Development of He-cooled Divertors for Fusion Power Plants

Presented by Prachai Norajitra

IAEA-TM-1
July 05 - 07, 2005, Vienna Austria
## Contributions to the EU PPCS task

<table>
<thead>
<tr>
<th>FZK -</th>
<th>EFREMOV (RF)</th>
<th>ENEA</th>
<th>UKAEA</th>
</tr>
</thead>
</table>

IAEA-TM-1, July 05 -07, 2005, Vienna Austria  
CD-IV (He-cooled divertor)  
P. Norajitra
Outline

1. Introduction
2. Modular cooling principle of the He-cooled divertor
3. Choice of material
4. Design
5. Fabrication technology
6. Analyses
7. Experiments
8. Conclusion and future work
Why Helium-cooled divertor?

1. Within the PPCS, it was recommended to use the same kind of coolant in divertor as in blanket systems. At present, this concerns the three blanket types HCPB (Mod. B), DC (Mod. C) and HCLL (Mod. A-B).

2. Unlike water, helium is compatible with:
   - hot refractory metals
   - any kind of blankets
   (in particular with those where incompatibility of water with breeding/multiplier materials is a safety concern)

3. Helium allows for high exit temperature favourable for increasing thermal efficiency
Developing a Helium-cooled divertor for future fusion power plants is a challenging task due to:

1. Uncertainty of the physical boundary conditions,

2. Existing properties of W-alloy and ODS steel (both unirradiated and even less irradiated data) are neither well developed nor understood to satisfy all engineering requirements.

3. At this stage, the W-divertor is a potential solution approach, but by no means the perfect one.
The main functions of the divertor are:

1. To remove the fusion reaction ash (α-particles), unburned fuel, and eroded particles from the reactor,

2. To resist high-heat-flux and high erosion and sputtering rates,

3. To serve as a shield for the magnetic coils behind it.
# Materials and anticipated operational temperature windows required for a high temperature divertor

<table>
<thead>
<tr>
<th>Component</th>
<th>Material</th>
<th>Min Temp.</th>
<th>Max Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tiles</td>
<td>W</td>
<td>tbd (600°C) DBTT (irradiated)</td>
<td>2500°C Melting temperature 3410°C</td>
</tr>
<tr>
<td>High heat flux structure (high pressure He containment)</td>
<td>W-alloy</td>
<td>600°C DBTT (irradiated)</td>
<td>1300°C re-crystallisation (irradiated)</td>
</tr>
<tr>
<td>Structure and manifolds</td>
<td>W-alloy ODS</td>
<td>600°C DBTT 400°C DBTT (irradiated)</td>
<td>1300°C re-crystallisation 700-750°C strengh limits</td>
</tr>
</tbody>
</table>
Goal and milestones

Goal:
• To develop a He-cooled divertor concept for a heat load of $10 \text{ MW/m}^2$ at least

Milestones:
• Definition of the reference concept and material specification (2005-06)
• ITER Test Divertor Module (TDM) : Design and out-pile mock-up test: 2004 – 2010
• Start of DEMO operation: 2038

[*] D-T phase with long pulse operation during 2020 -2023 (1st phase of ITER: 2013-2023)
History: Earlier conceptual designs

A) Plate design:
- PPA-1999: Porous body (FZK), \( q_{\text{max}} \sim 5 \, \text{MW/m}^2 \)
- PPCS 2000-01: Simple slot (FZK), \( \sim 6 \, \text{MW/m}^2 \)
- PPCS 2001: Modified slot (FZK), \( \sim 10 \, \text{MW/m}^2 \) (for Model B)

B) Modular design (thermal stress reduction):
- PPCS 2002: Modified HETS (ENEA), He-Jet \( \sim 10 \, \text{MW/m}^2 \)
- PPCS 2002 Model C: HEMP/S (FZK), Pin/Slot array \( \sim 10 \, \text{MW/m}^2 \)
- TRP-001 (2003-2004) – detailed investigation on design concepts HETS and new FZK design HEMJ
  → having now higher potential \( > 10 \, \text{MW/m}^2 \)
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Introduction: Fusion Power Plant (model C)

