Accident Analysis of Micro-Nuclear Reactor by Non-Injection Systems as Portable Submergence Reactor (PSR): Approaching to Concept of Perfect Safety

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1. Introduction

New kind of nuclear safety concept is introduced for the micro nuclear reactor to enhance the integrity. The micro reactor is defined as a kind of small nuclear reactor (SMR) which could produce up to 50 megawatts operating without the electric grid [1]. Comparing to the conventional nuclear power plants (NPPs), the important features are the smaller size, the lower enriched fuel and the movable reactor in Fig. 1 of the specified characteristics in micro nuclear-reactor [2]. This new conceptual design of portable reactor is analyzed for this work. Fig. 2(a) shows the conceptual change of safety system from injections to submergence. The conventional injection safety system is the piping-based safety where it was broken by the explosions in Fukushima and Chernobyl cases. If it is movable, one could maintain the permanent and perfect integrity of the exploded reactor in which there are still many nuclear fuel materials in the accident place (Fig. 2(b)). Hence, it is proposed to make the redundancy safety concept as the falling of reactor into the water pool by driving the reactor vehicle. The piping coolant system of conventional NPPs is added by the reactor-loaded truck gets into the pool when the reactor emergency cooling systems fails to make up the cooling integrity. So, it is desirable to be added as the redundancy system when all injection-based safety systems are failed.

2. Methods

The nuclear post-accident analysis (PAA) system is analyzed as the vehicle movement, the submerging mechanics, and the cooling capability, which is in Fig. 3. In order to realize this system, the reactor cooling is accompanied with the vehicle's capability and its state of submergence. In addition, this analysis could be extended as the improved speed of reactor-contained truck or the method of falling-down into the pool in this study. One of important matters in the vehicle's movement is needed to get into the water pool fast where it is used for cool down the residual heat of the reactor. So, it is needed that the vehicle including the reactor could fall down into the water pool. For the simple calculations of the free falling [3],

$$l = \frac{1}{2} \cdot g \cdot t^2 \quad (1)$$

$$v^2 = \frac{1}{2} \cdot g \cdot l \quad (2)$$

$$v = g \cdot t \quad (3)$$

where l is the length of falling-down, g is the gravitation acceleration, v is the final velocity, and t is the spent time. Hence, one can find the necessary time if the height is known as follows,

$$t = \sqrt{\frac{2l}{g}} \quad (4)$$

In the forces of going-down vehicle, the configuration is seen in Fig. 4. So, the forces are described as [4],

$$\frac{dV}{dt} = \frac{\sum F_d - \sum F_{rs}}{dM} \quad (5)$$

where $\sum F_d$ is the total tractive forces, $\sum F_{rs}$ is the total resistance forces, and M is the vehicle's mass. In addition, considering the fuel's radioactivity, the radioactive decay is described as [5],

$$-\frac{dN}{N} = \lambda dt \quad (6)$$

$$N(t) = N_o e^{-\lambda t} \quad (7)$$

Then,

$$-\frac{1}{\lambda} \hbar \left(\frac{N(t)}{N_o}\right) = t \quad (8)$$

So, using equations (4) and (8),

$$-\frac{1}{\lambda} \hbar \left(\frac{N(t)}{N_o}\right) = \sqrt{\frac{2l}{g}} \quad (9)$$

$$\hbar \left(\frac{N(t)}{N_o}\right) \propto -\sqrt{l} \quad (10)$$

In addition, using equation (4),

$$t \propto \sqrt{l} \quad (11)$$

Using equation (3),

$$v \propto t \quad (12)$$

It is shown that a linear proportional trend of the time to increase the velocity of the reactor-contained truck. The submerging reactor could be described by the drag force [6]. The Reynold number is greater than 1.0, which gives the drag force as follows,

$$Drag\ \ Force\ \ = \frac{1}{2} \cdot \rho \cdot X \cdot C_d \cdot v^2 \qquad (13)$$

where ρ is the density, X is the cross sectional area, C_d is the drag coefficient, and v is the velocity. Actually, the Reynold number is in the transition region between laminar flow (Re < 2,100) and turbulent flow (Re > 4,000). In case of the laminar flow, the viscosity force is greater than the inertial force. Therefore, the central fluid velocity is two times faster than the average velocity [7]. By the way, if it is the turbulent flow, it is 1.2 (one point two) times faster than the average velocity due to the molecular collisions of the turbulent. In the any situation, the pool water could be nearly suspended. If the weather is in a stormy day, the conditions of pool water could be variable. When one makes the ceiling cover on the truck, it is not affected by the external weather conditions.

