THERMALHYDRAULIC ANALYSIS OF SPENT FUEL BASKETS

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Abstract

This paper presents results from a thermalydraulic modelling and analysis of the cooling water surrounding spent fuel baskets in the spent fuel bays. The spent fuel basket is a design option to provide more self-shielding features for spent fuel storage. Two CFD models containing the spent fuel baskets are presented using 3D finite volume elements. The first model is for spent fuel baskets in stacks to simulate them in storage bay. The second model is for the "tilter" which is a part of the spent fuel handling equipment in the reception bay. The CFD software Ansys-CFX [1] was used to calculate heat transfer from the spent fuels to the cooling water. The analysis results of test cases demonstrate that these models can be used for detailed design assist for spent fuel handling systems and operations.

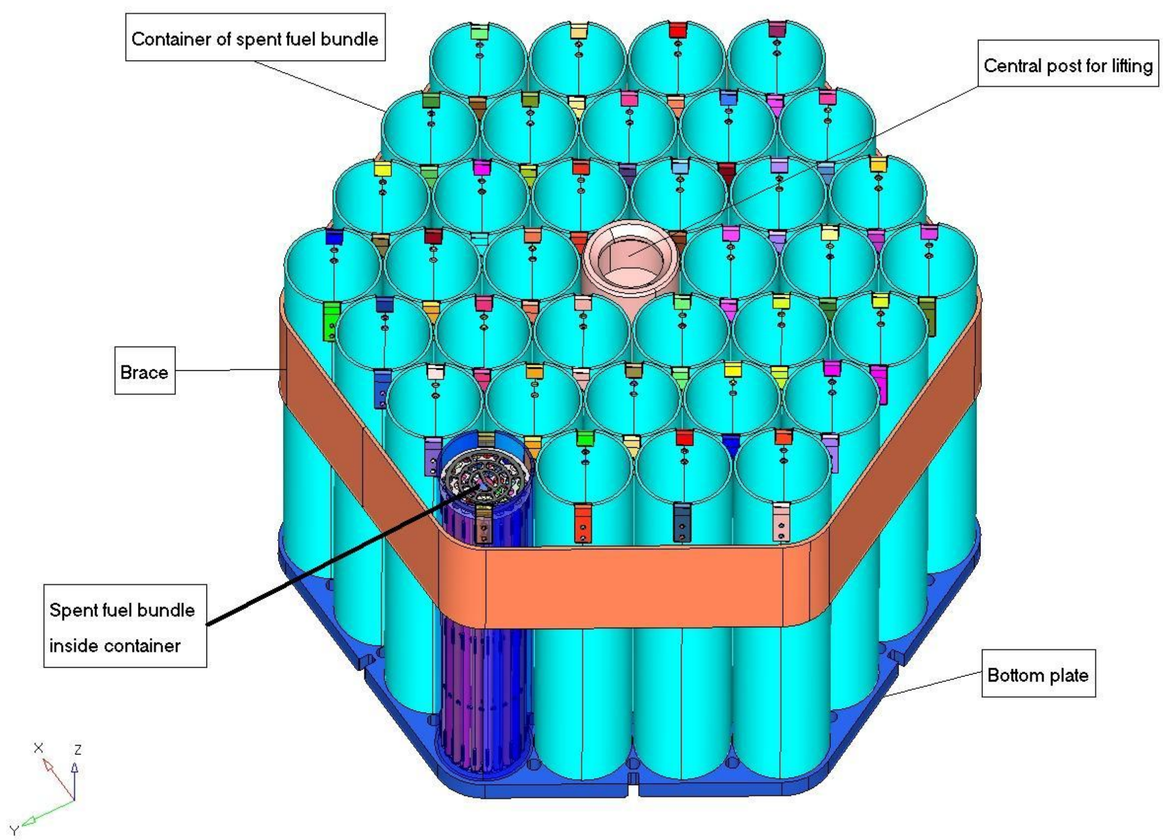

Figure 1 Illustration of a basket containing 36 spent fuel bundles

Introduction

When spent fuel bundles are removed from the fuel channels, they are packed into a spent fuel basket by operation of a spent fuel handling equipment in the reception bay which is filled with water for cooling. A fresh spent fuel bundle has significant remaining power which decays with time. During the time of packaging process and the initial storage term, the heat from the spent fuel bundles is transferred into the water which is circulated at a low rate by the spent fuel bay system. One of the concerns in the spent fuel bay design is to avoid water boiling because the bubbles decrease operators' visibility. Figure 1 shows an isometric view of a packed basket. Each basket contains 36 spent fuel bundles. One bundle sits in a steel tube (container). The water fills all the gaps between the fuel elements and containers. Once a basket is packed, it is moved off the tilter and placed in vertical orientation. The baskets can be placed into multiple stacks in the reception bay for a waiting period and eventually the stacks are moved into the storage bay for long-term storage.
The target of this analysis is to develop two CFD models for the spent fuel baskets in stacks and one basket in the spent fuel handling equipment, and calculate the temperature around the spent fuel bundles. Several test cases have been simulated to assess model capibilities for design assist with different options of fuel handle system and operation process to ensure that the design requirements can be met for spent fuel storage.

1. Spent fuel baskets in stacks

The spent fuel basket is designed to be placed in a number of stacks vertically and all the fuel bundles are parallel in the water. This design is to set the baskets in stacks to obtain a "chimney" effect for water circulation. Since a general challenge to a 3-dimensional CFD analysis is the significance of CPU time for convergent solutions, the model should be properly simplified for the available computing resources and time frame for the analysis.

1.1 Simplification of model

Based on the fact that all the baskets and bundles are parallel in the water, the CFD model can be first simplified as a hypothetic water column containing one basket per a stack (Figure 1). Then, this hypothetic water column is further divided into 36 identical water cylinders one of which contains a single bundle, and the diameter of the water cylinders is the same as the inside diameter of the steel container. These two simplification steps are both conservative because the water between the cylinder columns (i.e., between the containers) is not included in the model and this leads to a slightly higher temperature result. The next simplification step is to utilize the symmetry of the bundle. The fuel bundle is in unique symmetry geometry circumferentially, and it can be divided into 7 equal sections. Each section contains 6 full fuel elements as shown in Figure 2. This $1/7^{th}$ model is used and symmetry plane condition is applied to its two sides. Since the large fuel element in the bundle centre does not have heat decay power, its outer surface is used as a boundary wall of the analysis model (Figure 2).

