Improvement of hydraulic flow analysis code for APWR reactor internals

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Nuclear Power Engineering Corporation (NUPEC)

(PS) This study was performed under the sponsorship of METI
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2. Results of the hydraulic flow characteristics analysis of reactor internals
3. Results of the dynamic pressure analysis of downcomer
4. Conclusion
## Background

Schedule of the project: Improvement of hydraulic flow analysis code for APWR reactor internals

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<td>Improve CFD (Computational Fluid Dynamics) code</td>
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<td>Experiment</td>
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<td>Design &amp; Produce test facility</td>
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Safety Review
In safety review, it is necessary for the regulatory body to develop its own analysis codes in order to independently evaluate the safety analysis results done by applicant.

One of the most innovative design improvement of APWR is the neutron reflector which replaces the conventional baffle-former structure.

Concerns:

- Coolability of the neutron reflector by heating
- Fluid-structure interaction (FSI) caused by dynamic pressure fluctuation

Develop analysis codes to evaluate the concerns.

Verification of analysis code based on the results of hydraulic flow test using 1/5 scale mode.
The features of APWR reactor internal and concerns

**APWR** will be the first power plant to adopt the neutron reflector in the world.

**Concerns**

1. Coolability of the neutron reflector by $\gamma$-heating. (because the neutron reflector is thick stainless steel structure.)

2. FSI vibration caused by dynamic pressure fluctuation. (because the neutron reflector stands alone in the core barrel with the narrow water gap between the core barrel and itself. FSI vibration is induced by dynamic pressure fluctuation of the downcomer.)
Countermeasure to problem 1

Coolability of the neutron reflector by \( \gamma \)-heating

| Feature |  
|---------|---|
| As the neutron reflector is composed of 8 ring blocks made of stainless steel and 1500 cooling holes.  
| Open plenum is prepared in order to make uniform the coolant into the neutron reflector.  |

| Event |  
|-------|---|
| In the case of shortage of the coolant,  
| \( \Rightarrow \) Temperature of the neutron reflector rises.  
| \( \Rightarrow \) The neutron reflector will deform.  
| In the case of lack of uniformity of the coolant distribution,  
| \( \Rightarrow \) Lack of uniformity of the neutron reflector's temperature  
| \( \Rightarrow \) The neutron reflector will deform.  |

| Requirement | Coolant should flow into the neutron reflector uniformly.  |

\[\downarrow\]

Confirm the flow distribution into the flow hole of the neutron reflector

\[\downarrow\]

Countermeasure

Some analysis codes can simulate the hydraulic flow characteristic analysis. But they have not verified to applied to the complicated flow pass in APWR reactor internal.  
\( \Rightarrow \) Verify analysis code by using the results of experiment which is exactly imitated to the reactor internal structure reduced to a scale of one fifth.
Countermeasure to problem 2

FSI vibration caused by dynamic pressure fluctuation

| Feature | The neutron reflector stands alone in the core barrel with the narrow water gap. |
|         | The neutron reflector is fixed by the tie rods at the lower core plate. |

| Event | Vibration of the barrel and neutron reflector induced by dynamic pressure fluctuation at the downcomer. |
|       | It is concerned whether FSI vibration of the neutron reflector affects the fuel assembly integrity. |

| Requirement | Vibration magnitude of the neutron reflector should not be excessive. |

Confirm the magnitude of the neutron reflector's vibration.

| Countermeasure | There are no analysis codes verified to apply to the complicated structure in APWR reactor internal. |
|               | ⇒ Verify analysis code by using the results of experiment which is exactly imitated to the reactor internal structure reduced to a scale of one fifth. |
Flow pattern in APWR reactor vessel

Guide tube
Upper support plate
Outlet nozzle
Upper support column
Inlet nozzle
main flow
by-pass flow
Reactor vessel
Core barrel
Fuel assembly
Upper core plate
Neutron reflector
Lower core support plate
Lower core plate
Developing analysis codes utilizing IMPACT code modules

