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# Simulation of radionuclide diffusion in a dry storage of spent fuel under accident condition

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ABSTRACT

The prediction of radionuclide diffusion is one of the indispensable factors for the nuclear emergency decision. So far, it is still short of an accurate simulation for the radionuclide diffusion in a spent nuclear fuel storage. Compared with the radionuclide diffusion in atmosphere, the airflow inside a dry-storage is always in turbulent state with a ventilation system, and diffusion process of radionuclide in the spent fuel dry storage is very complex. Therefore, a choice of an appropriate model is key point to estimate radionuclide dispersion in the dry storage. In this paper, the radionuclide concentration equation with the consideration of room wind field, wall condition and the features of radionuclide is updated to simulate the radionuclide dispersion in the spent fuel dry-storage with four vents. A three-dimensional model of radioactive concentration is obtained based on the standard k-ε turbulence model. The simulation results reveal that the standard k-ε turbulence model combined with updated radionuclide concentration equation gives a reasonable description for radionuclide diffusion under accident condition so as to provide more actual information for early emergency and consequence assessment.

## 1. Introduction

The management of the spent nuclear fuel is a strategic activity that is adopted in the nuclear energy safety technology field (Wu and Team, 2009), which includes the safeguarding of the operating staff, the population, and the environment. The issue of the spent nuclear fuel storage is crucial for countries that possess nuclear reactor (Schroder et al., 2016). Development and improvement work on a variety of dry-storage technologies has been intensive over the last decade (Wu et al., 2016). Researches on the management of the spent fuel and on the design of a spent fuel dry storage should involve the assessment of the environmental impact and the prediction of the radionuclide diffusion, respectively. Compared with wet storage, dry spent fuel storage with features of practicability, economy, and safety, is more efficient for the nuclear fuel management and long-term storage (IAEA, 1999). Unfortunately, there are some unavoidable factors of leakage from the spent fuel vessel, such as vessel cladding corrosion (Liu et al., 2014), technical failure (World Nuclear News, 2016), force majeure factor (Povinec et al., 2013), and so on. Simulation of radionuclide diffusion in a spent fuel dry storage is very important, since the leaked radioactive pollutant will finally migrate from storage room to environment through the ventilation system. It gives a reasonable description for radionuclide diffusion under nuclear accident so as to provide more actual information for early emergency and consequence assessment.

Many models (Ádám Leelossy et al., 2014) have been developed to simulate air flow and airborne pollutants distribution between the scale of 1 km and 1000 km, such as Gaussian (Woo, 2013), Lagrangian (Park et al., 2016) and Eulerian (Soon-Ung Park and Moon-Soo, 2013) dispersion models. Airflow in the dry-storage room with a scale smaller than 2 km is complex, where the transport and diffusion of radionuclide is comprehensively governed by wind field, wall condition, turbulence, radioactive decay and deposition. In addition, radionuclide diffusion and migration is also cannot be ignored during the radiation field prediction. Therefore, a choice of an appropriate model is key point to estimate radionuclide dispersion in the dry-storage room.

Aerodynamic viscosity coefficient is very small in the ventilated room, and the airflow inside a dry storage is turbulent with a ventilation system. Currently, three methods, named Direct Numerical Simulation (DNS), Large Eddy Simulation (LES), and Reynolds Averaged Navier Stokes (RANS), are developed to numerically solve the turbulent flow. The most accurate solution is provided by Direct Numerical Simulation, yet which has a disadvantage of high

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computational complexity for the requirement of fine meshes, and it is difficult to simulate complex model. Therefore, the Direct Numerical Simulation is extremely costly with the consideration of the computational standing for engineering flow and is only useful as a basic research tool for flows with simple geometry. The Large Eddy Simulation only provides information of pulse inertial sub area, it cannot directly simulate small scale eddy, and so many challenges still need to be faced or to be overcame in order to achieve significant advancements in numerical simulations. Comparing with Direct Numerical Simulation and Large Eddy Simulation, the simulation accuracy of Reynolds Averaged Navier–Stokes probably is lower, due to its advantage of simple, quick, and possesses good numerical stability, Reynolds Averaged Navier–Stokes has been widely adopted by researchers.

As we all know, Computational Fluid Dynamics (CFD) is an important tool of numerical simulation (Wu et al., 2015) to simulate room airflow (Rohdin and Moshfegh, 2011). The standard k-ε turbulence model is effective for high Reynold number flow, some researchers analyzed the results about the airflow behavior in the ventilated room. Dieguez-Elizondo's (Dieguez-Elizondo et al., 2017) work mainly use CFD method to simulate $^{222}$Rn concentration in a granite workshop, and different decontamination scheme using ventilation system has been analyzed in Dieguez-Elizondo's work. Shuai Shao (Shao et al., 2016) simulate the fluid behavior in tunnel groups by using CFD model when four ventilation schemes are adjusted, and this study can provide more reasonable suggests of the ventilation scheme in tunnel groups. To deal with the near-wall turbulence anisotropy accurately, Kongqing Li and Guangcai Gong (Li and Gong, 2012) present a new method for the evaluation of the room suspension particle diffusion based on a $v^2$-f model, which can solve the problem as near wall turbulence, or low Reynolds number, but $v^2$-f model has a disadvantage of higher computational complexity.