1.2 Decay heat of spent fuels

The fuel decay heat depends on the spent fuel ages off the reactor core. It is considered that when a number of baskets are stacking together in the storage bay, all the fuel bundles are more than one day discharged from the reactor core. For example, "1-day decay heat" means the spent fuel bundle was off the reactor core 24 hours ago. The older the spent fuel is, the less power it remains.

1.3 Model of baskets in two stacks

Figure 2 shows all the boundary surfaces of the model of spent fuel baskets in stacks of two. It can be extended to models with more stacks (refer to Section 1.6 for a model of baskets in seven stacks). The fuel elements are simplified as solid cylinders and the surfaces of these cylinders are internal boundaries of the water model. The bottom plane is set as water inlet and the top plane is set as an opening of the water model. Beside the two symmetric planes described in Section 1.1, the cylinder surface of the water wall and the surface of the centre fuel are set as adiabatic boundary walls of the water model. The latter boundary condition is also conservative considering that there is a certain heat transfer inside a spent fuel bundle between the centre fuel and its neighbour fuel elements with decay power.

1.4 Boundary layer and boundary conditions

Software HyperMesh® [2] is used to generate the mesh of the fluid models with boundary layers. Figure 3 shows three boundary layers along the fuel element walls and the container wall. A tetrahedral mesh is generated between the boundary layers. The water temperature at the bottom of the spent fuel bay is assumed as 40°C and the inlet water speed is assumed as 0.01 m/s.

1.5 Fluid model of turbulence and calculation results

Under normal operation conditions, water circulation in the bays is maintained at a low flow level. However, the decay heat power in the spent fuels results in buoyancy effect and mass flow is formed. Therefore, turbulence model (k-epsilon) with buoyancy effect is selected to solve the problem. It is considered that when the two baskets are stacking together in the storage bay, all the fuel bundles are more than one day discharged from the reactor core. Therefore, the 1-day decay heat is applied to all the spent fuels in the two-stack model, which tends to overestimate the decay heat in the stack hence the water temperature. Figure 4 shows the calculated results of temperature distribution on the spent fuels surfaces as well as the inlet plane. The maximum temperature is 80.5°C on the spent fuels surfaces of the upper stack. The heat transfer in the water results in the flow of the water and Figure 5 shows the flow velocity field through the joint area of the two stacks. The maximum water velocity is 0.05 m/s compared to 0.01 m/s at the inlet.

