z = \begin{cases} 0 & \text{for } Re \leq Re_0 \ , \ \frac{a \rho_c C_D}{2} & \text{for } Re \geq Re_0 \end{cases} $$

• Hagen-Poiseuille: $C_l = 64/Re$

• Blasius: $C_l = 0.3164/Re^{0.25}$

where

$$ Re = 4 \frac{\alpha_r}{a} \rho_c |u| \frac{1}{\mu_c} , \ C_D = \frac{1}{4} \ C_f = 0.0791 \ Re^{-0.25} $$

$a$: interfacial area between solid and liquid per unit volume
Radial cross flow

Cross flow over the cylinder array (Tanino & Nepf 2008)

\[ C_{D,\text{radial}} = 2\left(\frac{\alpha_0}{Re_{\text{rad}}} + \alpha_1\right) \]

\[ \alpha_0 = 84 \quad \alpha_1 = 0.46 + 3.8\phi \]

where \( Re_{\text{rad}} \) is defined based on cross flow velocity \( u \) and pin diameter \( d \) and

\[ \phi = 1 - \alpha_c \]

It can be identified straightforward as

\[ A_r = \alpha_0 \frac{4\phi \mu_c}{\pi d^2} \quad B_r = \alpha_1 \frac{4\phi \rho_c}{\pi d} \]

SIMMER Simulations (Steady State and Blockage)

KIT Jäger’s Subchanflow Example:
Preliminary version of critical FASTEF

The central SA replaced by FA in the current SIMMER simulation
SIMMER Steady State Simulation Results

Main parameters of the average FA:

<table>
<thead>
<tr>
<th>SIMMER’s</th>
<th>Jäger’s Subchanflow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power:</td>
<td>1.440 MW</td>
</tr>
<tr>
<td>mass flow rate:</td>
<td>72.46 kg/s</td>
</tr>
<tr>
<td>Average temperature rise:</td>
<td>140.77 K</td>
</tr>
</tbody>
</table>

The reason for the deviation in the coolant temperature rise lies in LBE cp.
SIMMER Simulation Results

Jäger's Subchanflow (KIT, INR)

SIMMER's

$T_{av} = 407.3^\circ C$, $T_{max} = 426.08^\circ C$, $T_{min} = 347.9^\circ C$

$T_{av} = 410.8^\circ C$, $T_{max} = 437.6^\circ C$, $T_{min} = 347.4^\circ C$

$V_{av} = 1.9505 m/s$, $V_{max} = 2.014 m/s$, $V_{min} = 1.9014 m/s$

$V_{av} = 1.9172 m/s$, $V_{max} = 2.0813 m/s$, $V_{min} = 1.8723 m/s$
SIMMER Simulation Results

Axial coolant flow velocity

The axial velocity in the 7th ring is higher than that in others

Radial coolant flow velocity

The radial velocity is quite weak and its maximal Reynolds No. is about 40

SIMMER Simulation of 100MW Critical Core

FASTEF Critical Core with 100MW is considered
Central FA is added and Central fuel pin is included
Power = 2.3686 MW  \( (f_{\text{radial}} = 1.657) \)  
Mass flow rate = 74.266 kg/s 
Average temperature rise:  223 °C 
\( T_{\text{in}} = 270 \, ^\circ \text{C}, \, T_{\text{out}} = 493 \, ^\circ \text{C} \)
Subchannel Blockage in the Central FA by Fixed Power

Blockage of 1 subchannel ring

![Graph showing temperature distribution](image1)

Max. coolant temperature increase 62 °C

Blockage of 3 subchannel rings

![Graph showing temperature distribution](image2)

Max. coolant temperature increase 369 °C

Subchannel Blockage in the Central FA Started at 60 s

Blockage of 5 subchannel rings with blocked area of 50%

**Neutronic coupled calculation**

![Graph showing temperature distribution](image3)

Clad melting takes place between 4 and 5 sec after the blockage starts

![Graph showing temperature distribution](image4)
SIMMER Simulation of Blockages in the Central FA

Subchannel Blockage in the Central FA Started at 60 s
Blockage of 5 subchannel rings with blocked area of 50%

Neutronic coupled calculation

![Graph showing mass flow rate and power over time](image)

---

SIMMER Simulation of Blockages in the Central FA

![Images showing blockages at different times](image)
Conclusions

• The macroscopic model of pin-bundle flow has been set up and implemented in SIMMER III.
• The model can be applied in any CFD code, not only in SIMMER.
• The major effect is the different $D_h$ in the interior and side channels (meshes).
• The cross flow is quite weak in the steady state and the axial flow result is quite independent from the cross flow pressure drop coefficients.
• Whole core macroscopic pin bundle flow simulation for SIMMER III is possible as well.
• 50% area blockage (only 20% flow rate reduction) can lead to pin melting, but no pin failure propagation can take place.
• Power is decreasing after the local pin failure, because fuel particles move out of the active core.