- 16 TF coils
- 8 upper ports (f) (modules & coolant)
- 176 blanket modules (a) (5-6 yrs. lifetime)
- 8 central ports (g) (modules)
- Vacuum vessel 70 cm (e) (permanent)
- Lower divertor ports (h) (8 remote handling, 16 coolant)
- Divertor plates (b) (1-2 yrs. lifetime)
- Cold shield 30 cm (c) (permanent)
- Coolant manifolds (d) (permanent)
- 8 upper ports (g) (modules)
Divertor cassette for Model C and Target Plate Requirements

Target Plate (outboard):
- peak heat load: 10 MW/m²
- average heat load: 5 MW/m²
- moving strike point: 40 cm (pol., L = 1m)
- protection layer: 5mm (W)
- Pumping power / Thermal power < 10%
- temperatures and stresses in the materials to be kept allowable
Divertor cassette with modular target cooling units

- Divertor target plates with modular thermal shield (W alloy)
- Dome and structure (ODS RAFM)
- Divertor cartridge (RAFM)

Square or hexagonal shape of W tiles (thermal stress reduction)
Poloidal surface heat load distribution (toroidally symmetric)
HEMP / HEMS/HEMJ: Hydraulic lay-out data of a target plate

HEMP / HEMS: **31 fingers** in parallel, in 2 sections in series**

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</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>157.7</td>
<td>10</td>
<td>188</td>
<td>101</td>
<td>Cassette: 0.4434 ***</td>
<td>Reactor: 50.3 / 8.6</td>
</tr>
</tbody>
</table>

*) OB-16 mm stripe; **) OB-HHF, L=1 m; ***) Sum HHF (slot=0.11) + LHF + Manifolds + Bulk
Principle of the modular design and the radial cooling
Cooling technology: Heat transfer (HT) promoters with different HT mechanisms

\[ \dot{q} = htc \cdot \frac{A_c}{A_{\text{Armor}}} \cdot (T_w - T_c) \]

Impinging cooling

Convective cooling

HETS single-jet

HEMP pin array

HEMS slot array

HEMJ multi-jet
Cooling Technology: pin and/or slot array used as flow promoters

Pin array

Slot array

HEMP

HEMS
Cooling Technology: Jet Impingement

Cooling technology applied in the fields of:
- Aircraft Engines
- Gas Turbines
- Burners
...
→ DEMO Divertor

Jet Impingement

HOT

wall jet flow

free jet flow

impingement region

D

H
COOLING TECHNOLOGY: Jet Impingement in HEMJ

**Single-jet**

- Heat transfer coefficient (Low Re Number)
- Example

**Multi-jet**

- k-e Suga's cubic
- k-w
- \( v' \) Spalart-Allmaras

**Example**

- Distance from Jet Center [mm]
- Heat transfer coefficient \([W/m^2K]\)
- \(D_{\text{jet}} = 0.6 \text{ mm}\)
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1. Introduction
2. Modular cooling principle of the He-cooled divertor
3. Choice of material
4. The Design
5. Fabrication technology
6. Analyses
7. Experiments
8. Conclusion and future work
### Divertor Material

**Comparison of refractory metals as a cup materials**

<table>
<thead>
<tr>
<th>Priority</th>
<th>Material</th>
<th>Material</th>
<th>Material</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>Ta</td>
<td>Mo</td>
<td>W</td>
</tr>
<tr>
<td>2</td>
<td>Ta</td>
<td>W</td>
<td>Mo</td>
</tr>
<tr>
<td>3</td>
<td>W</td>
<td>(Mo, Ta)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Ta</td>
<td>Mo</td>
<td>W</td>
</tr>
<tr>
<td>5</td>
<td>W</td>
<td>Mo</td>
<td>Ta</td>
</tr>
<tr>
<td>6</td>
<td>W</td>
<td>Ta</td>
<td>Mo</td>
</tr>
<tr>
<td>7</td>
<td>Ta</td>
<td>(W, Mo)</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Mo</td>
<td>(W, Ta)</td>
<td></td>
</tr>
</tbody>
</table>