Furthermore, acceleration due to gravity is as follows considering the falling distance [6],

$$Distance \quad = v_o \cdot t + \frac{1}{2} \cdot g \cdot t^2$$

$$\approx v_o \cdot t + \frac{g \cdot t^2}{2}\left(1 - \frac{v_o^2}{v_T^2}\right) - \frac{g^2 \cdot v_o \cdot t^2}{3v_T}\left(1 - \frac{v_o^2}{v_T^2}\right) \qquad (14)$$

where v_o is the initial velocity, t is the time, g is the gravitational acceleration, and $v_T = \sqrt{m\,g/k}$ is the terminal velocity with a proportional constant k.

Considering the shape of the falling object, using the drag coefficient C_d, the flat shape of falling object to the flow is independent of the Reynold number, which is in Table 1, because the flow separation happens at the corners of the plate [8]. Additionally, if the plates are positioned parallel to the fluid flow direction, the drag coefficient decreases by a factor of 10 or more, and C_d increases further at high Re, depending on the Reynolds number. In the cases of circular and ellipse shapes, the drag coefficient is reduced in lower Reynold number and then increased in a higher Reynold number.

3. Results and discussions

In this work, the vehicle movement, the submerging mechanics, and the cooling capability are analyzed. It is necessary to the relations between the radioactive decay rate and the pool height in order to fall down as fast as possible for the moving analysis of the vehicle. Using equation (10), Fig. 5(a) shows the comparison between pool height and decay rate as a normalized value. It is proportional linearly in this graph. Additionally, using equation (11), Fig. 5(b) shows the comparison between pool height and falling time as a normalized value. In the falling mechanics of the truck, Fig. 6 shows the falling mechanics for velocity vs. time of several time cases where the values increase linearly in Fig. 6(a) and drag coefficient vs. diameter where there are arbitrary diameter cases in Fig. 6(b).

This new conceptual design of portable reactor is analyzed in this work. Table 2 shows the discussion for the reactor concept where the portability of reactor is the most particular feature in the Portable Submergence Reactor (PSR). Subsequently the submergence of reactor core could be the continued integrity after the severe accident state. In addition, Table 3 shows the discussion for the heat transfer concept of the reactor for perfect safety in which the injection based emergency coolant system of paintings could be added by the reactor falling down into the water pool as another redundant system. Once the reactor falls down, the cooling is performed as the natural convection. If the external pump is installed in the water pool, the forced convections continue and, eventually, the broken or damaged reactor core could be stabilized, which is called as 'Perfect Safety' system in this study. The presently ruined states of Chernobyl and Fukushima disaster sites could be remedied perfectly and permanently, if all stuff and debris of accident sites fall into the water pool.

4. Conclusions

Another kind of safety concept has been studied for the reactor falling-down by the vehicle in the micro nuclear reactor in which the smaller sized portable reactor is analyzed. The most important feature of the micro nuclear reactor is a mobile object in which another kind of cooling way as the falling-down of reactor to the water pool could be possible. There are some critical issues in the work as follows,

- The submergence is introduced as safety concept.
- It is studied for the reactor's falling-down as the vehicle movement, the submerging mechanics, and the cooling capability.
- The post-severe accident analysis is performed.
- Water pond with a feed water pump could be installed.