Acknowledgement

The authors appreciate the effort and support of all the scientists and institutions involved in IP EUROTRANS, CDT, SEARCH and MAXSIMA, as well as financial supports of the European Commission through the contracts FI6W-CT-2004-516520, FP7-232527, FP7-295736, and FP7-323312, respectively.

They thank also Dr. E. Kiefhaber, a retired scientist at KIT, for his careful reading and helpful corrections.

Thank you very much for your attention!
Blocked wire wrap HLM fuel assemblies: Coarse-Grid-CFD modelling for numerical support to experiments

A. Class(a), M. Viellieber(a)

(a) Karlsruhe Institute of Technology, KIT, Germany

Abstract

The core of a nuclear reactor is a few meters in height and in diameter. It is composed of several hundred fuel assemblies which are again composed of tenth of fuel rods with a diameter of about 10 mm. Therefore the relevant length scales for CFD simulations range from the sub millimetre range, relevant for the fuel rod space up to several meters. Describing multi scales is challenging and the historical approach was to use integral descriptions. These methods are called sub-channel analyses codes and are based on integral equations that are tuned by experiments. Computational Fluid dynamics (CFD) simulations of a complete nuclear reactor set up resolving all relevant scales requires exceedingly large computational resources. However, in most cases there are repetitive geometry and flow patterns allowing the general approach of creating a parametrized model for one segment and composing many of these reduced models to obtain the entire reactor simulation. With our method, the Coarse-Grid-CFD (CGCFD), we intend to replace the experimental or empirical input with CFD data.

In an application the methodology starts with a detailed and well-resolved CFD simulation of one representative segment. From this simulation we extract in tabular form so-called volumetric forces which upon parametrization is assigned to all coarse cells. Repeating the fine simulation for multiple flow conditions parametrized data can be obtained to the desired degree of accuracy. Note, that parametrized data is used to close an otherwise strongly under resolved, coarsely meshed model of a complete reactor setup. While the formulation so far accounts for forces created internally in the fluid, there are other influences, like obstruction and flow guidance by spacers and wire wraps, respectively. These still need to be accounted for when the geometric details are too fine to be directly resolved by the coarse mesh. In our methodology, these are modelled with an Anisotrop Porosity Formulation (APF). Within our previous work the focus has been on the flow field, the current work assesses thermal fields. These simulations help the experimentalist to position thermocouples at the location where maximum temperatures are expected. It is shown that CGCFD is a technique capable to simulate complex flows with repetitive flow patterns and additionally special localized abnormal flows.

References


Blocked wire wrap HLM fuel assemblies: Coarse-Grid-CFD modelling for numerical support to experiments

M. Viellieber, A. Class

Outline:

- The CGCFD-Method
- CGCFD validation cases
- CFD simulation LBE wire wrapped bundle OpenFOAM and STARCCM+
- CGCFD results LBE wire wrapped bundle setup blockage simulation
- Conclusion
Methods for simulating reactor components:

<table>
<thead>
<tr>
<th>Methods</th>
<th>Time and Space averaging</th>
<th>Physical details, modelling effort &amp; costs</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>DNS</td>
<td>No filtering, No averaging</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LES</td>
<td>Space filtering</td>
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<td></td>
</tr>
<tr>
<td>RANS</td>
<td>Time averaging</td>
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<tr>
<td>Subchannel Codes</td>
<td>Time averaging, Space filtering</td>
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</tr>
<tr>
<td>1D system analysis</td>
<td>Time averaging, Space filtering</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Thermal hydraulic Simulations:

Example HPLWR

- Conduct thermal hydraulic design studies of different HPLWR layouts
  - LPA-methods where not applicable, because of a lack of experimental data
  - Pure CFD simulations not possible due to lack of computational resources
  - Development of a CFD methodology for fast design analysis replacing the LPA methods

Coarse-Grid-CFD (CGCFD)
Methods for simulating reactor components: Coarse-Grid-CFD (CGCFD):

