Research on Emission Characteristics of Radioactive Resin on Floating Nuclear Power Plant

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Abstract. The development of floating reactors needs to take into account the marine ecological environment. The recycling of waste in floating nuclear power plant is different from the onshore nuclear power because of its limited space and resources. The purifying resin of primary circuit has a high radioactivity and accounts for a large proportion of floating solid waste, and the production of other radioactive waste generated during resin unloading is worthy of attention. In order to minimize the waste production during emission of radioactive resin, this paper uses the fluid dynamics theory of fluidized bed to calculate and analyze the waste production and emission effect in different media for transportation, and propose a reasonable resin emission program, which can provides a powerful design input for the waste treatment.

1. Introduction
The floating nuclear power plant has become a significant topic in the development of nuclear power due to its compact structure, flexible application, short construction time and one-time investment, which can meet diverse market needs. Radioactive waste treatment is also an important factor restricting its development. The resin of purification system plays a key role in the chemical control of the primary circuit on the floating nuclear power plant, which exchange ions with reactor coolant to remove impurities, such as corrosion and fission products in the coolant are adsorbed by resin, the remaining solid impurities may remain in the resin bed gap, therefore the resin has a radioactive intensity. Since the waste treatment is very difficult and uneconomical when the radioactive resin is regenerated, and the primary circuit water has high chemical purity requirements, the expired resin is treated as a waste no longer used [1]. There is little report on the amount of waste generated when the resin is discharged, thus effective control of resin waste is also a protection of the environment and marine ecology. Water or gas is required to unload resin which will be finally discharged to the waste collection system, contaminated radioactive water or gas should be minimized to reduce the burden of waste disposal on space-constrained floating nuclear power plant.

The resin unloading and discharging corresponds to the solid particles suspending in a flowing media, thus the resin has fluid properties, in view of which the fluidized process of the resin can be described in an ion exchanger. Under the conditions of different pressures, flow rates and operating time, the amount of waste generated with the resin discharging and the unloading effect are totally different. Therefore, it is necessary to analyze and calculate the optimal parameters and programs to make the waste minimize on the condition of superior resin unloading.
2. Resin fluidization process

The fluidized process of the resin bed is divided into three stages: fixed bed, fluidized bed and fluid transport. According to the fluid dynamics theory of the fluidized bed [2], when the fluid passes through the resin layer, the fluidized bed pressure drop $\Delta P$ increases with the media flow velocity $u$, which is illustrated in Fig.1.

![Figure 1. Relation between pressure drop $\Delta P$ and flow velocity $u$ in fluidized bed](image)

Section A-B: Fluidized bed pressure drop $\Delta P$ increases linearly with flow speed $u$, which named fixed bed stage. Section B-C: When the flow velocity rises to point B, $\Delta P$ is equal to the total gravity of the bed in per unit area, the bed begins to loosen and expands slightly; then the flow velocity continues to rise beyond point B, the resin particles will float and the bed will expand with the increase of $u$, but $\Delta P$ will remain almost unchanged, that is the fluidized bed stage. Section C-later: When the flow speed continues to increase beyond point C, the bed enters the fluid transport stage. If $u$ is slowly lowered to gradually return to the fixed bed, $\Delta P$ will backtrack along a slightly reduced path.

The flow velocity $u_{mf}$ at point B is called the critical fluidization velocity, the flow velocity $u_{gt}$ at point C named as carrying velocity, and the operational velocity $u$ in the actual fluidized bed is between $u_{mf}$ and $u_{gt}$, which can be calculated by formula (1) based on empirical formula [3]:

$$u = (1.5 - 10)u_{mf} \quad \text{or} \quad u = (0.1 - 0.4)u_{gt}$$

(1)

In line with the operational fluidized velocity $u$, the volume of the ion exchanger, and the delivery pipe diameter, the amount and fluidization time of exhausting gas/liquid required for fluidization of the resin can be calculated. Similarly, the amount and fluidization time of waste gas/liquid, which required for release of the resin can be calculated based on the upper gas discharge pipe diameter and the bottom resin discharge pipe diameter of the ion exchanger.

