A Conceptual Study of a system combines FS-MSR and ESS

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Topic Introduction

- **Development of clean energy system technology**
  - Without pollutant & supply of electricity stays constant the day
  - Distributed power ➔ high inherent safety

  - FS-MSR is new generation reactor which have long life time (50 years) without online-refueling
  - Target FS-MSR is 100MW\textsubscript{th} power
  - LAES has large energy storage capacity
  - LAES collects carbon dioxide and fine dust during energy conversion and supplies clean air.
Topic Introduction

- **Passive residual heat removal system (PRHRS) for Fast-Spectrum Molten Salt Reactor (FS-MSR).**
  - RVACS: Reactor Vessel Auxiliary Cooling System
  - Passive safety system which air cooled by natural circulation
  - Prevent the core temperature increasing after reactor shutdown.

- **Find out the feasibility of RVACS**
  - Simple evaluated by MATLAB calculation
  - Optimizing design parameters for 100MW$_{th}$ FS-MSR

![Fig1. RVACS System](Image)
Background Study -core

- Fuel efficiency: online-refueling problem
- Low waste production: fast neutron < thermal neutron

\[
\begin{align*}
\text{Uranium-238} + n^1 & \rightarrow \text{Uranium} \\
\text{Neutron} (\text{Fast}) & \rightarrow \text{Neptunium} \\
\text{Plutonium-239} (\text{Fissile isotope}) & \rightarrow \text{Pu}^{239}
\end{align*}
\]

\[
\begin{align*}
\text{Pu}^{239} + n^1 & \rightarrow \text{Pu}^{240} \\
\text{Neutron} (\text{Thermal}) & \rightarrow \text{Zirconium} \\
\text{Plutonium} (\text{Unstable}) & \rightarrow \text{Xenon} \\
\text{Neutrons} (\text{Fast}) & + 207.1 \text{MeV}
\end{align*}
\]

Fig2. U-238 reaction in Fast reactor

- Chloride based salt
  - Moderator effect: Fluoride based salt > Chloride based salt
  - Viscosity: Fluoride based salt > Chloride based salt → high power density by pump

<table>
<thead>
<tr>
<th>Molten salt</th>
<th>Viscosity (kg/m*s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LiF-NaF-KF  (46.5-11.5-42)</td>
<td>6.3e-3</td>
</tr>
<tr>
<td>LiF-NaF-ZrF₄  (26-37-37)</td>
<td>16.6e-3</td>
</tr>
<tr>
<td>LiCl-KCl   (59.5-40.5)</td>
<td>1.8e-3</td>
</tr>
<tr>
<td>NaCl-KCl-MgCl₂ (30-20-50)</td>
<td>2.1e-3</td>
</tr>
</tbody>
</table>
Background Study - core

**Target reactor core design parameters**

- Eutectic point: mole fraction 54%
- Fuel salt: 46KCl-54UCl₃
- Cl enrichment: 99 a/o
- U235 enrichment: 19.75 w/o
- Core temperature: 650 °C
- Core diameter (height): 218 cm
- Initial heavy metal inventory: 35,576 kg
- Initial excess reactivity: 6608 ± 15 pcm

**Helium bubbling ➔ remove noble metal**

**Off-gas system ➔ gaseous fission products**

Fig 2. Reactor core design
Background Study - ESS

- **Electricity consumption rate by hour in July**
  - 34.7% higher at noon to midnight ➞ need a energy storage

- **ESS type: Liquid air energy storage (LAES)**
  - LAES should have a capacity to store at least 14.8% of power generation
  - 4.44MWe/53.28MWh capacity energy storage system is needed.

Fig3. power consumption (July, 2020)
Background Study - ESS

A supercritical CO₂ power conversion system applied

- High temperature Brayton cycle, high efficiency than rankine cycle (< 5%)
- Carbon dioxide capture mechanism
- High density fluid make system simplify
- Propose system optimum turbomachinery speed is 10,000RPM, 40cm, type is radial multi stage.

Thermal energy storage (TES) to store heat transferred without temperature decrease

- Control the reactivity (temperature control)
- Hot & Cold insulated tank
- ex) Crescent Dunes (USA), Andasol (Spain), Aurora (Australia)

Fig 4. sCO₂ optimum
Background Study - ESS

Fig5. Combines System
Background Study - RVACS

- There are no previous study about RVACS application for FS-MSR.
  - Direct reactor auxiliary cooling system (DRACS), Primary reactor auxiliary cooling system (PRACS) exists
  - The RVACS heat removal capacity was investigated for similar types of reactor
  - The existing models were compared, and satisfactory heat removal criteria were determined

- IRACS fails completely, RVACS is able to remove shutdown heat as a fully passive system of air convection.

![Fig6. Heat removal path](image.png)

LOHS- Loss of heat sink
UHS- Ultimate heat sink
Background Study - RVACS

- PRISM reactor has RVACS that heat removal capacity was 0.7% of full power using the air. Also, SAFR reactor has 0.6% heat removal capacity and Phenix reactor has 0.7%.