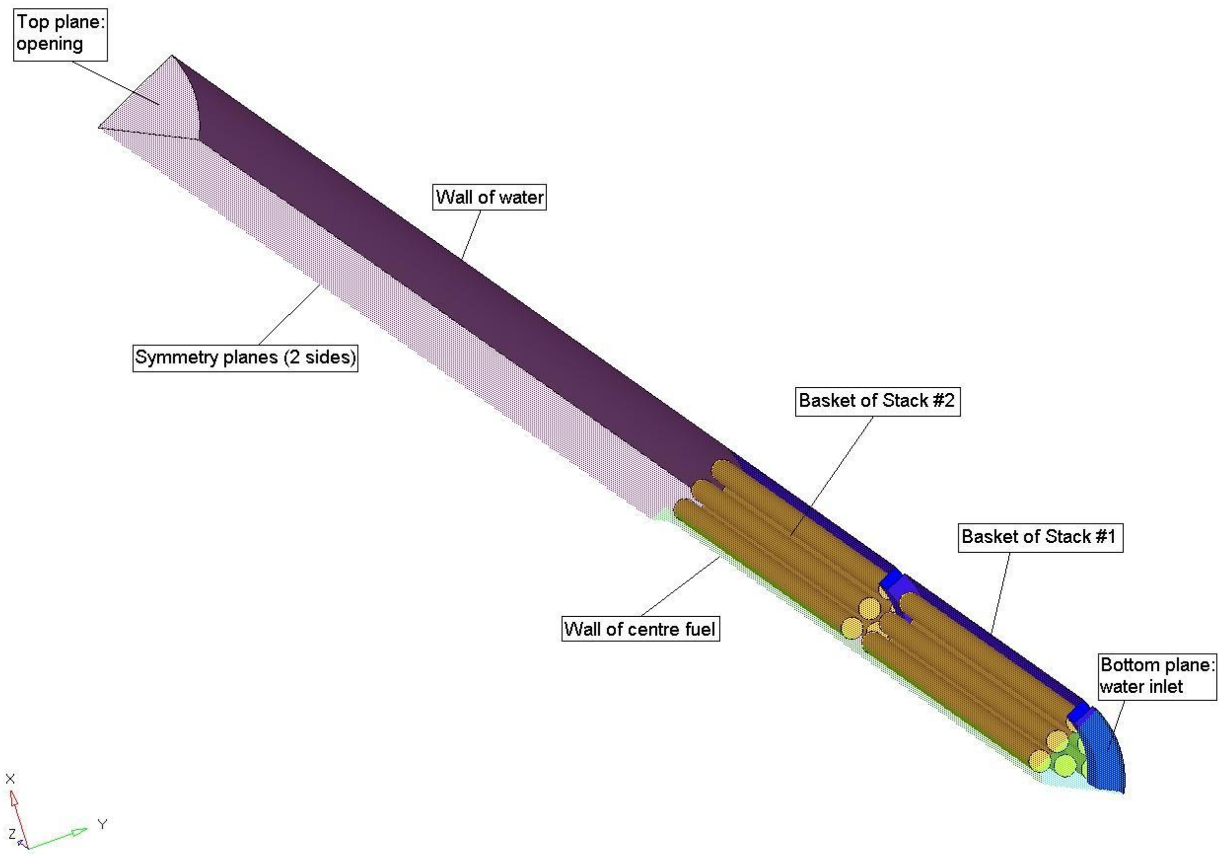

Figure 2 Boundary surfaces of water model of spent fuel baskets in two stacks

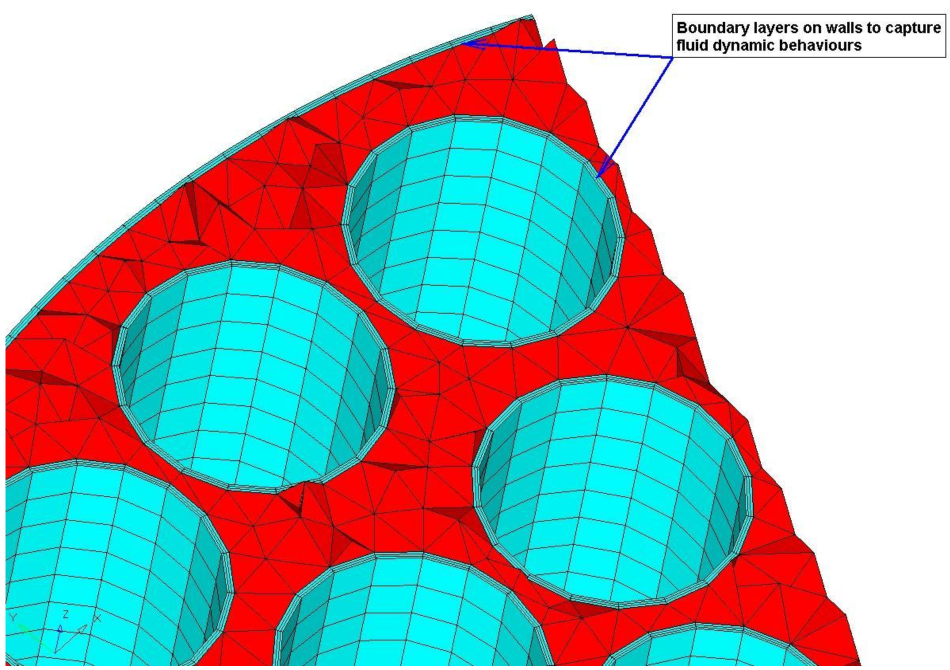

Figure 3 Part of water model with boundary layers

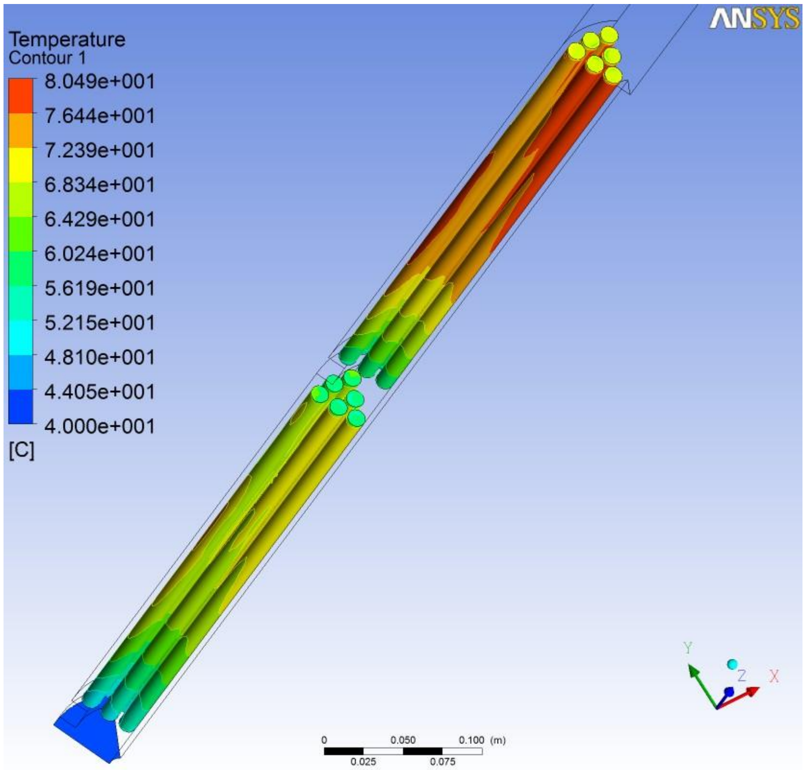

Figure 4 Temperature contour of water on fuel surfaces — model of two stacks with 1-day decay heat

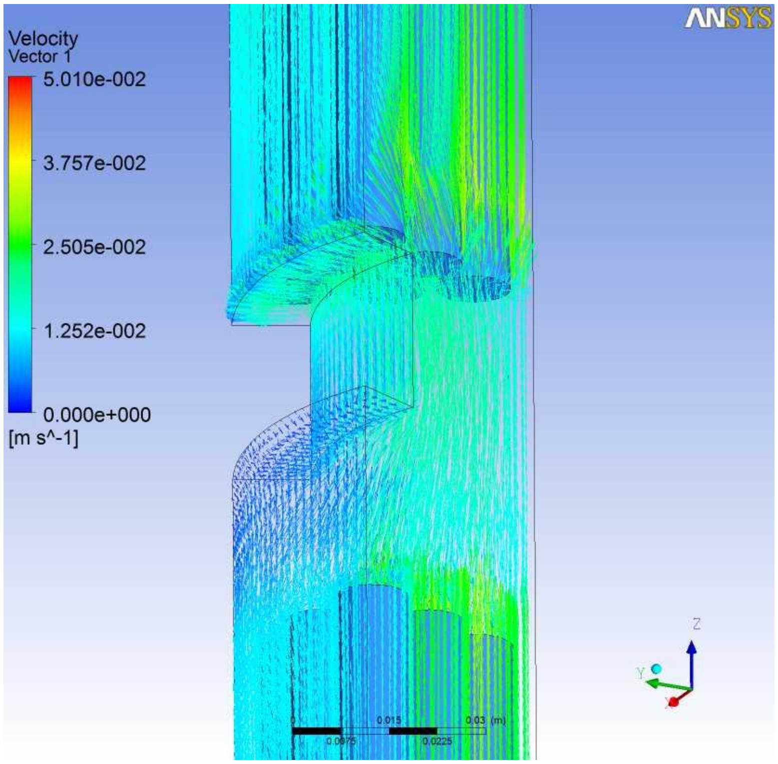

Figure 5 Flow velocity field of water — model of two stacks with 1-day decay heat

1.6 Model of baskets in seven stacks

The model of baskets in two stacks (Figure 2) is extended to a model of baskets in seven stacks. The same boundary conditions as defined in Section 1.4 are applied. The same as for the two stacks, it is considered that when the seven baskets are stacking together in the storage bay, all the fuel bundles are more than ten days discharged from the reactor core. Then, the 10-day decay heat is applied to all the spent fuels in the seven-stack model. Figure 6 shows temperature distribution on the spent fuels surfaces as well as the inlet plane. It demonstrates temperature increase from the lower stacks to the higher ones due to the buoyancy effect. The maximum temperature is 70.2°C on the spent fuels surfaces of the upper stack.