3. Media parameters and computational theory

When unloading the resin in the ion exchanger, it is more common to suspend and transport the resin particles by air, water or a combination of the both.

3.1. Media parameters

After preliminary calculation [4], the ion exchanger has a bed diameter ($D$) of 0.55m, a bed height ($L_0$) of 1.5m, a total height of 2.0m, and a resin volume of about 0.36m$^3$. In addition, the fluid pipe size is φ40mm×4.5mm and the gas discharge pipe is φ25mm×3mm. The calculation parameters are shown in Table 1 and Table 2.

| Type               | Resin model | Resin wet density/$p_s$ | Bed height $L$ | Average particle size/$d_p$ |
|--------------------|-------------|-------------------------|----------------|----------------------------|
| Cation exchange resin | 001×7MB    | 800 kg/m$^3$            | 0.65m          | $6 \times 10^{-4}$m        |
| Anion exchange resin | 201×7MB    | 700 kg/m$^3$            | 0.85m          | $6 \times 10^{-4}$m        |
The average density of the mixed resin: \( \rho_s = \frac{800 \times 0.65 + 700 \times 0.85}{0.65 + 0.85} = 743.3 \text{ kg/m}^3 \)

**Table 2. Parameters of media for delivering**

| Transport media | Pressure | Temperature | Density/\(\rho_f\) | Kinematic viscosity/\(\mu\) |
|------------------|----------|-------------|--------------------|--------------------------|
| Compressed air   | 3 MPa    | 25°C        | 35.6 kg/m\(^3\)   | 1.8 \times 10^{-5} Pa\(\cdot\)s |
| Water            | 0.4 MPa  | 25°C        | 1000 kg/m\(^3\)   | 1 \times 10^{-3} Pa\(\cdot\)s |

3.2. Computational theory

The initial fluidization speed \( u_{mf} \) of the resin is only related to the physical properties of fluid media and resin. In the critical fluidization state, the stress analysis of the resin in the bed can be described by an equation:

\[ \Delta P = \frac{W}{A} = L_{mf}(1 - \varepsilon_{mf})(\rho_s - \rho_f)g \]  

(2)

The fluidized bed pressure drop can also be calculated by the Ergun formula [3]:

\[ \frac{\Delta P}{L_{mf}} = 1.75 \frac{1 - \varepsilon_{mf} \rho_s u_{mf}^2}{\varepsilon_{mf} \phi d_f^2} + 150 \frac{(1 - \varepsilon_{mf})^3}{\varepsilon_{mf}^3} \frac{\mu u_{mf}}{(\phi d_f^2) \varepsilon_{mf}^3} \]  

(3)

Due to the fluidized bed stage \( \Delta P = \Delta P' \), it is organized:

\[ \frac{1.75}{\phi \varepsilon_{mf}^3} \left( \frac{d_s u_{mf} \rho_f}{\mu} \right)^2 + 150 \frac{(1 - \varepsilon_{mf})^3}{\varepsilon_{mf}^3} \frac{d_s u_{mf} \rho_f}{\mu} = \frac{d_s \rho_f (\rho_s - \rho_f)g}{\mu^2} \]  

(4)

Where \( \phi \) is the shape coefficient of resin, \( \varepsilon_{mf} \) is the critical void ratio, which value is related to the particle diameter and shape. They can be estimated by formula (5) and simplified as follows [2]:

\[ \frac{1}{\phi \varepsilon_{mf}^3} \approx 14, \quad \frac{1 - \varepsilon_{mf}}{\varepsilon_{mf}^3} \approx 11 \]  

(5)

\[ \frac{d_s u_{mf} \rho_f}{\mu} = \left[ 33.7^2 + 0.0408 \frac{d_s^3 (\rho_s - \rho_f)g \mu^2}{\rho_f} \right] - 33.7 \]  

(6)