- CGCFD simulation reasonable for simulations where flow situations repeating many times
- Determine representative section
- Setup numerical grid
- Detailed CFD-simulation with different flow conditions
- Extract volumetric forces
- Parameterization of forces
- Perform simulation of complete geometry with parameterized source terms and Euler equation (goal: complete reactor core)

Details CGCFD: Derivation of volumetric source terms

- RANS CFD and Euler momentum equation
  \[ \rho [\partial_t u_i + \partial_x (u_i u_j)] + \partial_x p = \partial_x [\mu (\partial_x u_i + \partial_x u_j)] \]
  \[ \rho [\partial_t u_i + \partial_x (U_i U_j)] + \partial_x p = \vec{R}_j \]
- Definition of volume and surface averages
  \[ \langle f \rangle_{\Omega_j} = \frac{1}{|\Omega_j|} \iiint_{\Omega_j} f \, dV, \quad \langle f \rangle_{\Omega_{jm}} = \frac{1}{|\partial \Omega_{jm}|} \iint_{\partial \Omega_{jm}} f \, dA \]
- Balance between the single terms
  \[ \langle u_i \rangle_{\Omega_j} = \langle U_i \rangle_{\Omega_j} \]
  \[ \langle \partial_x (u_i u_j) \rangle_{\Omega_j} = \langle \partial_x (U_i U_j) \rangle_{\Omega_j} \]
  \[ \langle \partial_x p \rangle_{\Omega_j} = \langle \partial_x p \rangle_{\Omega_j} \]
- Conditional equation for the volumetric source term
  \[ \vec{R}_j = \sum_m \langle \mu (\partial_x u_i + \partial_x u_j) \vec{n}_{jm} \rangle_{\partial \Omega_{jm}} \]
Outline:

- The CGCFD-Method
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**CGCFD Validation and Implementation: Subchannel**

<table>
<thead>
<tr>
<th>Solver</th>
<th>Re</th>
<th>Turbulence-model</th>
<th>No. cells</th>
<th>Reduction-factor</th>
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<tbody>
<tr>
<td>RANS CFD</td>
<td>20000</td>
<td>Isotrop/ anisotrop</td>
<td>1281852</td>
<td>-</td>
</tr>
<tr>
<td>CGCFD</td>
<td>20000</td>
<td>-</td>
<td>2700</td>
<td>156</td>
</tr>
</tbody>
</table>

![Graph of CGCFD Validation and Implementation: Subchannel]
### CGCFD Validation and Implementation: Subchannel

#### CFD Subchannel (OpenFOAM)

<table>
<thead>
<tr>
<th>P/D</th>
<th>( d_{\text{hydraulic}} )</th>
<th>Re</th>
<th>Media</th>
<th>BC</th>
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</thead>
<tbody>
<tr>
<td>1.4</td>
<td>1.29 mm</td>
<td>20000</td>
<td>Water 25°</td>
<td>Cyclic</td>
</tr>
</tbody>
</table>

---

![Diagram](image1)

![Diagram](image2)

---

**Sekundärströmungen**
- 1.500e-03
- 1.250e-03
- 7.500e-04
- 3.750e-04
- 0.000e+00

---

Lauder-Sharma

RSMEBM
## CGCFD Validation and Implementation: Subchannel

<table>
<thead>
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<td>2700</td>
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</tr>
</tbody>
</table>

![Graph showing M1 model for CGCFD and RANS CFD](image)

## CGCFD Validation and Implementation: Subchannel

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<td>2700</td>
<td>156</td>
</tr>
</tbody>
</table>

![Graph showing U Magnitude and Dimensionless length](image)
Implementation of the energy equation to CGCFD:

<table>
<thead>
<tr>
<th>Approach 1</th>
<th>Approach 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho \mathbf{v} h) = q$</td>
<td>$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho \mathbf{v} h) = \nabla \cdot (\lambda \nabla h) = q$</td>
</tr>
</tbody>
</table>

Example:

![Example](image1)

Example:

![Example](image2)

Implementation of the energy equation to CGCFD:

**Approach 1**

$$Q_{KV} (z = z_j) = Q_{max} \cdot \sum_{z_{i-1}}^{z_{i-1}+1} \sin \left( \pi \cdot \frac{z}{L_{beh.}} \right) \cdot dz$$

$$Q (z = z_i) = Q_{max} \cdot \sin \left( \frac{z_i}{L_{beh.}} \cdot \pi \right)$$

Temperature difference between subchannel code COBRA IIIC and CGCFD:

- **$T_{max}$ at outlet:** $\approx 610°C$
- **$\Delta T_{max}$ at outlet:** $\approx 60°C$

Between 5°C and 9°C
Implementation of the energy equation to CGCFD: Approach 2

- Determine thermal diffusivity from RANS Simulation

\[
\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho \vec{v} h) - \nabla \cdot \lambda \nabla h = q
\]

- CGCFD simulation with thermal diffusivity

Generalization CGCFD with anisotropic Porosity:

- Why anisotropic parameters?