**W has high resistance against HHF and sputtering energy**

Tentatively W is selected as a primary candidate with further attempts to improve those properties which are not the best.
2. Material selection

**Cup**
Operational temperatures $T=700$-$1200$ $^\circ$C, so refractory metals: W, Mo, Ta, Nb

*List of candidate materials:*

1. Graded PM non-doped tungsten (WMP):
   - Rolled sheet (2 direction)  
   - Forged rod (RF, Plansee)

2. Doped tungsten:
   - $W$-$La_2O_3$ (Plansee)  
   - $W$-$HfC-Re$  
   - $W$ (mech. allowing)

3. Sintered/composite tungsten
   - $W$-$Fe$-$Ni$ (tentative)  
   - $W$-$Cu$ (5-10%)  
   - Gradient mater. (W-Cu)

4. CVD-tungsten
5. Single crystal W (40 m$^2$, 2 cm thick, 15 tonn, 4.5 mln.$\)  

6. **TZM (EU)**  
   - CM-3 (tentative)  
   - Mo-single crystal  

7. **Ta-$10W$**
Resulting conceptual design

- **W tile** as thermal shield (5 mm thick)

- **W-1%La$_2$O$_3$$** as structural material for cooling finger (thimble)

- **RAFM ODS Eurofer** as structure

- **$T_{\text{He}, \text{in}}/\text{out} = 600/700 \, ^{\circ}\text{C}$** (target plate)
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The HETS Design (ENEA)
HETS Design
HETS: Detail of the flow mechanism

Calculated heat transfer coefficient in HETS
($\theta$ is the angle from the dome top)
### HETS: Hydraulic lay-out

- **Finger type and dimens.**: HEX 35 mm
- **He in/out**: 600-669°C
- **Coolant pressure**: 10 MPa
- **Mass flow**: 30 g/s
- **Average Heat Transfer Coeff.**: ~30 kW/m² K
- **Pressure drops**: 0.06 MPa

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</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>182</td>
<td>10</td>
<td>180</td>
<td>195</td>
<td>&gt;0.3</td>
<td>&gt;6.3</td>
</tr>
</tbody>
</table>
HETS Manufacturing sequences (preliminary) 1/2

- **Cup/Dome**
  - First brazing: filler based on Pd, Zr or Ni alloy to withstand 1000°C

- **Mushroom**
  - Second brazing: same filler as the first brazing
HETS Manufacturing sequences (preliminary) 2/2

third brazing: filler based on Cu or Ni alloy to withstand ~800°C

fourth brazing: same filler as the 3th brazing
The HEMJ Design (FZK)
Design: HEMJ Features

- Direct impingement cooling He jet-to-wall
- No need for flow promoter (pin or slot)
- Uniform coolant temperature over the cooling surface
- Valve function of the jet flow, i.e. stable mass flow rate distribution of the cooling system (finger units + manifold)
- Curved thimble bottom (Kloepper) is stable against mechanical loads and deformations
- Hexagonal form: high packing density
Design: HEMJ modular system of cooling units favorable for separate tests and exchange
Design: Construction Kit

Construction Kit Principle:
Small Units advantageous for R&D progress
Small Units can be tested before assembling

9-Finger Unit  Stripe-Unit  Target Plate  Divertor Cassette

Test, Assembly  →  Test, Assembly  →  Test, Assembly  →  …
Design: W/Steel transition piece with conic lock