With different \( \text{Re} \), Ergun formula can be described as follows:

\[ u_{mf} = \frac{d_s^3 (\rho_s - \rho_f)g}{1650 \mu} \quad \text{Re}_{mf} < 20 \]  

(7)

\[ u_{mf} = \left[ \frac{d_s (\rho_s - \rho_f)g}{24.5 \rho_f} \right]^{3/2} \quad \text{Re}_{mf} > 1000 \]  

(8)

The carrying speed \( u_{gt} \) can be determined by the Stokes formula [3] as follows:

\[ u_{gt} = \frac{gd_s^2 (\rho_s - \rho_f)g}{18 \mu} \quad \text{Re} < 0.4 \]  

(9)

\[ u_{gt} = \left[ \frac{4d_s (\rho_s - \rho_f)g \mu}{225 \rho_f \mu} \right]^{3/2} \quad 0.4 \leq \text{Re} \leq 500 \]  

(10)

\[ u_{gt} = \left[ \frac{4d_s (\rho_s - \rho_f)g \mu}{3 \cdot 0.43 \rho_f} \right]^{3/2} \quad 500 < \text{Re} < 200000 \]  

(11)
4. Quantitative analysis of resin waste

4.1. Calculation and analysis of air or water transporting process

When using compressed air or water to transport resin, different formulas should be adopted in different Re. An iterative calculation method will be adopted during the trial calculation process.

4.1.1. Calculation of fluidization velocity \( u_{mf} \).

| Media        | Assumptions | Formula | \( u_{mf} \) (m/s) | Calculated Re | Conclusion | \( (Fr)_{mf} \) | \( S_{mf} \) | State            |
|--------------|-------------|---------|--------------------|---------------|------------|----------------|-------------|------------------|
| Compressed air | Re < 20     | (7)     | 0.084              | 99.9          | unreasonable |               |             |                  |
|              | 20 ≤ Re < 1000 | (6)     | 0.046              | 55.0          | reasonable  | 0.36           | 1085.3      | aggregated fluidized state |
|              | Re > 1000   | (8)     | 0.069              | 82.0          | unreasonable |               |             |                  |
| Water        | Re < 20     | (7)     | 0.00055            | 0.33          | reasonable  | 5.13 × 10^{-3} | -1.53 × 10^{-1} | scattered fluidized state |
|              | 20 ≤ Re < 1000 | (6)     | 0.00055            | 0.33          | unreasonable |               |             |                  |
|              | Re > 1000   | (8)     | 0.00785            | 4.71          | unreasonable |               |             |                  |

Note: As criterion proposed by Romero and Johanson [2], Freude can be calculated in critical fluidization state.

\[
(Fr)_{mf} = \frac{u_{mf}^2}{(gd)} , \quad S_{mf} = (Fr)_{mf} (Re_{mf}) \left( \frac{p_f - p_i}{\rho_f} \right) \left( \frac{L_{mf}}{D} \right), \quad \text{while } S_{mf} > 100 \text{ named aggregated fluidized state, otherwise called scattered fluidized state.}
\]

4.1.2. Calculation of carrying velocity \( u_{gt} \).

| Media        | Assumptions | Formula | \( u_{gt} \) (m/s) | Calculated Re | Conclusion |
|--------------|-------------|---------|--------------------|---------------|------------|
| Compressed air | Re < 0.4   | (9)     | 7.71               | 9154.3        | unreasonable |
|              | 0.4 ≤ Re < 500 | (10)    | 0.66               | 784.4         | unreasonable |
|              | 500 < Re < 200000 | (11)    | 0.60               | 714.8         | reasonable  |
| Water        | Re < 0.4   | (9)     | 0.050              | 30.21         | unreasonable |
|              | 0.4 ≤ Re < 500 | (10)    | 0.029              | 17.39         | reasonable  |
|              | 500 < Re < 200000 | (11)    | 0.068              | 41.07         | unreasonable |

From Table 3, the \( u_{mf} \) can be selected as 0.046m/s by air and is taken as 0.00055m/s by water. Table 4 instructions \( u_{gt} \) could be an air speed of 0.6m/s and be set to 0.029m/s when water delivering.

