Investigating the Cooling Ability of Reactor Vessel Head Injection in the Maanshan PWR Using CFD Simulation

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ABSTRACT

In order to reduce the crack growth rate on the welding of penetration pipe, Pressurized Water Reactor (PWR) of Maanshan nuclear power plant (NPP) uses vessel head injection to cool vessel lid and control rod driving components. The injection flow from the cold leg is drained by the pressure difference between cold leg and upper internal components. In this study, 10 million meshes model with 4 sub-models have been developed to simulate the thermal-hydraulic behavior by commercial CFD program FLUENT. The results indicate that the injection nozzles can provide good cooling ability to reduce the maximum temperature for lid on the vessel head. The maximum temperature of vessel lid is about 293.81°C. Based on the simulated temperature, ASME CODE N-729-1 was further used to recount the effective degradation years (EDY) and reinspection years (RIY) factors. It demonstrates that the EDY and RIY factors are still less than 1.0. Therefore, the re-inspection period for Maanshan PWR would not be significantly affected by the miner temperature difference.

1. INTRODUCTION

In February 2010, a maintenance check for the Davi-Basses PWR found 24 cracks on the welding between penetration pipe and reactor vessel head again. The reactor coolant leaked to the outlet of reactor and forms visible boron crystals on the penetration pipes. This means that the pressure boundary for the D.B. NPP is not safety enough. The same problem was found in the NPP at 2002 and caused 2 years operating benefit loss for the NPP owner-FirstEnergy Co. Based on ASME code N-729-1[1], the growth rate of cracks is directly related to the temperature of the vessel lid. As the lid temperature being higher than reference temperature ($T_{ref}=588.71K$), the crack on the welding would fast grow due to a positive factor which causes a higher crack energy. Reversely, the crack would slowly grow because a lower lid temperature forms a negative factor in an exponential equation. Actually, the D.B. NPP has no cooling designs to reduce the lid temperature, and that would cause the core water heating the vessel lid via the upper plate of the upper internal component (Fig. 1). This design causes a high
temperature situation around the vessel lid due to the maximum core flow temperature (> 605K) higher than \(T_{ref}\). This is the major reason why the welding on vessel lid for D.B. NPP has the serious crack growing problem.

In Taiwan, the issue has been highly paid attention by the Atomic Energy Council (AEC). ACE demands that the Taiwan Power Company, TPC, should provide enough evidence to prove the safety of Maanshan PWR. Maanshan PWR is a 2-units with 3-loop Westinghouse PWR and operated by TPC since 1984. Actually, a new design of vessel lid with vessel head injection cooling system has been used to cool down the lid temperature in this series of Westinghouse PWR. This design drains the cold water from the cold leg by pressure difference and injects the cold water into the vessel head (Fig. 1) by 24 nozzles with two inches diameter. The cold water carries the heat from the upper internal component. Finally, the cooling water would flow out the vessel head via the gaps between control rod guide tubes (CRGT) and driven rods, and that water can reduce the temperature of CRGT.

However, even the TPC states the cooling design has been used in the Maanshan PWR, AEC still demands TPC to prove its safety by confidence quantification evaluation. Considering the hydraulic phenomenon and cooling ability for the vessel head injection design is difficult modeled by a traditional analysis tool, such as RETRAN [2]. Therefore, a CFD model based on the commercial CFD code, FLUENT [3], has been developed to predict the temperature value for the vessel lid of Maanshan PWR in this work. Entire model includes control rod, cold lets, CRGT and upper internal component are details constructed in the CFD model.

2. MATHEMATICAL MODELS DESCRIPTIONS

2.1 Governing Equation [4]

In view of the injection flow driven by the pressure difference between cold leg side and upper internal component side, the entire CFD model is composed of cold leg, core forging, fuels, upper internal component, and CRGT.

The flow condition in PWR system can be set as a single phase, high Reynolds number with incompressible fluid problem. Therefore, the governing equations can be written as follows:

2.1.1 Continuity Equation

\[
\nabla \cdot \left( \rho \mathbf{v} \right) = 0
\]

where,

\(\rho = \text{fluid density}\)

\(\mathbf{v} = \text{velocity vector}\)

2.1.2 Momentum Equation

\[
\nabla \cdot \left( \rho \mathbf{v} \cdot \mathbf{v} \right) = -\nabla p + \nabla \cdot \left( \tau \right) + \mathbf{F}
\]

where,

\(p = \text{static pressure}\)

\(\mathbf{F} = \text{additional force term per unit volume}\)