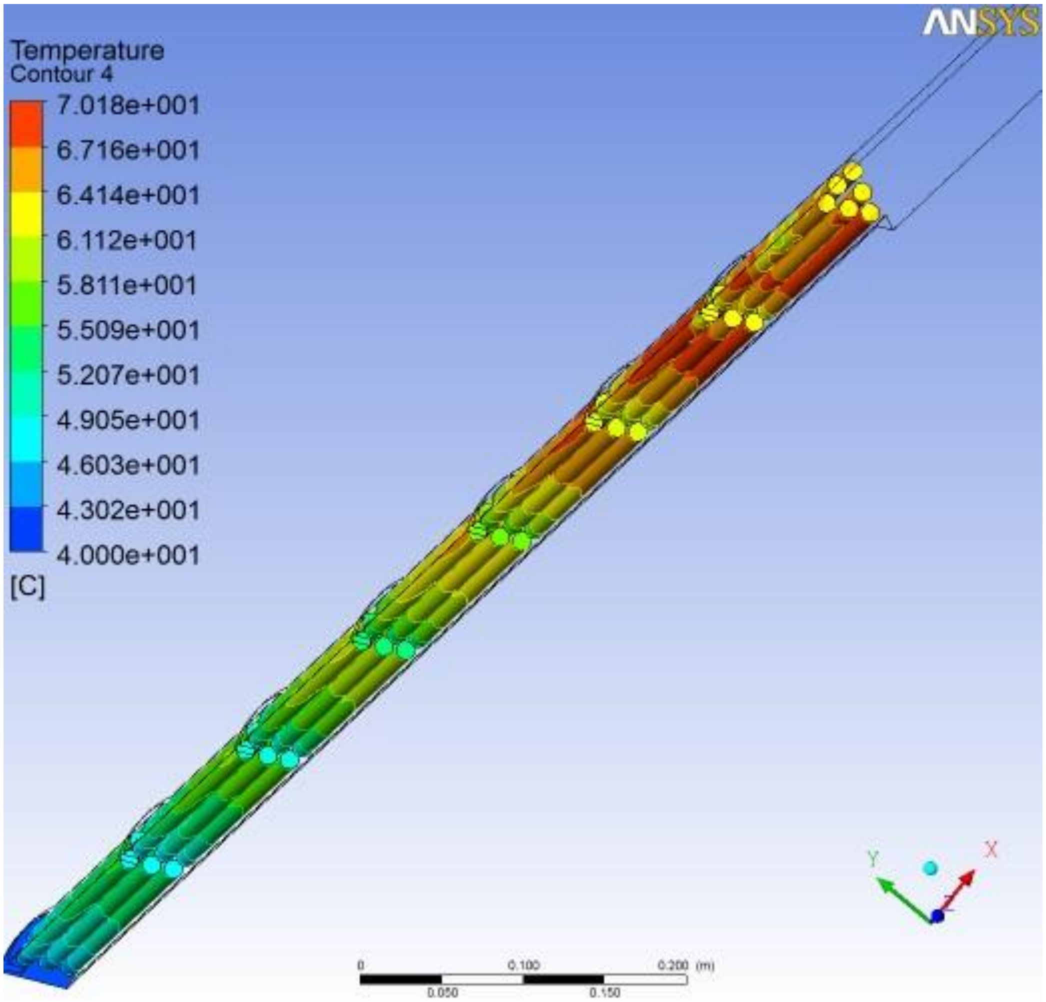

Figure 6 Temperature contour of water on fuel surfaces — model of seven baskets with 10-day decay heat

1.7 Summary

The calculated temperature results of the spent fuel baskets in stack of two demonstrate that when the decay age is older than 1-day, there is no local water boiling in the water. In the case of baskets in stack of seven, the calculated temperature results show that when the decay age is

10-day old, no local water boiling exists. In another test case, a set of individual decay ages are applied to the seven baskets in a frame in the storage bay, and the calculated results indicate no local boiling in the water. It has shown that for application of this simplified modeling, the decay heat level and stacked number of baskets can be changed to check stack cooling conditions where there would be local boiling in the water which may affect operators' visibility.

2. Spent fuel baskets in tilter

When the spent fuels are removed from the reactor channels, they are transferred to the Spent Fuel (SF) Reception Bay and loaded into one of the 36 steel tubes in the SF Basket Tilter (Figure 7) in sequence. When an SF basket is filled with 36 SF bundles, it is removed from the SF Basket Tilter and remains in the Reception Bay for a period of time before being transferred to the SF Storage Bay.

2.1 Tilter: a component of spent fuel handling equipment rotatable between horizontal and vertical orientations

The mechanism of the SF Basket Tilter allows the tilter to rotate between horizontal position (Figure 7) and vertical position. The SF Basket Tilter is oriented horizontally when the SF bundles are being loaded into it. It is expected that the SF Basket Tilter loaded with the SF bundles is subjected to a worse flow condition and higher temperatures in the horizontal position than in the vertical position. Since the spent fuel bundles are removed from the reactor core in time sequence, they are divided into three groups shown in color in Figure 7 with different heat decay ages.

2.2 Analysis modelling

Figure 8 shows the model cut by an YZ plane to show the details of the tetrahedral mesh. The spent fuel elements within a bundle are simplified by three pipes to represent the three rings of the fuel elements in the fuel bundle. The heat fluxes converted from the decay heat ages are applied to the surfaces of the three pipes of each fuel bundle.

<u>Tilter in horizontal orientation</u>

The model shown in Figure 8 is a part of the water surrounding the horizontal tilter in the SF Reception Bay. The model height is 1.22 m and the volume of the water is about 15 times of the volume of the solids of the SF Tilter. This model dimension is used considering the current computing capability and the calculation results are conservative because only the water included in the model is involved in the heat transfer calculation.