4.2. Selection of operational fluidization velocity and check calculation of fluidized bed

The operational fluidization velocity \( u \) should be between the \( u_{mf} \) and \( u_{gt} \). In the light of the trial calculations of Table 3 and Table 4, combined with the empirical range of formula (1), more calculation details need to be discussed.

4.2.1. On the condition of air transporting. \( u \) should between 0.06m/s and 0.46m/s. However, in actual operation process, the actual \( u \) should be as high as possible, so \( u \) is taken as 0.46m/s, considering the principle of personnel radio-protection and the operation time should be minimized.

The expansion ratio \( R \) of the fluidized bed is generally between 1.15 and 2 [3]. \( R \) is difficult to determine for bed in aggregated fluidized state, which can refer to the fluidized bed with baffles.

\[
R = \frac{0.517}{1 - 0.76u^{1.924}} , \quad 0.07<u<0.92
\]
While $u=0.46\text{m/s}$, the mixed bed expansion ratio $R=1.497$. The height $Lmf$ of the resin bed is 1.5m. When the air is leaded into the bottom of the mixed bed to fluidization, the concentrated phase of the bed height $Lf=R Lmf=2.24\text{m}>2.0\text{m}$, which is higher than the total height of resin bed thus lead to invalid result.

4.2.2. On the condition of water transporting. $u$ should range from 0.0008m/s to 0.012m/s. Similarly, $u$ is set to 0.012m/s. Scattered hydraulic conveying process has a regular pattern that the void ratio changes uniformly with the fluidization. For bigger solid particles such as spherical resins, the bed void fraction $\epsilon_{mf}$ is not much different from the fixed bed $\epsilon_0$ under critical fluidization velocity. The computational mixed bed void ratio $\epsilon_0$ is about 0.35 [5].

$$\epsilon = u / u_g = 0.012 / 0.029 = 0.414 \quad R = (1 - \epsilon_0) / (1 - \epsilon) = (1 - 0.35) / (1 - 0.414) = 1.109$$

To the same reason, while water is brought to the bottom of the mixed bed for fluidization, the concentrated phase of the bed height $Lf=R Lmf=1.109\times1.5=1.66\text{m}<2.0\text{m}$, which can fulfil the requirements of total height of the ion exchanger.

4.3. Calculation of waste discharge

Contrasting the two programs of compressed air and water conveying resin, it can be known that the discharge of resin must be achieved by means of hydraulic method.

The volume of water filled in the ion exchanger is related to the volume of the dense phase and the proportion of the resin volume. The resin is spherical particles with a bed void ratio $\epsilon_0$ of 0.35, so the volume $V_{water}$ of water required for unloading the resin is

$$V_{water} = \pi D^2 [L_f - (1 - \epsilon_0) Lmf] / 4 \approx 0.2 \text{m}^3$$

According to the pipe design of the purification system, the specification of the water-passing pipe is $\phi 40\text{mm} \times 4.5\text{mm}$ when resin discharging, so the inner diameter of the pipe is $D_1=31\text{mm}$, and the water filling time during resin unloading as follows:

$$t = V_{water} / (\pi D_1^2 u / 4) \approx 5.7\text{h}$$

In engineering practice, in order to shorten the fluidization time, the operating flow rate can be increased while keeping the fluidization volume constant. The water flow rate supplied by other system is about 1m/s , and the water filling time $t = V_{water} / (\pi D_1^2 u / 4) = 265s \approx 4.5\text{min}$

To sum it up, when the bottom of the ion exchanger is filled with water at a flow rate of 1m/s, it needs 4.5min to fluidize the resin, which produces an amount of waste liquid about 0.2 m$^3$.