- Anisotropic parameters:
  - Surface permeability: \( \gamma_A \)
  - Volume porosity: \( \gamma_V \)

- CGCFD equation with implemented volume porosity and surface permeability

\[
\rho \{ \gamma_A \partial_{x_j} (U_i U_j) \} + \gamma_V \partial_{x_i} P = \gamma_V \vec{F}_CV
\]

- Surface permeability:

\[
\gamma_{A_{jm}} = \langle u_i \bar{u}_j \bar{n}_{jm} \rangle_{\Omega_j} \frac{\partial \Omega_j}{\partial \Omega_{jm}} \frac{1}{\langle \bar{u}_i \bar{u}_j \bar{n}_{jm} \rangle_{\bar{\Omega}_{jm}}}
\]

- Volume porosity:

\[
\gamma_{V_j} = \langle \partial_{x_i} P \rangle_{\Omega_j} \frac{1}{\langle \partial_{x_i} P \rangle_{\Omega_j}^{-1}}
\]
Generalization CGCFD with anisotropic Porosity:

- Explanation anisotropic surface permeability

AP-CGCFD Validation and Implementation:

<table>
<thead>
<tr>
<th>Solver</th>
<th>Inlet velocity</th>
<th>Turbulence-model</th>
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<th>Reduction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>RANS CFD</td>
<td>U= 1 m/s</td>
<td>K-ω-SST</td>
<td>88000</td>
<td>-</td>
</tr>
<tr>
<td>AP-CGCFD</td>
<td>U= 1 m/s</td>
<td>-</td>
<td>200/800/3200</td>
<td>440/110/30</td>
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Proceedings of the SEARCH/MAXSIMA 2014 International Workshop, Karlsruhe, Germany, October 7-10, 2014
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19 10/9/2014 SEARCH/MAXSIMA International Workshop 2014 AREVA Nuclear Professional School (ANPS)
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Outline:

- The CGCFD-Method
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- Conclusion
Challenges in CFD calculations of LBE:

- **Characteristics LBE:**
  - \[ \rho_{LBE} \frac{kg}{m^3} = 11096 - 1.3236T \quad \Rightarrow \rho_{LBE} \approx 10 \ast \rho_{H2O} \]
  - \[ c_{p,LBE} \frac{J}{kg K} = 159 - 2.72 \ast 10^{-2}T + 7.12 \ast 10^{-6}T^2 \]
  - \[ \mu_{LBE} \frac{Pa}{s} = 4.94 \ast 10^{-4} \exp\left(\frac{754.1}{T}\right) \]
  - \[ Pr = \frac{\nu}{\alpha} \approx 0.025 \text{ for LBE} \]

- Prandtl- Führer durch die Strömungslehre

- Turbulenzmodellierung von Strömungen niedriger molekularer Prandtlzahl (T. Baumann)

---

Set up LBE solver OpenFOAM:

- **Energy equation:**
  - \[ \frac{\partial T}{\partial t} + u_i \frac{\partial T}{\partial x_i} = \frac{\partial}{\partial x_i} \left( \alpha \frac{\partial T}{\partial x_i} \right) \]
  - \[ a = \frac{\lambda}{\rho c_p} \quad \text{For turbulence} \quad a_{Eff} = (a + a_t) \]
  - \[ Pr_{t,LBE} = 0.025 \]
  - \[ Pr_t = \frac{\nu_t}{\alpha_t} \quad \text{Correlation after Kays:} \quad Pr_t = \frac{0.7a}{\nu} + 0.85 \]

- **Implementation OpenFOAM**
  - `fvm::div(phi,T)`
  - `-fvm::Sp(fvc::div(phi),T)`
  - `-fvm::laplacian(alphaEff,T)`

- \[ Pr = \frac{\nu}{\alpha_{lam}} \quad Pr_t = \frac{\nu_t}{\alpha_t} \]