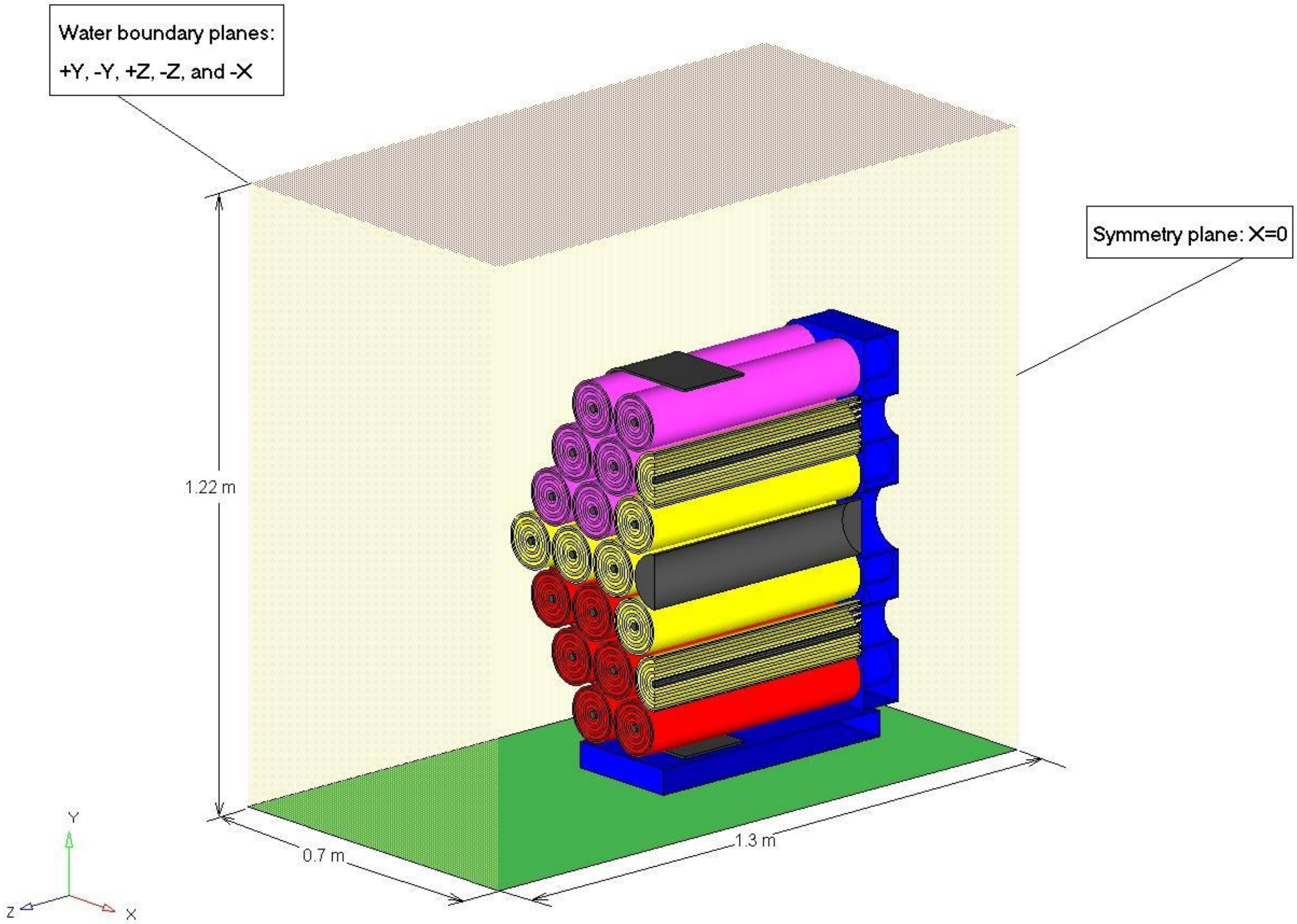

Figure 7 Spent fuel basket in horizontal tilter with symmetry and boundary planes (fuel bundles are grouped by color for different decay heat ages)

<u>Tilter in vertical orientation</u>

The mesh of the tilter in vertical orientation is obtained from the horizontal tilter (Figure 8) by a -90° rotation around X-axis. The model height is 1.3 m. Figure 9 shows a cut-view by an XY plane to show the details of the tetrahedral mesh.

2.3 Fluid model of turbulence and calculation results

The turbulence model (k-epsilon) with buoyancy effect is used in the case of the tilter. A test case presented here is considered with a worst decay heat, 12 bundles with decay heat age of only 2.5 hours (red colored bundles in Figure 7), 12 bundles with about one more decay day (50.7 hours, yellow colored bundles in Figure 7) and the rest 12 bundles with about two more decay days (98.5 hours, pink colored bundles in Figure 7).

