Development of the high temperature PbLi experimental platform for CFETR

Kecheng Jiang¹, Lei Chen¹, Juancheng Yang⁴, Xuebin Ma¹, Xiaoman Cheng³, Long Chen², Yue Yu¹,⁵, MingJiu Ni², Songlin Liu¹

¹ Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP), Hefei, 230031, China
² School of Engineering Science, University of Chinese Academy of Sciences, Beijing 101408, China
³ Institute of Energy, Hefei Comprehensive National Science Center, Anhui, 230031, China
⁴ School of Aerospace Engineering, Xi’an Jiaotong University, Xi’an 710049, China
⁵ University of Science and Technology of China (USTC), Hefei, 230026, China
COOL blanket design

➢ Design features
  • Single Module Segment,
  • RAFM steel as structural material
  • S-CO₂: 8 MPa, 350 °C ~ 400 °C
  • PbLi: 1~2 MPa, 460 °C ~ 700 °C
  • FCIs to mitigate the MHD effect and corrosion
  • PbLi “once-through” scheme
  • Thermoelectric conversion efficiency: ~42%

➢ Main advantages
  • Economic: Beryllium-based material is not used as the neutron multiplier
  • Efficiency: Coolant outlet temperature can reach 700°C, thermoelectric conversion efficiency is high
  • Online refueling and tritium extraction can be realized

Ref. Chen L., Jiang K., Ma X. and Wu. Q. 2021 Conceptual design of the supercritical CO₂ cooled lithium lead blanket for CFETR Fusion Eng. and Des. 173 112800
COOL blanket design

- Complicate turbulent (Re~10^5)
  - Algorithm and mesh
- High magnetic (Ha~10^4)
  - Thin BL and large velocity gradient
- Large temperature difference (Gr~10^{12})
  - Heat convection instability

Multi-physics coupling

Experiment and computing face great challenges!!


Critical scientific issues to be addressed: 1. MHD effects; 2. Mixed convection
Key scientific issues

➢ MHD effects

- $H_a \approx 10^4$
- $R_e \approx 10^5$
- $G_r \approx 10^{10}$

FCIs can largely reduce the pressure drop →10 times comparing case 1 and case 4

- The FCIs performance under magnetic field needs verification by experiments
- The pressure drop and magnetic have strong nonlinear relationship, the existing experimental parameters are low, thus it is necessary to carry out strong magnetic field related experiments.
Key scientific issues

➢ Mixed convection

Buoyancy has significant effects on flow and heat transfer, even the deterioration of local heat transfer and thermal fatigue occurred, threatening the blanket structure safety.

- Experiments on the mixed convection under strong magnetic and buoyancy are scarce, thus the development on the PbLi experimental loop is necessary to study its mechanism.
Summary on experiments

- MHD effects
  - Phase diagram and turbulent transition mechanism under different Re/Ha
  - The effects of FCI on the flow and heat transfer
  - MHD flow in complex geometry channel
  - Multi channel under electromagnetic coupling effect

- Mixed convection
  - One-side heat flux conditions
  - Large magnetic/heat source

- Out-pipe of Mockup test
  - Mockup prototype component
MHD effects and Mixed convection

- **Main purpose**
  - Turbulent phase diagram under different Re/Ha/Gr
  - The effects of FCI on the mixed convection
  - Mixed convection in complex geometry channel
  - Create models: \( f, u, Nu = f(Re, Ha, Gr) \)

- **Test section**
  - FCIs are inserted into the straight channel and complex geometries (the thermal and electrical conductivity are variables)
  - **Operating conditions**: magnetic, heat flux
  - Instruments: thermocouple, potential probe, differential pressure meter, UDV

Experiment design
Experiment design

➢ Out-pipe of Mockup test

• Main purpose
  – PbLi flow characteristics
  – Mass flow distribution in parallel multi-channels
  – MHD flow in complex geometry channel
  – Create models: $f,u = f(Re)$

• Test section
  – Mockup prototype component
  – Operation conditions: flow, heat insulation
  – Instruments: thermocouple, potential probe, differential pressure meter, UDV

➢ Operation modes
  • Low temperature: 400/450 °C; 1.41kg/s
  • High temperature: 460/600 °C; 0.88kg/s
Experiment design