\(\mathbf{v} \cdot \mathbf{v} = \text{dyadic product}\)

\[
\mathbf{v} \cdot \mathbf{v} = \begin{bmatrix}
u_1^2 \quad \nu_1 \nu_2 \quad \nu_1 \nu_3 \\ 
\nu_2^2 \quad \nu_2 \nu_1 \quad \nu_2 \nu_3 \\ 
\nu_3^2 \quad \nu_3 \nu_1 \quad \nu_3 \nu_2 
\end{bmatrix}
\]

(3)

\[\mathbf{F} = \text{stress tensor} = \mu \left[\nabla \mathbf{v} + \nabla \mathbf{v}^T - \frac{2}{3} \nabla \cdot \mathbf{I}\right]
\]

(4)

where

\(\mu = \text{viscosity of fluid}\)

\(\mathbf{I} = \text{unit tensor}\)

2.1.3 Energy Equation

\[
\nabla \cdot \left( \rho E + p \right) = \nabla \cdot \left( \kappa \nabla T \right)
\]

(5)

where

\(h = \text{enthalpy}\)

\(\kappa_{eff} = \text{effective thermal conductivity}\)

\(= k + k_t\)

(6)

where

\(k = \text{molecule conductivity}\)

\(k_t = \text{turbulent conductivity}\)

2.2 Turbulence Model

In this work, a \(k - \omega\) turbulent model [5, 6] is utilized to model the turbulent characteristics. The \(k - \omega\) can be represented as two equations (\(k\) and \(\omega\)) as follows.

\[
\frac{\partial}{\partial x_j} \left( \rho u_i \right) = \frac{\partial}{\partial x_j} \left( \Gamma_k \frac{\partial k}{\partial x_j} \right) + \hat{G}_k - Y_k + \hat{S}_k
\]

(7)

\[
\frac{\partial}{\partial x_j} \left( \rho \omega_i \right) = \frac{\partial}{\partial x_j} \left( \Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + \hat{G}_\omega - Y_\omega + \hat{S}_\omega
\]

(8)

where

\(k = \text{turbulent kinetics energy}\)

\(\omega = \text{dissipation rate}\)

\(\hat{G}_k = \text{gradient of turbulent kinetics energy}\)

\(\hat{G}_\omega = \text{gradient of dissipation rate}\)

\(Y_k = \text{turbulent dissipation term in } k\) equation

\(Y_\omega = \text{turbulent dissipation term in } \omega\) equation

\(\hat{S}_k = \text{source term for the } k\) equation

\(\hat{S}_\omega = \text{source term for the } \omega\) equation

\(\Gamma_k\) and \(\Gamma_\omega\) are effective diffusion terms

\[
\Gamma_k = \mu + \frac{\mu}{\sigma_v}
\]

(9)

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\[ \Gamma_\omega = \mu + \frac{\mu_i}{\sigma_\omega} \]  
(10)

where

\[ \sigma_k \text{ and } \sigma_\omega = \text{turbulent Prandtl number} \]
\[ \mu_i = \text{turbulent viscosity of fluid} \]

\[ = \alpha^* + \frac{\rho k}{\omega} \]  
(11)

where

\[ \alpha^* = \text{turbulent damping} \]

\[ = \alpha^* + \left( \alpha^* + \frac{Re / R_i}{1 + Re / R_i} \right) \]  
(12)

where

\[ \alpha^*_0 = \text{damping} \]

\[ Re_i = \frac{\rho k}{\mu \omega} \]  
(13)

\[ R_i = 6 \]  
(14)

\[ \alpha^*_o = \frac{\beta}{3}, \beta_i = 0.072 \]  
(15)

2.3 Crack Growth Evaluation

In the work, ASME CODE N-729-1 [1] has been used to evaluate the crack growth factor, EDY can be calculated as:

\[ EDY = \sum_{j=1}^{n} \left\{ \Delta EFPY \exp \left[ \frac{Q_1}{R \left( \frac{1}{T_0} - \frac{1}{T_w} \right)} \right] \right\} \]  
(16)

and RIY can be calculated by:

\[ RIY = \sum_{j=1}^{n} \left\{ \Delta EFPY \exp \left[ \frac{Q_1}{R \left( \frac{1}{T_0} - \frac{1}{T_w} \right)} \right] \right\} \]  
(17)

where,

\[ Q_1 \text{ is the activation energy for crack initiation} = 130 \text{ kJ/mol;} \]
\[ Q_1 \text{ is the activation energy for crack growth} = 209 \text{ kJ/mol;} \]
\[ R \text{ is the universal gas constant} = 8.314 \text{ J/mol-K.} \]

\[ \Delta EFPY \text{ is the effective full power years accumulated during time period } j. \]

3. NUMERICAL TREATMENTS

3.1 Assumptions and Simplifications

According to above-mentioned assumptions and simplifications, Maanshan PWR reactor can be simulated by using a half model.
illustrated as the Fig. 2. In this mode, the whole reactor with major geometries has been carefully modeled but the core forging, fuel, and the inside components of CRGT were lumped as the above assumptions. The detail guide card geometries have been separated as four sub-models (Fig. 3) to calculate their flow resistances via CFD simulation.