<table>
<thead>
<tr>
<th>item</th>
<th>code</th>
<th>remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coolability of the neutron reflector by heating</td>
<td>CFD-1</td>
<td>CFD-1 should be parallel simulation code with Reynolds averaged numerical simulation method (k- model).</td>
</tr>
<tr>
<td>Flow-induced vibration by dynamic pressure fluctuation</td>
<td>CFD-2 + FELIOS</td>
<td>CFD-2 should be parallel simulation code with Large Eddy Simulation method or dynamic numerical simulation method.</td>
</tr>
</tbody>
</table>
Hydraulic flow analysis codes for APWR reactor internals

- **Hydraulic flow characteristics analysis of reactor internals**
  Improvement of Reynolds averaged numerical simulation method (k-model) with unstructured grid

- **Dynamic pressure analysis of the downcomer**
  Improvement of Large Eddy Simulation method with structured grid
Objective of hydraulic flow characteristics analysis of reactor internals

To establish the numerical method to exactly calculate flow distribution into the neutron reflector

Measurement items in this experiment

- Flow distribution into the neutron reflector
- Pressure distribution on the lower core plate
- Pressure distribution of the lower plenum
### Calculation Conditions

| Analysis Case | Hydraulic flow characteristics analysis  
| Flow rate: 100 , Temperature: 150 |
|---|---|
| Calculation Grid System | Unstructured /or structured (BFC with Multi-block Methodl) |
| Time Marching Method | SIMPLE (Semi-Implicit Method-for Pressure-Linked Equation) |
| Turbulent Model | k- model (Reynolds averaged numerical simulation method) |
| Discretization | Transient term | Euler implicit |
| | Convection term | Donor-Cell method |
| Properties | Density | 917.0 [kg/m³] |
| | Viscosity | 1.80 \(10^{-4}\) [Pa. s] |
| Boundary Condition | Inlet | Constant: \(Vin=16.674\) [m/s] |
| | Outlet | Free out |
| | Wall | Log-Law |
Velocity distribution in the Reactor vessel

90° - 270° cross section

180°  90°

Velocity m/s

18

0
Comparison between Calculation and Experiment

(Flow distribution into radial reflector)

Flow distribution
(Ratio to average)

Structured grid
(770,000 meshes)

Unstructured grid
(620,000 meshes)

Flow hole

Flow hole number

Lower core plate
(test facility)
Comparison between Calculation and Experiment

(Flow and pressure distribution at the entrance of neutron reflector)

Flow rate distribution into neutron reflector (ratio to average)

Pressure distribution on lower core plate (difference from average kPa)
Comparison between Calculation and Experiment

(Pressure distribution in the lower plenum: bottom surface of test vessel)

Experiment

Calculation
Objective of dynamic pressure analysis of downcomer

To establish the numerical method to calculate dynamic pressure induced by turbulent flow in downcomer.

Improve the code with LES to calculate adequately dynamic pressure by turbulent flow, selected in the 3-dimensional flow analysis code which can simulate the model of flow passage.
Measuring Points of Dynamic Pressure

- Upper
- Middle
- Lower

compared with experiment

Circumferential point
Reference point
Axial point
## Calculation Conditions

<table>
<thead>
<tr>
<th>Analysis Case</th>
<th>LES (Analysis for optimized Cs value)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flow rate: 100, Temperature: 150</td>
</tr>
<tr>
<td>Calculation Grid System</td>
<td>BFC with Multi-block Method</td>
</tr>
<tr>
<td>Time Marching Method</td>
<td>SMAC (Simplified Marker And Cell Method)</td>
</tr>
<tr>
<td>Turbulent Model</td>
<td>LES (Smagorinsky eddy viscosity model: Cs=0.17)</td>
</tr>
<tr>
<td>Discretization</td>
<td>Transient term: Euler Explicit</td>
</tr>
<tr>
<td></td>
<td>Convection term: QUICK</td>
</tr>
<tr>
<td>Calculation of Time Interval</td>
<td>4.0 $\times 10^{-5}$ [s]</td>
</tr>
<tr>
<td>Properties</td>
<td>Density: 917.0 [kg/m$^3$]</td>
</tr>
<tr>
<td></td>
<td>Viscosity: 1.80 $\times 10^{-4}$ [Pa .s]</td>
</tr>
<tr>
<td>Boundary Condition</td>
<td>Inlet: Constant: $V_{in}$=16.674 [m/s]</td>
</tr>
<tr>
<td></td>
<td>Outlet: Sommerfeld Condition</td>
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<tr>
<td></td>
<td>Wall: Log-Law</td>
</tr>
</tbody>
</table>
Calculation Grid