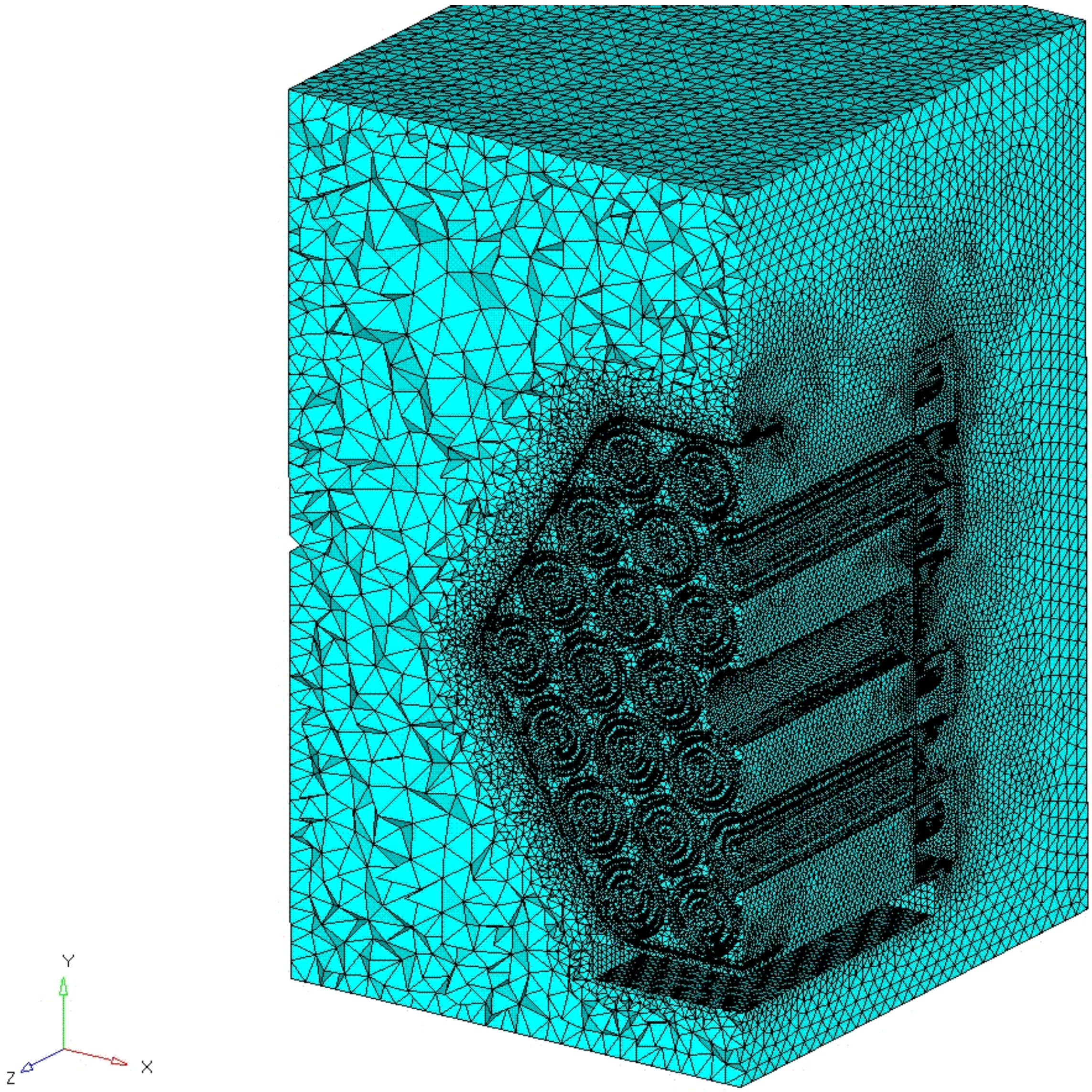

Figure 8 Mesh of water of horizontal tilter (cut-view)

2.3.1 Results of horizontal tilter

Figure 10 shows the temperature contour on the surfaces of the fuel elements. The maximum temperature is 144.1°C at the centre of the fuel bundle at decay heat 2.5 hours. Since in this CFD calculation, two phase (fluid and vapour) flow effect is not accounted for, the above calculated temperature of 144.1°C just means that the water boiling occurs at local area surrounding the spent fuel surfaces. The maximum temperatures of the fuel bundles at decay heat 50.7 hours and 98.5 hours are 98.44°C and 89.76°C, respectively. Figure 11 shows the water flow velocity field. It demonstrates the water flow variation passing through the surfaces of the solids (fuel bundles, metal strap, and tilter components).

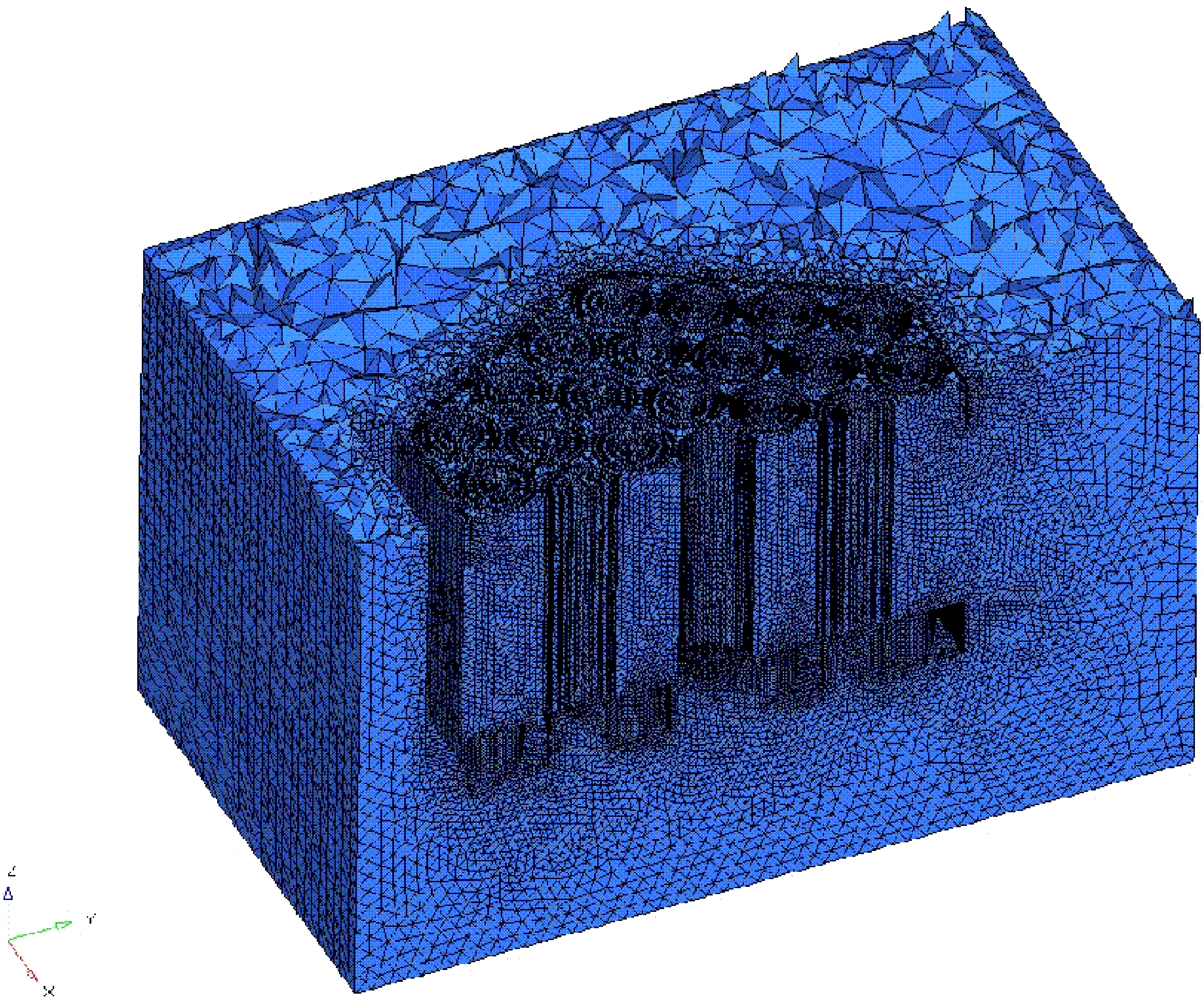

Figure 9 Mesh of water of vertical tilter (cut-view)