- \[ \alpha_{eff} = \alpha_{lam} + \alpha_t \quad \text{Turbulence-model} \]
CFD wire wrapped fuel bundle: Mesh generation:

M. Daubner (KALLA)

<table>
<thead>
<tr>
<th>Mesh type</th>
<th>Used cells</th>
<th>Prism layers</th>
<th>Turbulence mod.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trimmer</td>
<td>13501248</td>
<td>1</td>
<td>K-Ω-SST</td>
</tr>
</tbody>
</table>
CFD wire wrapped fuel bundle:
KALLA experimental test matrix:

![Thermal power vs Mass flow rate matrix](image)

Figure 2.7: Envisaged test matrix, combination of thermal power ($Q$) and mass flow rate ($\dot{m}$). 
Notes: X: $T_{in}=200^\circ C$, O: $T_{in}=270^\circ C$, - = no experiments.

---

CFD wire wrapped fuel bundle:
Mesh generation:

<table>
<thead>
<tr>
<th>CFD Bundle (OpenFOAM &amp; STARCCM+)</th>
<th>Cells</th>
<th>$d_{\text{hydraulic}}$</th>
<th>Mass flow rate</th>
<th>Flow medium</th>
<th>BC:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>13501248</td>
<td>5.2016 mm</td>
<td>16 kg/s</td>
<td>LBE $T_{in} = 270^\circ C$</td>
<td>Cyclic</td>
</tr>
</tbody>
</table>

![Velocity and Pressure profiles](image)
CFD wire wrapped fuel bundle: Results:

CFD Bundle (OpenFOAM & STARCCM+)

<table>
<thead>
<tr>
<th>Cells</th>
<th>$d_{\text{hydraulic}}$</th>
<th>Mass flow rate</th>
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</tr>
</tbody>
</table>

Temperature profile

![Temperature profile graph](image)

Temperature profile pos. 1

Position 1

Temperature profile pos. 2

Position 2
Detailed CFD simulation with blockages

Geometry KIT

Geometry NRG

<table>
<thead>
<tr>
<th>Cells</th>
<th>$d_{\text{hydraulic}}$</th>
<th>Mass flow rate</th>
<th>Flow medium</th>
<th>Heating power</th>
</tr>
</thead>
<tbody>
<tr>
<td>8001248</td>
<td>5.2016 mm</td>
<td>4.5 kg/s</td>
<td>LBE $T_{\text{in}} = 270^\circ C$</td>
<td>97.4 kW</td>
</tr>
</tbody>
</table>
Outline:

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CGCFD fuel bundle simulation:
Set up:

<table>
<thead>
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<th>$U_{Inlet}$</th>
<th>Turbulence-model</th>
<th>No. cells</th>
<th>Reduction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>RANS CFD</td>
<td>$1.5 \text{ m/s}$</td>
<td>K-ω-SST</td>
<td>&gt; 13.5 Million</td>
<td>-</td>
</tr>
<tr>
<td>CGCFD</td>
<td>$1.5 \text{ m/s}$</td>
<td>-</td>
<td>92000</td>
<td>147</td>
</tr>
</tbody>
</table>

Wall: slip BC
Wires: via APF
Rods: slip BC
### CGCFD fuel bundle simulation:
#### Results:

<table>
<thead>
<tr>
<th>Solver</th>
<th>( U_{\text{Inlet}} )</th>
<th>Turbulence-model</th>
<th>No. cells</th>
<th>Reduction factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>RANS CFD</td>
<td>( 1.5 \text{ m/s} )</td>
<td>K-( \omega )-SST</td>
<td>( &gt; 13.5 \text{ Million} )</td>
<td>-</td>
</tr>
<tr>
<td>CGCFD</td>
<td>( 1.5 \text{ m/s} )</td>
<td>-</td>
<td>92000</td>
<td>147</td>
</tr>
</tbody>
</table>

#### Pressure profile

![压力分布图](attachment:image.png)

### CGCFD fuel bundle simulation with blockages:
#### Set up:

<table>
<thead>
<tr>
<th>Solver</th>
<th>( U_{\text{Inlet}} )</th>
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- Issues with APF and energy equation → WIP
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Conclusion:

- CGCFD with the Anisotropic Porosity Formulation is able to reproduce RANS CFD simulations with mesh reduction factors of up to 400
- No experimental deduced factors are needed
- Easy mesh generation for CGCFD simulations (except representative geometry)
- Geometrical details like spacers, wire wraps are treated via the APF
- Simulation of blocked bundle with CGCFD is in progress