In this work, the standard k-ε turbulence model is suitable for the simulation of radionuclide diffusion under nuclear accident in a dry storage of spent nuclear fuel so as to provide actual information for early emergency and consequence assessment.

## 2. Mathematical modeling

Due to the manufacturing defect, aging, or thermal fatigue, there eventually appears cracks on the surface of the vessel. In order to predict the leakage possibility of radioactive pollutants caused by the cracks to the atmosphere, the model with the consideration of room wind field, wall condition and the features of radionuclide is built to simulate the radionuclide dispersion in the spent fuel dry-storage with four vents. An updated three-dimensional model of radioactive concentration is obtained based on the standard k-ε turbulence model.

### 2.1. Spent fuel dry storage and the spent fuel container

The spent fuel containers are stored in wells at the dry storage. The container consists of a thick-walled ductile cast iron steel cask body similar as CASTOR cask, it is designed to store PWR, BWR or HLW fuel assemblies (IAEA, 1999). According to IAEA regulations, the container consists of a primary and a secondary lid installed one on top of the other to prevent leakage from spent fuel, and impact limiters attached at the top and bottom of the container is designed for the safe storage and transport.

Consideration of the large majority of the spent fuel type for the nuclear power plant in China, the graph shown in Fig. 1 is designed to store PWR fuel assemblies and it illustrates the geometrical structure of a dry storage of spent nuclear fuel which has two inlets and outlets, respectively. The size of inlets with diameter of 0.1 m is the same as the outlets. The geometry has a ground area of 17 m × 6.6 m with a height of 10 m. 55 (5 × 11) storage wells with a radius 0.3 m and a height of 10 m is located in the middle of the dry storage. The spent fuel container are stored in wells that are apart with 0.5 m spacing between wells, which provides sufficient space for air circulation and cooling. Concrete peripheral dry storage walls of 1.3 m thickness prevent the radiation from the spent fuel. The dry storage is ventilated by force ventilation through the vents. Along the positive direction of X axis, airflow entered the dry storage through tunnel inlets and exited from the outlets. The inlets situate at a height of 1 m and the outlets situate at a height of 8 m above the floor (IAEA, 1999).

### 2.2. Airflow model

The standard k-ε model is the most common choice to simulate turbulence (Ferziger, 1996). In order to simulate the airflow field in the spent fuel storage, the steady state wind speed is obtained by conversation equations of mass, momentum (de With and de Jong, 2011).

The mass conversation equation:

$$\rho \nabla u_i = 0 \tag{1}$$

The momentum conversation equation:

$$\rho((\partial u_i - \partial t) + \nabla u_j u_i) = -\nabla P + \nabla[\mu \nabla u_i] + S_u \tag{2}$$

where i is the index for the x, y, z direction, ρ is the density of the fluid, $P$ is the pressure (N m$^{-2}$), $\mu$ is the viscosity coefficient, which is sum of the dynamic viscosity ($\mu_d$) and fluid turbulent viscosity ($\mu_t$), $S_u$ is the momentum source term.

Turbulence is considered in the spent fuel dry storage by calculated Reynold's number (greater than 10,000), and the effect of which in the dry storage is simulated by the standard k-ε model (Ferziger, 1996).

### 2.3. Radionuclide simulation

In the spent fuel dry storage, the leaked radionuclide $^{131}$I is simulated by the concentration equation.

$$\frac{\partial C}{\partial t} + \nabla(uC) = \nabla(\Gamma \cdot \nabla C) + S - C \tag{3}$$

$C$ is the pollutant concentration on the point of (x, y, z) at each time step (k Bq m$^{-3}$), $u$ presents the flow field (m s$^{-1}$), Γ is the turbulent diffusion coefficient (m$^2$ s$^{-1}$), $S_C$ represents the source in the model (k Bq m$^{-3}$ s$^{-1}$).

As soon as the leakage is considered, radionuclide diffusion in the ventilated room is affected by wall conditions, indoor wind field, radioactive decay, and dry deposition. The wall condition can be set with a no-slip condition at the solid wall and indoor wind field can be obtained by solving momentum conversation equation. To achieve an accurate radionuclide distribution, consideration of process of airborne $^{131}$I dispersion have characteristic of decay and deposition, the following updates are made to the concentration equation.

#### 2.3.1. Dry deposition

The removal of the leaked radionuclide $^{131}$I in a ventilated room can occur by the deposition, which depends on air resistance and gravitational balance. The dry deposition velocity can be expressed as:

$$v_s = \frac{\rho g D^2}{18\mu} \tag{4}$$

where $\rho$ is the airborne $^{131}$I density (~1 × 10$^{-12}$ kg m$^{-3}$)(Atwood, 2010), $g$ is the acceleration of gravity (9.8065 m s$^{-2}$), $D$ is the particulate $^{131}$I diameter (~10 μm), $\mu$ is the aerodynamic viscosity coefficient (1.8 × 10$^{-5}$ kg·(m s)$^{-1}$).

#### 2.3.2. Radioactive decay

The atomic properties are changed during the process of radioactive decay. The radioactive decay constant can be expressed as:

$$\lambda = \frac{0.693}{T_{\frac{1}{2}}} \tag{5}$$