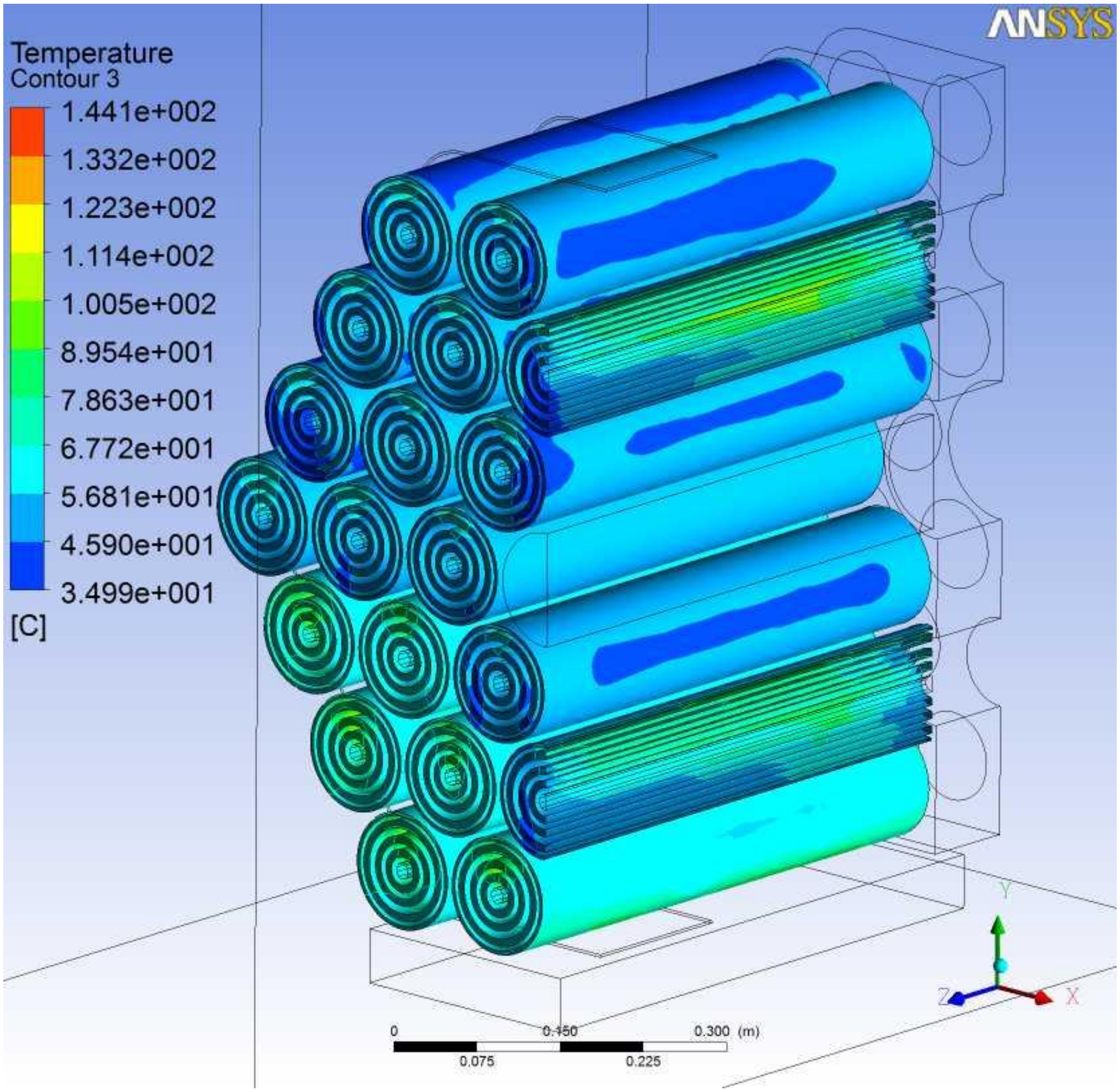

Figure 10 Temperature contour of fuels in horizontal tilter (spent fuel bundles are grouped at three different heat decay ages)

2.3.2 Results of vertical tilter

Figure 12 shows the temperature contour on the surfaces of the fuel elements. The maximum temperature is 106.9°C at the outer surfaces of the fuel bundles at decay heat 2.5 hours (red coloured bundles in Figure 7). The maximum temperatures of the fuel bundles at decay heat 50.7 hours (yellow coloured bundles in Figure 7) and 98.5 hours (pink coloured bundles in Figure 7) are 69.43°C and 66.27°C, respectively. Figure 13 shows the water flow velocity field, which is different from the water flow velocity field in the case of horizontal tilter shown in Figure 11 due to the difference of tilter orientation.

2.4 Summary

The CFD analysis results demonstrate that the basket tilter is under a significantly better ventilation condition in vertical orientation than in horizontal orientation. The developed models can be used to calculate the water temperature distribution and predict existence of local boiling.

3. Conclusions

A number of CFD models are established for thermal hydraulic analysis of spent fuel baskets in stacks and in tilter. With given input conditions such as spent fuel decay heat and boundary condition, the models can be calculated to obtain temperature distribution in the water. The analysis results of test cases demonstrate that these models can be used for detailed design assist for spent fuel handling systems and operations.

4. References

[1] Ansys CFX, Version 12.0, ANSYS Inc., 2009.

[2] HyperMesh® Version 10.0, Altair Engineering, 2009.