Test parameters derivation

**Re** = \( \frac{\rho VL}{\mu} \sim 10^5 \)

**Ha** = \( \frac{BL \sqrt{\sigma}}{\mu} \sim 10^4 \)

**Gr** = \( \frac{g \alpha v \Delta t L^3}{\nu^2} \sim 10^{10} - 10^{12} \)

Mixed convection

### Test Section

- **CFETR COOL**
- **Flow area (mm²)**
- **B (T)**
- **Heat flux (kW/m²)**
- **M (kg/s)**
- **High Temp. (°C)**
- **Ha**
- **Re**
- **Gr**

<table>
<thead>
<tr>
<th>Flow area (mm²)</th>
<th>B (T)</th>
<th>Heat flux (kW/m²)</th>
<th>M (kg/s)</th>
<th>High Temp. (°C)</th>
<th>Ha</th>
<th>Re</th>
<th>Gr</th>
</tr>
</thead>
<tbody>
<tr>
<td>100×120</td>
<td>3</td>
<td>250</td>
<td>32</td>
<td>700</td>
<td>7676</td>
<td>10^5</td>
<td>6×10^9</td>
</tr>
</tbody>
</table>
Flow diagram and P&ID design

- **Main components**
  - Recuperator
  - Heater
  - Mechanic pump
  - Supermagnet
  - Storage tank
  - Mixer
  - Cold trap
  - Heat exchanger

- **PbLi system**
  - 300°C @ 64 kg/s
  - 533°C

- **Argon system**
  - 700°C @ 32 kg/s
  - 533°C

- **Coolant water system**
  - Water inlet
  - 25°C
  - 55°C

- **Oil system**
  - 300°C
  - 285°C
  - 270°C

- **Heat insulation system**
  - 700°C
  - 533°C

- **Charge and discharge system**
  - 1.5 MPa
  - Storage tank

- **Liquid meter**

- **Main components**
  - Mechanical pump
  - Expansion tank
  - Oil pump
  - Oil-water HX

- **Other components**
  - Safety valve
  - Control valve
  - Pressure reducing valve
  - Electromagnetic valve
  - Thermocouple
  - Pressure meter
  - Liquid meter
  - Differential pressure gauge
  - Flowmeter
  - Vacuum pump
Key components design

➢ Superconduct magnet

- Includes both **vertical and horizontal channels**
- Able to study the **Multi-physics performance** under: (1) Complex geometric; (2) Electromagnetic force; (3) Buoyancy effects
- Wide range uniform magnetic field, the non-uniformity is 8%; Surface magnetic leakage 1 m ≤ 300 Gs
Key components design

➢ Superconduct magnet

Step 1: Orientation  Step 2: Install bottom iron  Step 3: Install middle iron  Step 4: Install bottom connect

Step 5: Install iron core 1  Step 6: Install iron core 2  Step 7: Install upper iron  Step 8: Install upper connect
Key components design

➢ Main heater

- Heat the PbLi to the required temperature
- Through DCS control to adjust the running power
- With over temperature protection feedback system

### Design parameters

<table>
<thead>
<tr>
<th>Items</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>Heat bundles</td>
</tr>
<tr>
<td>Power</td>
<td>1.0 MW</td>
</tr>
<tr>
<td>Design power</td>
<td>1.2 MW</td>
</tr>
<tr>
<td>Operation temp.</td>
<td>700 ℃</td>
</tr>
<tr>
<td>Design temp.</td>
<td>750 ℃</td>
</tr>
<tr>
<td>Design pressure</td>
<td>2 MPa</td>
</tr>
<tr>
<td>Mass flow rate</td>
<td>0~64 kg/s</td>
</tr>
</tbody>
</table>
Key components design

➢ Cold trap

- The 5% PbLi is extracted from the main pipe, the metal and non-metallic impurities are captured
- After running for 100min, the impurity purification rate reached 95%