Finger components

- W Tile
- Thimble (W Alloy)
- Cartridge (ST)
- Transition piece (ODS-Eurofer or 12YWT)
- Conic sleeve ST
- Distance ring (spacer) ST

Finger unit (tile/thimble) with transition piece and cartridge spacer

- W Tile
- Thimble (W Alloy)
- Conic Sleeve ST
- EB seal welding
- Spacer ST
Inserting brazing foil
HT Brazing
W tile with W thible
Joining W thimble with steel (conic lock + Cu casting)
Welding ST spacer with ST structure (from below)
Inserting and fixing the cartridge
HIP welding
Welding
1. Introduction
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### HEMJ: Proposed fabrication and joint technologies

<table>
<thead>
<tr>
<th>Component</th>
<th>Process Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tiles</td>
<td>Cutting from rods and grinding</td>
</tr>
<tr>
<td>Thimble</td>
<td>Deep drawing from cross rolled WL10 + finishing</td>
</tr>
<tr>
<td>Structure</td>
<td>Standard ODS alloy machining; tube: extrusion</td>
</tr>
<tr>
<td>Joining: Tiles – Thimble</td>
<td>Brazing ($T=1300 , ^\circ , C$) by commercial alloys, Zr, V, Stemet alloys, NiCu, NiTi</td>
</tr>
<tr>
<td>Joining: Thimble – ST Structure</td>
<td>Transition piece (Mechanical interlock + Cu sealing)</td>
</tr>
</tbody>
</table>
Examples of W mock-up fabrication for thimble and slot array (old design)

Mock-up of W-thimble with integrated slot array fabricated by EDM process.

W-slot array prepared by Laser process

EFREMOV under FZK contract
R&D on fabrication technologies: Thimble manufacturing

WL-10 showed satisfactory machining ability in comparison with conventional tungsten
R&D on fabrication technologies: high temperature W/W-joint

Mock-up brazed with STEMET 1311 filler metal undergone successfully HHF screening tests
R&D on fabrication technologies: high temperature curved W-joint

Brazing successful, survived up to 100 temperature cycles at 14 MW/m²
R&D on fabrication technologies: W-steel joint

Finger mockup (without armour tile) after casting (left) and after post-testing examination (right).

10 thermocycles (pin=10 MPa) ok

Main elements for W-Steel joint with new (conic) lock

EFREMOV under FZK contract
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CFD Analyses: HEMJ result 3 (pressure loss)

Fig. Pressure loss vs He mass flow rate (q=10 MW/m²), calculated for the reference HEMJ geometry (Ø0.6 mm holes, 1.2 mm jet-to-wall gap, 6.8 g/s nominal)
CFD Analyses: HEMJ result 4 (htc)

**Fig. Heat transfer coef.** vs He mass flow rate \((q=10 \text{ MW/m}^2)\), calculated for the reference HEMJ geometry (\(\varnothing 0.6 \text{ mm holes, 1.2 mm jet-to-wall gap, 6.8 g/s nominal}\))

**Heat transfer coefficient [kW/m²K]**

**Mass flow rate [g/s]**

htc, \(q = 10 \text{ MW/m}^2\)
CFD simulations with FLUENT

Reference case: Heat load 10 MW/m², mass flow 6.8 g/s, inlet pressure 10 MPa

$T_{\text{max}} = 1711 \, ^\circ\text{C}$

$T_{\text{max}} = 1164 \, ^\circ\text{C}$
CFD Analyses: HEMJ result 1 (Tmax thimble)

The current HEMJ design under material assumptions could master at least 12 MW/m² (pessimistically).