An unstructured mesh system with multi-block setting was employed to generate the mesh in the very complex reactor system. In order to increase the accuracy in simulations, the minimum mesh size (0.25") was set as the meshing condition for the injection nozzles, upper-internal component. The maximum mesh size (2") was considered in downcomer, fuel, and forging. The growth rate for the meshes is controlled below than 1.1 in this problem. Through above meshing condition, the geometric model with about 10 million meshes for the half PWR model and 3 million for the one-eighth CRGT models were developed for following investigations. A preliminary sensitivity test also confirmed that the simulation difference in the selected mesh and 50% fining mesh is acceptable and can be ignored.

3.3 Boundary Conditions

In this study, the boundary conditions for the Maanshan PWR model can be listed as followed.

(1) Adiabatic boundary

All of the external walls are assumed as adiabatic walls.

\[
\frac{\partial T}{\partial N} = 0 \quad (18)
\]

(2) Velocity inlet

For the condition of cold-leg is assumed as velocity flowing. The inlet temperature and velocity are defined as:

\[
\bar{V}_{\text{in}} = \bar{V}_{\text{cold- leg, average}} \quad , \quad T_{\text{in}} = 291.96 ^\circ \text{C} \quad . \quad (19)
\]

(3) Pressure outlet

For the outlets of the model, a pressure boundary is utilized to model them:

\[
P_{\text{out}} = P_{\text{atm, gage}} \quad . \quad (21)
\]

(5) Core Temperature

The fission energy in the core is conservatively assumed as a fixed temperature:

\[
T_{\text{core}} = 337.78 ^\circ \text{C} \quad . \quad (22)
\]

(6) Flow resistance in the porous media

In this work, the behavior of flow resistance in the simplified core forging, fuel, and guide card was modeled by the porous media. The flow resistance can be presented as an additional source term in the momentum equations:

\[
\bar{F} = - \left( \frac{\mu}{\alpha} \bar{V} + C_s \frac{\rho \bar{V}^2}{2} \right) \quad . \quad (23)
\]

where,
\( \mu \) is the flow viscosity,
\( \rho \) is the density of water,
\( \bar{V} \) is the mean axis velocity,
\( \frac{1}{\alpha} \) is the friction loss coefficient,
\( C_s \) is the form loss coefficient.

The flow resistance of the fuel and forging in the Maanshan PWR analysis method [8] was utilized to set the flow behaviors. For the part of CRGT, the flow resistances were calculated by the developed one-eighth models with corresponding velocity range. Figure 5 shows the comparison between real one-eighth model and porous model pressure drop, and that proved that the porous model results fitted in with the real model results well. The calculated friction and form loss coefficients are listed in Table 1.

Fig. 2 The CFD model for Maanshan PWR in this simulation.

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Fig. 3 The detail geometry model for CRGT: (a) Part_I, (b) Part_II, (c) Part_III, (d) Part_IV.

Fig. 4 The mesh distribution for CFD model.

Table 1 The loss coefficients for CRGT.

<table>
<thead>
<tr>
<th>Model</th>
<th>1/α</th>
<th>C₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRGT-I</td>
<td>780875.15</td>
<td>5.2</td>
</tr>
<tr>
<td>CRGT-II</td>
<td>4505024</td>
<td>118.73</td>
</tr>
<tr>
<td>CRGT-III</td>
<td>267510.72</td>
<td>107.70</td>
</tr>
<tr>
<td>CRGT-IV</td>
<td>423534.85</td>
<td>71.98</td>
</tr>
</tbody>
</table>

4. RESULTS AND DISCUSSION

Figure 6 shows the pressure distribution on the entire PWR model. The cold water flows into the reactor via cold legs, and forms a high pressure region between the cold legs and vessel lid flange surface. This is because that the water flow with high velocity impacts the core liner and forms a stagnation region. The pressure also provides the driven force to overcome the flow resistance of injection nozzle and CRGT, so the vessel lid pressure is significantly lower than the cold-legs. Furthermore, the simulated result indicates that approximate 0.47% core flow would inject into vessel head. This result is close to the value (0.5%) proved from Westinghouse.