### Design parameters

<table>
<thead>
<tr>
<th>Item</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structure</td>
<td>Oil cooler</td>
</tr>
<tr>
<td>Power</td>
<td>50 kW</td>
</tr>
<tr>
<td>Design temp.</td>
<td>450 ℃</td>
</tr>
<tr>
<td>Design pressure</td>
<td>2.8 MPa</td>
</tr>
<tr>
<td>Tube side</td>
<td>PbLi</td>
</tr>
<tr>
<td>Shell side</td>
<td>Oil</td>
</tr>
<tr>
<td>Inlet temp.</td>
<td>300~350 ℃</td>
</tr>
<tr>
<td>Outlet temp.</td>
<td>270 ℃</td>
</tr>
<tr>
<td>Motor</td>
<td>Frequency change</td>
</tr>
<tr>
<td>PbLi flow range</td>
<td>0~3.2 kg/s</td>
</tr>
<tr>
<td>Wires</td>
<td>Metal</td>
</tr>
</tbody>
</table>

Impurity residual rate varies with time
Key components design

- **Experimental data measurement and characterization**

  - The traditional method, i.e. PIV, cannot be used due to the opacity of PbLi
  - The velocity field in liquid metal is plan to be measured by ultrasonic Doppler UDV and potential probe technologies

---

- **Theory**

  - Ohm’ law: \( \mathbf{j}/\sigma = -\nabla \varphi + \mathbf{u} \times \mathbf{B} \)
  - Velocity: \( u = \frac{1}{B_0} \frac{\partial \varphi}{\partial z} \), \( w = -\frac{1}{B_0} \frac{\partial \varphi}{\partial x} \)
  - Vorticity: \( \omega = \nabla^2 \varphi / B_0 \)
Components and system layout

Summary on the design parameters

<table>
<thead>
<tr>
<th>Item</th>
<th>Unit</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating pressure</td>
<td>MPa</td>
<td>2</td>
</tr>
<tr>
<td>Design pressure</td>
<td>MPa</td>
<td>2.8</td>
</tr>
<tr>
<td>Operating temp.</td>
<td>°C</td>
<td>270~700</td>
</tr>
<tr>
<td>Materials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low temp. (316L)</td>
<td>°C</td>
<td>550</td>
</tr>
<tr>
<td>High temp. (800 H)</td>
<td>°C</td>
<td>750</td>
</tr>
<tr>
<td>Mass flow rate (PbLi)</td>
<td>m³/h</td>
<td>30</td>
</tr>
<tr>
<td>PbLi consumption</td>
<td>t</td>
<td>25</td>
</tr>
<tr>
<td>Design temp. (oil)</td>
<td>°C</td>
<td>350</td>
</tr>
<tr>
<td>Mass flow rate (oil)</td>
<td>m³/h</td>
<td>130</td>
</tr>
<tr>
<td>Design temp. (water)</td>
<td>°C</td>
<td>25-35</td>
</tr>
<tr>
<td>Design pressure (water)</td>
<td>MPa</td>
<td>0.5</td>
</tr>
<tr>
<td>Electricity power</td>
<td>MW</td>
<td>≤1.5</td>
</tr>
<tr>
<td>Design life</td>
<td>year</td>
<td>20</td>
</tr>
</tbody>
</table>

17.5 m (length) × 9.5 m (width) × 16 m (height)
Project schedule

- Engineering design
- Infrastructure construction
- Installation and first operation *(2024.05.01)*
- Experiments

2023 | 2024 | 2025
Concluding remarks

➢ The COOL blanket is being researched at ASIPP for CFETR
  - The Beryllium-based material is not used as the neutron multiplier → **Economic**
  - Coolant outlet temperature can reach 700℃, thermoelectric conversion efficiency is high → **Efficiency**
  - Online refueling and tritium extraction can be realized

➢ The PbLi loop is necessary to address the following scientific issues:
  - Turbulent heat transfer, MHD effects and mixed convection under large heating source and magnetic fields
  - Based on the experimental requirements, the test section and parameters are clearly designed
  - Moreover, the out-pile of Mockup will be fully tested before it is installed into the fusion reactor

➢ The PbLi loop facility with high performance is designed, including:
  - For the flow diagram and P&ID, it mainly consists of the PbLi, oil and water system et al.
  - The key components, i.e. mechanic pump, main heater, cold trap, are carefully selected to satisfy with the requirements
  - The superconducting magnetic with 3T is adopted, which has the vertical and horizontal channels capable of studying the multi-physics coupling under buoyancy and electromagnetic
  - The 3D layout of system and main components is built and this facility will be under construction soon
Thank you for your attention!