Fig.: Max. thimble temperature vs He mass flow rate and heat flux, calculated for the reference HEMJ geometry (Ø0.6 mm holes, 1.2 mm jet-to-wall gap, 6.8 g/s nominal).
Yield strength for 886°C: 495 MPa;
3Sm for 886°C: 564 MPa;
Max. stress intensity at 886°C:
HEMJ: 390 MPa (safety margin 1.45)
HEMS & HEMJ: Temperature windows

<table>
<thead>
<tr>
<th>Material</th>
<th>Temperature (°C)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tile</td>
<td>2500°C</td>
<td>Tmax, allow. W tile</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(ELMs, Disr.)</td>
</tr>
<tr>
<td>Thimble</td>
<td>1711°C (Tmax, tile, calculated)*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1300°C</td>
<td>Tmax, allow. W thimble</td>
</tr>
<tr>
<td></td>
<td>1164°C (calculated)*</td>
<td></td>
</tr>
<tr>
<td>Cartridge</td>
<td>700°C</td>
<td>He 700°C</td>
</tr>
<tr>
<td></td>
<td>600°C</td>
<td>(DBTT, irr.)</td>
</tr>
<tr>
<td>Cooling finger</td>
<td>300°C</td>
<td>700 °C outl.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>600 °C inl.</td>
</tr>
<tr>
<td>W</td>
<td>600°C</td>
<td>700 °C outl.</td>
</tr>
<tr>
<td>WL10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ODS Eurofer</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* HEMJ, reference, 10 MW/m²

Altern. Mat. (plan B): DENSIMET, 12YWT, or Inconel
1. Introduction
2. Modular cooling principle of the He-cooled divertor
3. Choice of material
4. Design (HEMJ cooling finger)
5. Fabrication technology
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ENEA experiment: pressure drop measurement for HETS with air

Measurement device (left) and detail of the test section (right) for pressure drop experiments.
# FZK Experiments: Helium experimental stages for DEMO divertor

<table>
<thead>
<tr>
<th>Mock-up class</th>
<th>Small Parts 1:1</th>
<th>large-scaled 10 : 1</th>
<th>Big Parts 1:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strategy</td>
<td>'Design screening' &amp; 'Proof of principle'</td>
<td>'CFD code validation'</td>
<td>'complete test program'</td>
</tr>
<tr>
<td>Test Facility</td>
<td>Efremov, Russia: GPF2, E-beam, He-Loop</td>
<td>FZK: HEBLO</td>
<td>FZK: HELOKA</td>
</tr>
<tr>
<td>TOPIC</td>
<td>Heat Transfer &amp; Pressure Drop Measurements</td>
<td>Detailed Temp. and Pressure Data for CFD Validation</td>
<td>Heat Transfer &amp; Pressure Drop Measurements, Qualification of TDM for ITER</td>
</tr>
</tbody>
</table>
### 6. Experiments

**Test Facilities for 1-Finger-Units and Multi-Finger-Units**

<table>
<thead>
<tr>
<th>EFREMOV GPF + reversed HHF</th>
<th>EFREMOV He-Loop + E-Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>- quasi-stationary helium flow (&gt; 10s)</td>
<td>- stationary helium flow</td>
</tr>
<tr>
<td>- 600°C</td>
<td>- 700°C</td>
</tr>
<tr>
<td>- Pressure of 10-15 MPa.</td>
<td>- Pressure of at least 10 MPa.</td>
</tr>
<tr>
<td>- Helium supply (up to 25 g/s)</td>
<td>- Pressure drop up to 0.5 MPa</td>
</tr>
<tr>
<td>- Pressure drop and HTC are determined.</td>
<td>- Helium supply up to 50 g/s in Stage 1</td>
</tr>
<tr>
<td></td>
<td>- up to 600 g/s in Stage 2</td>
</tr>
<tr>
<td></td>
<td>- E-beam up to 120 kW</td>
</tr>
<tr>
<td></td>
<td>(15 MW/m² on up to 28 small fingers)</td>
</tr>
</tbody>
</table>
6. Experiments