Resin may be remained during discharging; whose amount is about 10% of the total resin based on experience. The emission of fluidized resin and total volume of waste water at the first time is calculated as follows:

$$V_1 = 0.2 + \pi D_1^2 (1 - \epsilon) Lmf \times (1 - 10\%) / 4 \approx 0.4 \text{m}^3$$

Assuming a flow rate of 1m/s, the emission time of solid-liquid waste is approximately 9min. In order to unload the resin completely, the residual 10% resin needs to be discharged by secondary fluidization. Refer to the analogy of fluidization process at the first time, the calculation results of the secondary fluidization process are shown in Table 5.

| Resin layer height (m) | Concentrated phase height (m) | Waste water amount (m$^3$) | Water filling time (min) | Discharge volume (m$^3$) | Emission time (min) |
|-----------------------|-------------------------------|-----------------------------|-------------------------|-------------------------|-------------------|
| 0.15                  | 0.1665                        | 0.02                        | 0.45                    | 0.04                    | 0.9               |

Table 5. Computation results of resin secondary fluidization

After secondary fluidization, the remaining resin bed height $Lf=0.015\text{m}$, considering that it is difficult to unloading the resin at the corner of the ion exchanger completely, it is proposed to use compressed air to fluidize the residual resin at a rate of 0.5m/s, thus the concentrated phase of the bed height $L_f=RL_3=1.497\times0.015=0.0225m$. Choose a speed of 2m/s higher than $u_{gf}$ for fluidization, the total volume of the exhaust gas is 0.5m$^3$(3MPa, 20℃)equals the total volume of the ion exchanger. In view of the size of the air venting pipe is $\phi 25\text{mm} \times 3\text{mm}$ and the inner diameter $D_2$ is 19mm, during resin...
unloading the gas emission time is \[ t = \frac{V_{aw}}{(\pi D^2 u / 4)} \approx 15 \text{min}. \]

The containment ventilation system can meet exhaust demand under accident conditions, the amount of radioactive waste gas while resin unloading is quite few in contrast, which is completely inclusive by radioactive waste gas treatment system.

4.4. Resin Emission Program

To sum it up, the following program can be implemented when discharging the resin:

1) Open the bottom inlet valve of the ion exchanger, fill the water at a speed of 1 m/s for 4.5 min to fluidize the resin, then close the valve. Afterwards, open the bottom resin emission valve to discharge fluidized resin for about 9 min, which produces waste water of 0.2 m\(^3\) and waste resin of 0.324 m\(^3\), the mixture of waste resin and waste water is about 0.4 m\(^3\), then close the valve;

2) Open the bottom inlet valve of the ion exchanger and fill the water at a speed of 1 m/s for 0.45 min to fluidize residual resin the second time. Analogously, the emission time is about 0.9 min with a waste water of 0.02 m\(^3\) and waste resin of 0.0324 m\(^3\), whose mixture is about 0.04 m\(^3\), then close the bottom resin discharge valve;

3) Open the bottom inlet valve of the ion exchanger, utilize 2 m/s compressed air to purge the residual resin. The purge time is about 15 min, and the amount of exhaust gas generated is 0.5 m\(^3\) (3 MPa, 20°C), which is about 15 m\(^3\) under standard temperature and pressure (referred to as “STP”).

5. Conclusion

The solid fluidization theory was applied in this paper to analyze the amount of waste generated when pneumatic and hydraulic fluids are used as a media to unload resin. Comparing the calculation results, it is found that the better emission effect is by the combination of both. The program of unloading resin in the ion exchanger is recommended as follows: Fluidization at the bottom → Resin discharge by gravity for the first time → Secondary bottom fluidization → Resin discharge via gravity for the second time → Final pneumatic conveying of residual resin.

For a purified resin with a volume of 0.36 m\(^3\), the amount of liquid waste generated is about 0.22 m\(^3\) and the amount of exhaust gas is about 15 m\(^3\) (STP) during emission process. The solid-liquid waste production is about 0.44 m\(^3\) due to the resin void ratio.

In summary, the resin emission program produces a small amount of waste, which reduces the burden of floating nuclear power plant and provides a strong basis for the designed input of the radioactive waste. The calculation method and the resin emission scheme have a significant reference to the engineering project which has strict requirements for the amount of radioactive waste.

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