(a) Core Barrel

(b) Reactor Vessel

Calculation grid both side of wall
Calculation Results

(a) Core Barrel

(b) Reactor Vessel

Mean Velocity contour of downcomer

CFD meeting presentation
Calculation Results

(a) Core Barrel

(b) Reactor Vessel

Turbulent energy contour of downcomer
Calculate the dynamic pressure by turbulent flow to t = 0.6s. The data from t = 0.24s to t = 0.6s was used in statistical analysis.

Figure.4 Dynamic Pressure  
(90 of downcomer see page 17)
## Calculation Results

<table>
<thead>
<tr>
<th>Axial position</th>
<th>Circumferential Position</th>
<th>Calculation</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper</td>
<td>0 [deg]</td>
<td>2.80 1.40</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>45 [deg]</td>
<td>6.20 1.27</td>
<td>4.9</td>
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<td></td>
<td>90 [deg]</td>
<td>11.75 2.35</td>
<td>5.0</td>
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<tr>
<td></td>
<td>135 [deg]</td>
<td>6.49 1.30</td>
<td>5.0</td>
</tr>
<tr>
<td>Middle</td>
<td>0 [deg]</td>
<td>1.75 1.03</td>
<td>1.7</td>
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<tr>
<td></td>
<td>90 [deg]</td>
<td>2.50 1.39</td>
<td>1.8</td>
</tr>
<tr>
<td>Lower</td>
<td>0 [deg]</td>
<td>1.57 0.79</td>
<td>2.0</td>
</tr>
<tr>
<td></td>
<td>90 [deg]</td>
<td>1.45 0.90</td>
<td>1.6</td>
</tr>
</tbody>
</table>

\[
\tilde{P}_{RMS}^2 = \int_{f_{\min}}^{f_{\max}} P_{xx}(f) \cdot df \approx \sum_{k=k_{\min}}^{k_{\max}} P_{xx}(f) \cdot \Delta f \quad (f = k \cdot \Delta f)
\]

( ) : C/E value

### RMS Value of Dynamic Pressure

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Definition: RMS Spectrum

\[
S_{xx}(f) = \frac{\tilde{p}_{RMS} \cdot C_{xx}(f)}{\sqrt{\sum_{k} \{C_{xx}(f)\}^2 \cdot \Delta f}}
\]

\( f = k \cdot \Delta f \)

\( C_{xx} \) is the magnitude of Fourier coefficient

\( \tilde{p}_{RMS} \) is RMS value

Spectrum Analysis

Sampling cycle is \( 8 \cdot 10^{-5} \) [s]

The spectrum is the ensemble average of Fourier coefficient calculated by 2048 samples per one section.
Calculation Results

RMS Spectrum (90° of downcomer)

CFD meeting presentation
**Definition: Normalized Cross-Spectrum**

\[ \Gamma_{xy}(f) = \frac{P_{xy}(f)}{\sqrt{P_{xx}(f) \cdot P_{yy}(f)}} \]

- \( P_{xy}(f) \) is the real part of the cross spectrum.
- \( P_{xx}(f), P_{yy}(f) \) is the power spectrum.

**Normalized Cross-Spectrum Approximated by Turbulent Theory**

‡ @Axial Correlation

\[ \Gamma_{xy}^*(f) = \Gamma_0 \cdot e^{-C_1 f} \cdot \cos \left( 2\pi f \frac{|x - y|}{U_c} \right) \]

‡ @Circumferential Correlation

\[ \Gamma_{xy}^*(f) = \Gamma_0 \cdot e^{-C_1 f} \]

**Uc:** Convection velocity is calculated from the peak of the cross-correlation coefficient.

**C1:** Is approximated by the method of least squares using the normalized cross-spectrum ranging the frequency shown by thick line.