The most of water flows to the core forging and through the fuel. Then, the water flows into the upper-internal component via the apertures on the lower-plant or the end of CRGT of upper-internal component. Finally, the water leaves the reactor via the hot leg. Hence, the relative lower pressure value can be found in the hot-leg region.

The detail quantitative results (Table 2) further demonstrate that the CFD simulation results are quite equal to the reliable RETRAN results, except for a higher pressure drop can be found between upper-internal to hot-leg. This is because that a complex flow on the cross section induced by the leak flow from CRGT side would affect the flow distribution, and this phenomenon can not be modeled by RETRAN code.

Figure 7 shows the pressure distribution in the
upper-internal region. As the upward hot coolant from the core flows into upper-internal by the bottom windows of CRGTs, it will flows to hot leg. Based on the flow path, the pressure in the center of upper-internal would higher than the outside especially for the region near the hot leg. For this reason, the pressure on the center of upper-internal is higher than that near hot legs. The pressure distribution also demonstrates that the downward flow rate for the outside CRGTs will higher than the central CRGTs.

In the vessel head, the coolant would flow into this region by the injection nozzles and flow out via the gap of CRGTs. The high speed injection flow provides a large momentum for the coolant. Therefore, the cold coolant would flow to the top of vessel head along the curve of vessel lid (Fig. 8). As the upward injection flow reaches the top of vessel lid, it will flow down and exit the vessel head via the CRGT gaps. This flow pattern also demonstrates that the hot water from the core outlet would not flow into the vessel head, so the major heat transfer mechanism in the vessel head can be concluded by the conduction mechanism. This statement can be proved by the temperature distribution on the up-plate for the upper-internal component (Fig. 9). The decreased temperature on the up-plate shows the heat transfer direction between vessel head and upper-internal component.

The heat transfer mechanism also means that the maximum temperature for the vessel head would be higher than that for vessel lid. As shown in table 3, the simulated result shows the maximum temperature on the vessel lid was about 293.81°C, and the maximum temperature for the fluid in vessel head was 293.97°C.

Through above discussion, some findings can be concludes as follow:

1. The maximum temperature in the vessel lid was higher than cold-leg temperature. Even if the hot water of core outlet could not flow into vessel head, the hot water still heated up the vessel head via conduction mechanism.

2. The maximum temperature on the vessel head only slightly higher than that on the cold leg, but it was still lower than the $T_{ref}$.

3. Based on the Eqs. 16 and 17, a conservative EDY and RIY factor can be calculated from Table 4. The factors are slightly increased by the temperature, and their values still were less than 1.0. This result demonstrates that the re-inspection period would not be affected even if TPC re-calculates the EDY and RIY based on the CFD simulated temperature.

5. CONCLUSIONS

In this paper, the CFD methodology is developed to investigate flow distribution of the vessel head and the lid temperature. A 10 million meshes reactor model with 4 CRGT sub-model have been used to simulate the entire and local flow behaviors in Maanshan PWR. It found that the pressure and temperature distribution can be reasonable calculated by this model. The pressure difference in each components and injection flow rate demonstrated that the simulation results met with the Westinghouse design values well. Furthermore, the results indicated that the injection nozzle design could provide good cooling ability to reduce the maximum lid temperature on the vessel head. The maximum temperature of vessel lid was about 293.81°C, which slightly higher than cold-leg temperature. Finally, the recounting EDY and RIY factors demonstrated that the re-inspection period would not be significantly affected by the minor temperature difference.
Fig. 7 The simulated pressure distribution for the upper-internal component.

Fig. 8 The simulated flow path in the vessel head region.

Fig. 9 The simulated temperature distribution for the vessel head.

Table 3 the quantitative values for the Maanshan PWR

<table>
<thead>
<tr>
<th>Location</th>
<th>TEMP. (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Temp.</td>
<td>337.78</td>
</tr>
<tr>
<td>Vessel Head Fluid $T_{\text{max}}$</td>
<td>293.97</td>
</tr>
<tr>
<td>Vessel Lid $T_{\text{max}}$</td>
<td>293.81</td>
</tr>
</tbody>
</table>

Table 4 the quantitative values for the Maanshan PWR

<table>
<thead>
<tr>
<th>Temperature</th>
<th>EDY factor</th>
<th>RIY factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>291.69°C</td>
<td>0.998878</td>
<td>0.998982</td>
</tr>
<tr>
<td>293.81°C</td>
<td>0.998197</td>
<td>0.998363</td>
</tr>
</tbody>
</table>

Reference