- These reactors have different characteristics from FS-MSR, because neutron leakage rate and temperature distribution are totally different. However these reactor was designed heat removal capacity is about 0.6~0.7 % of full power. Therefore, it is applicable if the target heat removal of FS-MSR satisfies under 0.6%

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Power (MWth)</th>
<th>Coolant</th>
<th>RVACS method</th>
<th>Heat remove (% full power)</th>
<th>mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRISM</td>
<td>840</td>
<td>Sodium</td>
<td>RVACS with air</td>
<td>0.7</td>
<td>Natural</td>
</tr>
<tr>
<td>SAFR</td>
<td>900</td>
<td>Sodium</td>
<td>RVACS with air</td>
<td>0.6</td>
<td>Natural</td>
</tr>
<tr>
<td>IMSR</td>
<td>400</td>
<td>Molten Salt</td>
<td>RVACS with Nitrogen</td>
<td>unknown</td>
<td>Natural</td>
</tr>
<tr>
<td>Phenix</td>
<td>840</td>
<td>Sodium</td>
<td>RVACS with water</td>
<td>0.7</td>
<td>Forced</td>
</tr>
<tr>
<td>CLEAR-I</td>
<td>45</td>
<td>Lead</td>
<td>RVACS with air tubes</td>
<td>0.2</td>
<td>Natural</td>
</tr>
</tbody>
</table>

Table 3. RVACS application reactor features [3]
Research Question

- **Find out the feasibility of Reactor Vessel Auxiliary Cooling System (RVACS)**
  - The exist RVACS’s target feature ability is 0.2 ~ 0.7%
  - RVACS target for FS-MSR is remove 0.6% of full power (600kW<sub>th</sub>)

- **Optimizing design parameters for our target reactor**
  - CV outer wall temperature affects heat removal ability
  - Total heat removal capacity
  - Stack height
  - Air path thickness
RVACS test methods

- Using MATLAB code calculation (natural circulation)
  - Simplified geometry (overflow x)
  - Considering: pressure drop, Convection & Radiation heat transfer
  - Changing values: Air patch thickness, mass flow rate

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air inlet Temperature</td>
<td>50 °C</td>
</tr>
<tr>
<td>CV temperature</td>
<td>600 °C</td>
</tr>
<tr>
<td>CV diameter</td>
<td>3 m</td>
</tr>
<tr>
<td>Air path thickness</td>
<td>3 – 7 cm</td>
</tr>
<tr>
<td>Air mass flow rate</td>
<td>1 – 3 kg/s</td>
</tr>
</tbody>
</table>

Table1. RVACS design parameter

Fig7. RVACS cross section

Fig8. RVACS side view drawing
RVACS test results

- **Target of heat removal capacity is 0.6% of the full power.**
  - 100MW\textsubscript{th} reactor using, so 600kW\textsubscript{th} decay heat removal capacity design
  - Case3 is optimization design (stack height is acceptable (<15m) and high heat removal)

<table>
<thead>
<tr>
<th>Case</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air path thickness</td>
<td>3cm</td>
<td>3.5cm</td>
<td>4cm</td>
<td>4.5cm</td>
</tr>
<tr>
<td>Air mass flow rate</td>
<td>2kg/s</td>
<td>2.5kg/s</td>
<td>3kg/s</td>
<td>3kg/s</td>
</tr>
<tr>
<td>Stack height</td>
<td>12.4m</td>
<td>13.2m</td>
<td>14.0m</td>
<td>10.5m</td>
</tr>
<tr>
<td>Heat remove</td>
<td>552.0kW</td>
<td>588.0kW</td>
<td>611.0kW</td>
<td>560.0kW</td>
</tr>
<tr>
<td>Air outlet temperature</td>
<td>317.3°C</td>
<td>278.5°C</td>
<td>248.4°C</td>
<td>232.1°C</td>
</tr>
<tr>
<td>Air heat transfer coefficient</td>
<td>27.6W/m2K</td>
<td>27.7W/m2K</td>
<td>27.6W/m2K</td>
<td>24.4W/m2K</td>
</tr>
</tbody>
</table>

Fig9. Heat removal rate  
Fig10. Stack height  
Table2. Code calculation results
RVACS test results

- The percent of convection decay heat removal is 55%.
- If containment vessel wall temperature increase
  - Heat removal capacity is increase.
  - Necessary stack height is decrease.

Fig11. The ratio of convection to radiation heat removal

Fig12. Heat removal

Fig13. Stack height
RVACS test results

- Evaluate the applicability to higher reactor power ($200, 300 \text{MW}_{th}$)
  - Air path thickness is 4 cm fixed
  - CV diameter, stack height are variables

- Increase CV diameter is essential to improve RVACS performance

Fig 14. Stack height (200MWth)

Fig 15. Stack height (300MWth)
Limitation of Study & Future work

- This is preliminary conceptual study about RVACS application for FS-MSR
  - There many assumptions (especially concrete silo temperature was unapplied)
  - It is difficult to obtain the CV outer wall temperature distribution (viscosity, heat conductivity coefficient)
  - The placement of Internal Heat Exchanger(IHX) and internal structure of reactor vessel also need to considered

- Ar41 is produced from irradiation of air due to neutron leakage
  - Looking for a solution to prevent air pollution
  - Closed circuit geometry (valve or damper)
  - Compare heat loss in normal operation and mechanical operation
Conclusion

- **Combination system**
  - Fast spectrum Molten salt reactor
  - TES + LAES + sCO$_2$ power conversion
  - RVACS, residual heat removal

- The feasibility of RVACS evaluation result is enough to decay heat removal after 100MWth reactor shutdown.

- **Optimized design for 611kW$_{th}$ decay heat removal using RVACS**
  - Air path thickness is 4cm, air mass flow rate is 3kg/s
  - The required stack height is 14m
  - Air heat transfer coefficient is 27.6 W/m$^2$ K
References


Thank you