CFD meeting presentation
Calculation Results

Normalized Cross Spectrum (90° of downcomer)

Calculation

Cross spectrum [-]

Frequency [Hz]

Upper point  Middle point  Lower point

Experiment

Cross spectrum [-]

Frequency [Hz]

Upper point  Middle point  Lower point
Calculation Results

Definition: Coefficient of Cross Correlation

\[
R_{xy}(\tau) = \frac{C_{xy}(\tau)}{\sqrt{C_{xx}(\tau)|_{\tau=0} \cdot C_{yy}(\tau)|_{\tau=0}}}
\]

\(C_{xy}(\tau)\): cross-correlation function

\(C_{xx}(\tau), C_{yy}(\tau)\): auto-correlation function

Auto-Correlation Function. Inverse-Fourier transform of power-spectrum

\[
C_{xx}(\tau) = \int_{-\infty}^{\infty} P_{xx}(f) \cdot e^{-2\pi ft} dt
\]

\[
C_{yy}(\tau) = \int_{-\infty}^{\infty} P_{yy}(f) \cdot e^{-2\pi ft} dt
\]

Cross-Correlation Function. Inverse-Fourier transform of cross-spectrum

\[
C_{xy}(\tau) = \int_{-\infty}^{\infty} P_{xy}(f) \cdot e^{-2\pi ft} dt
\]
## Calculation Results

### Convection velocity

<table>
<thead>
<tr>
<th>Axial position</th>
<th>Circumferential Position</th>
<th>Calculation</th>
<th>Experiment</th>
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</thead>
<tbody>
<tr>
<td>Upper</td>
<td>0 [deg]</td>
<td>7.38</td>
<td>5.4</td>
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<td>45 [deg]</td>
<td>9.82</td>
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<td></td>
<td>90 [deg]</td>
<td>12.00</td>
<td>12.6</td>
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<td></td>
<td>135 [deg]</td>
<td>9.58</td>
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<td>Middle</td>
<td>0 [deg]</td>
<td>9.19</td>
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<td>90 [deg]</td>
<td>8.93</td>
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<td>Lower</td>
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<td>90 [deg]</td>
<td>10.78</td>
<td>9.4</td>
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</table>
Calculation Results

**Definition : Correlation Length**

\[ \lambda = - \frac{|x - y|}{\ln |\Gamma_{xy}|} \]

|Γ_{xy}| : Absolute normalized cross-spectrum approximated by turbulent theory

|x - y| : Distance between measuring point x to y (=50mm)
Calculation Results

**Calculation**

![Graphs showing correlation length vs. frequency for different points.](image)

**Experiment**

![Graphs showing correlation length vs. frequency for different points.](image)

Correlation length (90 deg Axial direction)

CFD meeting presentation
Calculation Results

Correlation length (90 deg Circumferential direction)

Calculation

<table>
<thead>
<tr>
<th>Frequency [Hz]</th>
<th>Correlation length [mm]</th>
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<tbody>
<tr>
<td>Upper point</td>
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<td>Middle point</td>
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<td>Lower point</td>
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Experiment

<table>
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<tr>
<th>Frequency [Hz]</th>
<th>Correlation length [mm]</th>
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<td>Middle point</td>
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<td>Lower point</td>
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CFD meeting presentation
Conclusion

- CFD-1 with unstructured grids, SIMPLE method and k-turbulent model show good agreement with the experiments data.
- Considering present CFD technique, CFD-2 with structure grids (BFC method), SMAC method and LES turbulent model is the best combination for the analysis of dynamic pressure fluctuation.
- Basically, CFD-1 and CFD-2 are applicable to plant operating condition. For better evaluation, it is planned to confirm that the numerical method of 1/5 scaled model is rightly applied to a real scale simulation.