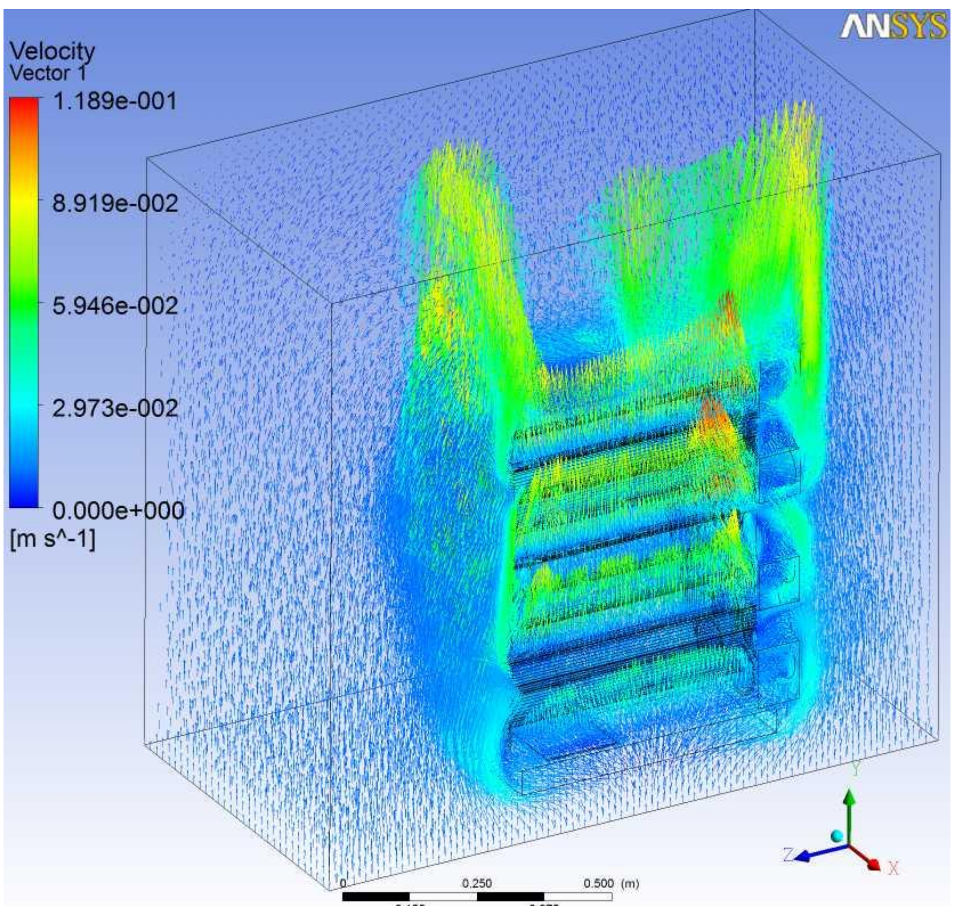

Figure 11 Water flow velocity field in horizontal tilter

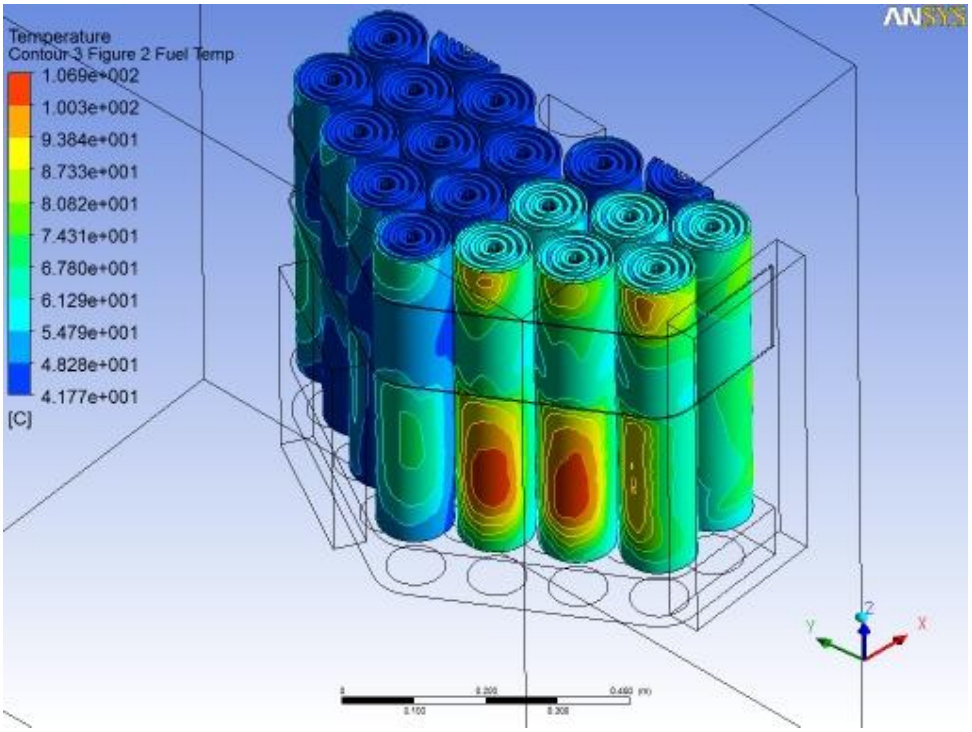

Figure 12 Temperature contour of fuels in vertical tilter (spent fuel bundles are grouped at three different heat decay ages)

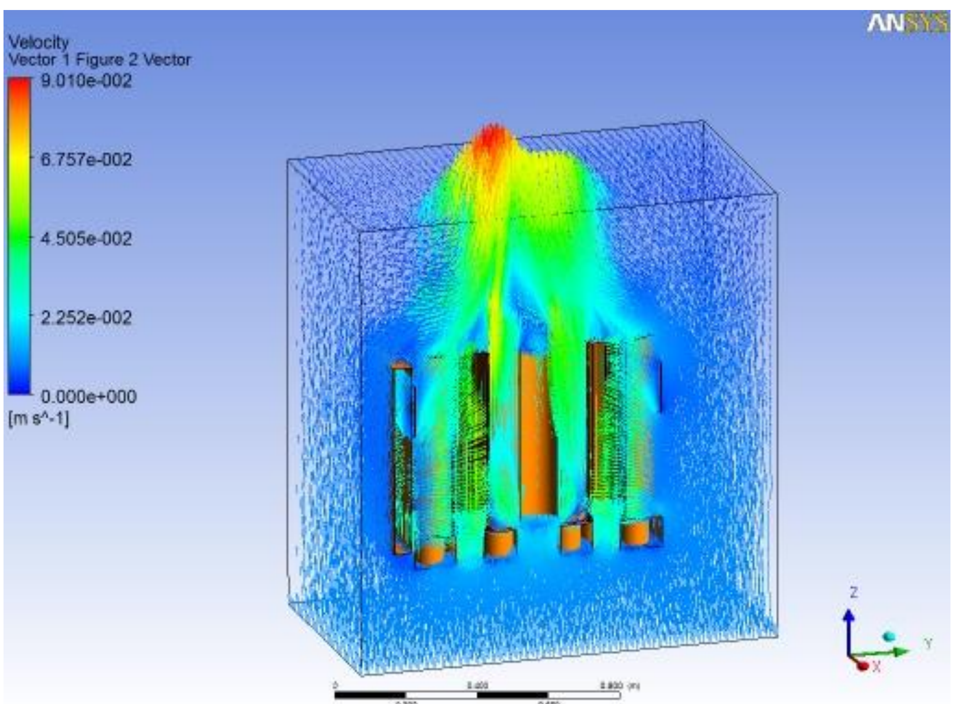

Figure 13 Water flow velocity field in vertical tilter