In cases of Chernobyl and Fukushima accidents, it is not calculable for the time to make the stabilized state, because the currently melted core can't be removed from the accident place. So, it is needed to wait to be stabilized in the radioactive dose level to the non-hazard to control by the human. It is very plausible to make the potable reactor in the plant construction stage.

Acknowledgments

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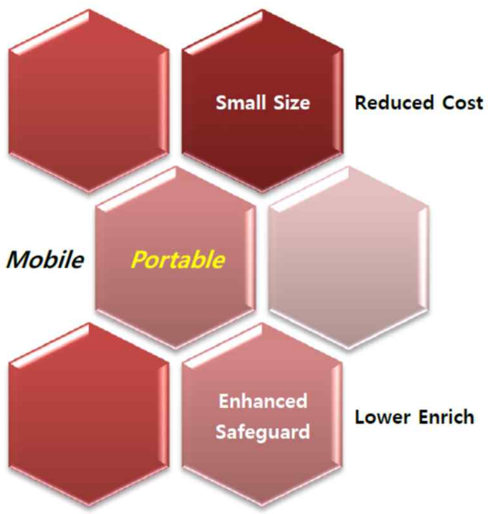
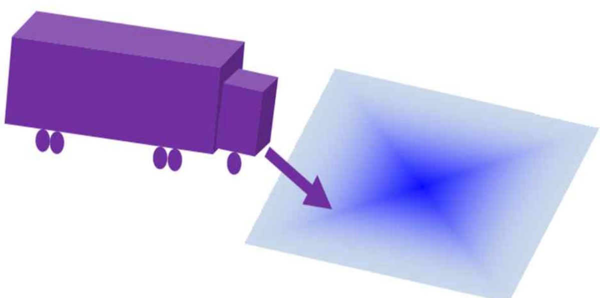


Fig. 1. Characteristics in micro nuclear reactor specialty [2].



(a)

(b)

Fig. 2. (a) Conceptual change of safety system from injections to submergence and (b) Perfect safety.

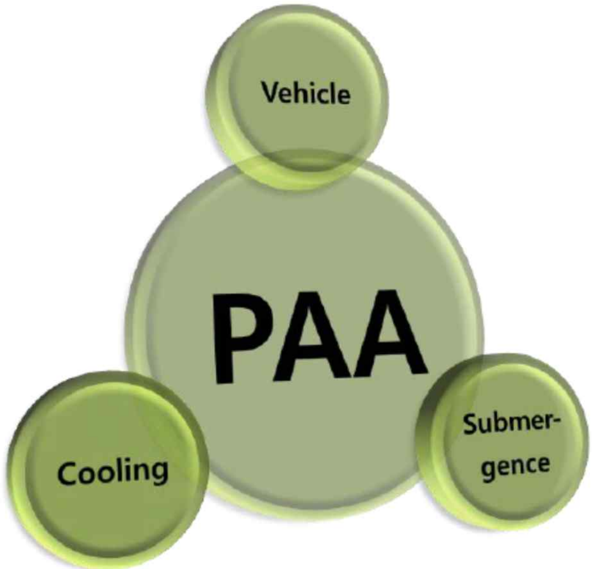


Fig. 3. Analysis for the post-accident analysis (PAA).

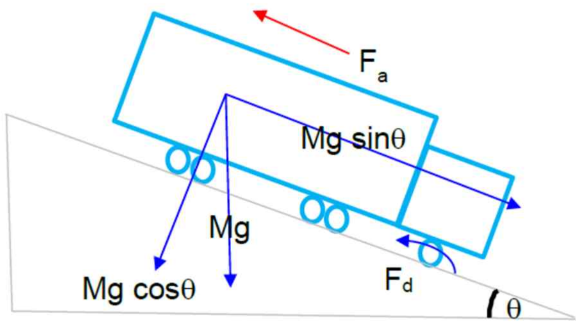
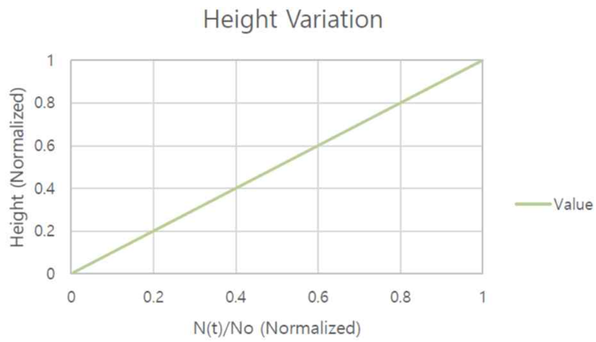


Fig. 4. Forces of going-down vehicle.