Test Program 2004 to 2006

**EFREMOV GPF + reversed HHF**

**EFREMOV He-Loop + E-Beam**

**Test program for 2004:**
- 9 x 1-Finger-Cu-Mock-ups for HEMJ
- 3 x 1-Finger-Cu-Mock-ups for HEMS

**Test program for 2005:**
- 7 x 1-Finger-W-Mock-ups for HEMJ
- 4 x 1-Finger-W-Mock-ups for HEMS

**Test program for 2006:**
- 4 x 9-Finger-W-Mock-ups for HEMJ
- 2 x 9-Finger-W-Mock-ups for HEMS

2004 only stationary tests,
2005 and 2006 additional
transient and destructive tests
HEMJ cartridges for GPF2 experiments

HEMJ J1-a

HEMJ J1-b

HEMJ J1-c

HEMJ J1-d

HEMJ J1-e

Tube for mockup
GPF 2 (NOVEMBER) RESULTS (Δp)

- HEMS S1c24 N3
- HEMJ-J1a, D/h = 0.6/1.2
- HEMJ-J1e, D/h = 0.85/0.9

CFD J1a

CFD J1e

Pressure loss (MPa) vs Mass flow rate (g/s)

- Nominal 6.8 g/s

S1c24 N3, MJ1e N1, MJ1e N2, MJ1e N3, MJ1a N3, MJ1a N4, dp-J1a cal., dp-J1e-cal.
GPF 2 (NOVEMBER) RESULTS (power)

- HEMJ-J1a, D/h = 0.6/1.2
- HEMJ-J1e, D/h = 0.85/0.9

- CFD J1a
- CFD J1e

Mass flow rate (g/s) vs. Divertor performance (MW/m²)

- S1c24 N3
- MJ1e N1
- MJ1e N2
- MJ1e N3
- MJ1a N3
- MJ1a N4
- MJ1a N5
- pow-J1a-cal.
- pow-J1e-cal.

Nominal 6.8 g/s
Experiments: HEBLO (FZK) – Test facility for CFD-Validation

Testprogram for 2004 / 2005:
- 10:1 Mock-up for HEMJ
- 10:1 Mock-up for HEMS
- 10:1 Mock-up for HEMP

HEMJ: to start summer 2005
HEMS: finished, evaluation under way
Experiments: HEBLO (FZK) – Test facility for CFD-Validation

Temperature Cycle
- Operation pressure: 8 MPa
- Helium flow rate: 120 g/s
- Helium temp. (max.): 430 °C
- He-heating power: 60 kW
- Surface heating: 3 kW

Testprogram for 2004 / 2005:
- 10:1 Mock-up for HEMJ
- 10:1 Mock-up for HEMS
- 10:1 Mock-up for HEMP
Manufacturing of the mock-ups for 2005-2006 R&D programme

Domed thimbles (manufacturing step 4)
Conclusion and outlook (1/2)

- Two divertor conceptual designs based on HETS (ENEA) and HEMJ (FZK) have been defined.
- The designs are based on extrapolations of the materials data and physical boundary conditions from today’s knowledge with many factors of uncertainty.
- Results of systematic investigations show that 10 MW/m² could be achieved with satisfactory performances (pressure drop, Helium temperatures, efficiency of power generation systems, etc).
- Pressure loss and heat transfer coefficient have been calculated. A verification with experiments is ongoing (programme started in 2004).
- Promising fabrication methods for divertor components have been defined, further R&D works required.
- Technological experiments concerning W/W and W/steel joints successfully performed at Efremov, further R&D needed for improvement (FZK).
Conclusion and outlook (2/2)

- Building of helium loop in EFREMOV started in 2004, first experiments can start presumably this autumn.

Long-term:
- The development of a suitable W alloy as structural material today is the main feasibility issue.
- Irradiation-induced properties of these advanced alloys are also needed.
- Development of the manufacturing technologies for tungsten divertor components will be continued.
- Preparatory task for TDM is being launched.
Objectives: He-cooled Divertor on the way to ITER & DEMO