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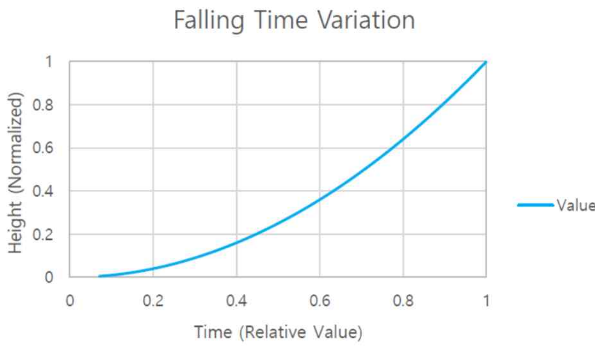
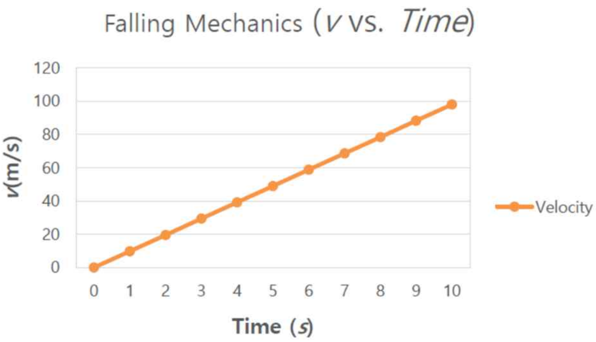
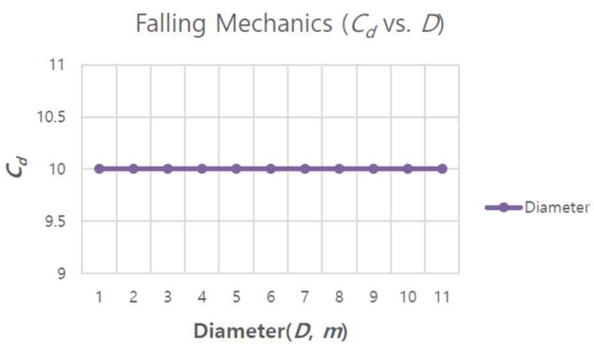


(b)

Fig. 5. Graphs for (a) comparison between pool height and decay rate and (b) comparison between pool height and falling time as normalized value.



(a)



(b)

Fig. 6. Falling mechanics graphs for (a) velocity vs. time and (b) drag coefficient vs. diameter (arbitrary diameter).

Table I: Variables by falling object [8].

Shape	*Re* (Reynold Number)	Rank of C_d (Drag Coefficient)
Flat Plate	Constant	1 (Highest)
Circle	Lowest between 10^5 and 10^6	2
Ellipse	Lowest between 10^5 and 10^6	3
Float Plate	Lowest between 10^5 and 10^6	4

Table II: Concept of reactor for discussions.

Feature	Concept & Discussion
Portability	Whole reactor parts are movable
Reactor Core	Easily movable
Submergence System	Fully falling of reactor into water pool
Post Core-Melted Severe Accident	Possible to submerge into water

Table III: Heat transfer concept of the reactor for perfect safety for discussions.

Feature	Concept & Discussion
Submergence System (This Study)	Fully cooling down of reactor in water pool
Injection System (Conventional Piping System)	Eternally impossible to cool the core-melted facility such as Chernobyl and Fukushima cases
Natural Convection	Convections continue after falling down
Forced Convection Added	External pump installment possible for forced convection