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Radioactive Waste Gas Treatment System in Hualong One Innovative Pressurized Water Reactor

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SUMMARY: *Radioactive waste gas treatment system of the Hualong One Innovative Pressurized Water Reactor is designed by analyzing the volume and characteristics of the upstream waste gas and adopting the "activated carbon pressurized retention decay" technology for treatment. The system operation parameters are determined through performance bench tests; meanwhile, a hydrogen-oxygen recombiner is introduced in the explosion-proof design to eliminate hydrogen from the source. The final design of the radioactive waste gas treatment system can meet the requirements of radioactive waste gas treatment and ensure the compliance of gaseous effluents. Compared with the waste gas treatment technologies of different reactor types, it is found that the waste gas treatment process of the Hualong One Innovative Pressurized Reactor has the advantages of smaller floor space, better treatment effect, less waste activated carbon generation, and improved safety performance.*

KEYWORDS: *Hualong One Innovative Pressurized Water Reactor; activated carbon pressurized retention decay; radioactive waste gas treatment*

1 Introduction

After the Fukushima incident, nuclear safety issues have received high attention, and nuclear power regulatory authorities in various countries have put forward stricter requirements for the safety design of nuclear power plants [1, 2]. The main components of radioactive waste gas in pressurized water reactor nuclear power plants are nitrogen (N2) and hydrogen (H2), as well as radioactive fission product gases krypton (Kr) and xenon (Xe). When the hydrogen concentration in the waste gas exceeds a certain range, there is a risk of explosion. Therefore, the hydrogen explosion prevention measures in the radioactive waste gas treatment system are closely related to nuclear safety [3].

Meanwhile, to implement the innovation-driven development strategy, comprehensively enhance the core competitiveness and sustainable development capacity of the nuclear industry, and continuously optimize the Hualong One technology, China aims to significantly improve the market competitiveness of the Hualong One Innovative reactor (referred to as AHPR1000 in the following paper) by developing pressurized water reactor nuclear power technology with higher safety, better economy, innovative technical features, and major performance improvements [4, 5].

This paper analyzes the current status of waste gas treatment technology, compares the design principles and on-site operation feedback experiences of the waste gas treatment systems used in the current mainstream third-generation pressurized water reactor nuclear power plants,

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summarizes the advantages and limitations of each system design, and based on the upstream waste gas volume and characteristics as well as the treatment requirements for radioactive waste gas, obtains the design scheme for the radioactive waste gas treatment unit of the AHPR1000. At the same time, from the perspective of enhancing safety performance, the explosion-proof design is optimized to eliminate the risk of hydrogen explosion from the source. The radioactive waste gas treatment system of AHPR1000 must meet the requirements of radioactive waste gas treatment for the project and achieve the standard discharge of gaseous effluents. Through comparisons with the European Pressurized Water Reactor (referred to as EPR in the following paper), AP1000, and VVER reactor types in terms of treatment effects, the advantages of the AHPR1000 in radioactive waste gas treatment are demonstrated in aspects such as equipment floor area, waste gas treatment effect, waste activated carbon generation, and safety performance.

2 Current Status of Waste Gas Treatment Technology

Currently, the main treatment processes for radioactive waste gas in domestic pressurized water reactor nuclear power plants are "compression + storage decay" for the EPR reactor types, "activated carbon retention decay" for the AP1000 reactor type, and "hydrogen-oxygen recombination + activated carbon retention decay" for the VVER reactor type [6].

In the EPR reactor type, the hydrogen-containing waste gas collected in the nuclear island condensate exhaust system's gas collection pipe is received by a buffer tank; the waste gas then enters two parallel compressors for compression, passes through a cooler to be cooled to 50°C, and enters a gas-water separator to remove condensate water, and then enters the decay tank; the waste gas to be discharged from the eight decay tanks is discharged into the ventilation system through a common exhaust pipe [7, 8]. **Figure 1** shows the flow diagram of the hydrogen-containing waste gas treatment subsystem for the EPR reactor type.

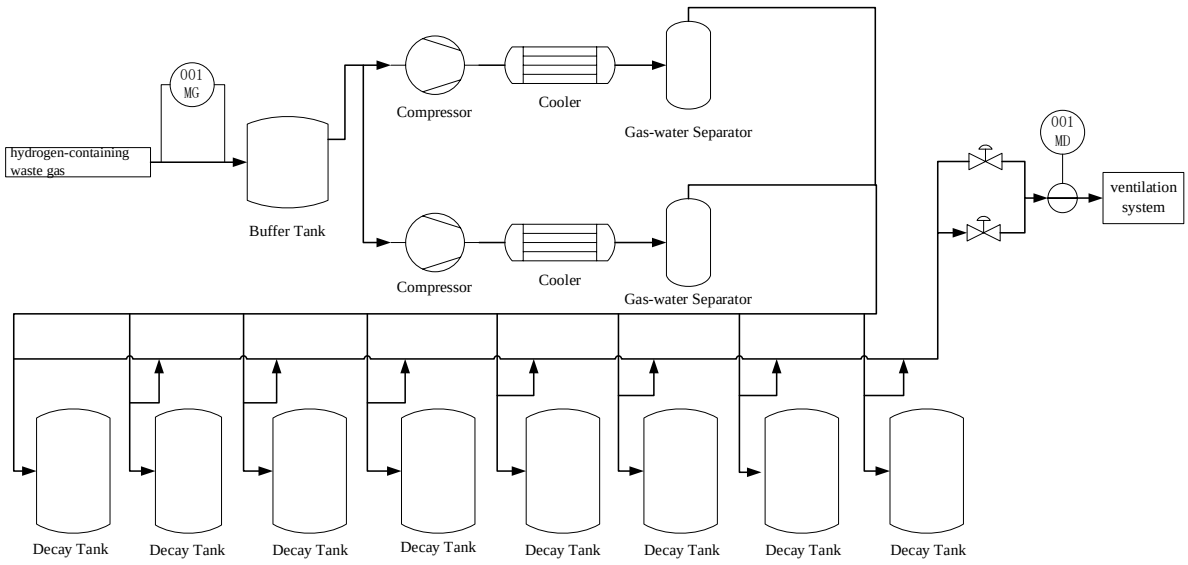

Figure 1: The flow diagram of the hydrogen-containing waste gas treatment subsystem for the EPR reactor type

In the AP1000 reactor type, the collected waste gas comes from the dehydrater and the reactor coolant condensate tank. It first passes through a gas cooler to be cooled to 4.4°C, and the generated condensate is removed in the gas-water separator. The dehumidified gas then

flows through a protection bed to prevent the decay beds from being contaminated by carried water vapor or chemical substances; subsequently, it passes through two series-connected activated carbon decay beds, and the decayed waste gas is discharged to the plant exhaust system through a pipeline equipped with a radioactive monitor [9]. **Figure 2** shows the flow diagram of the gas radioactive waste treatment system for the AP1000 reactor type.

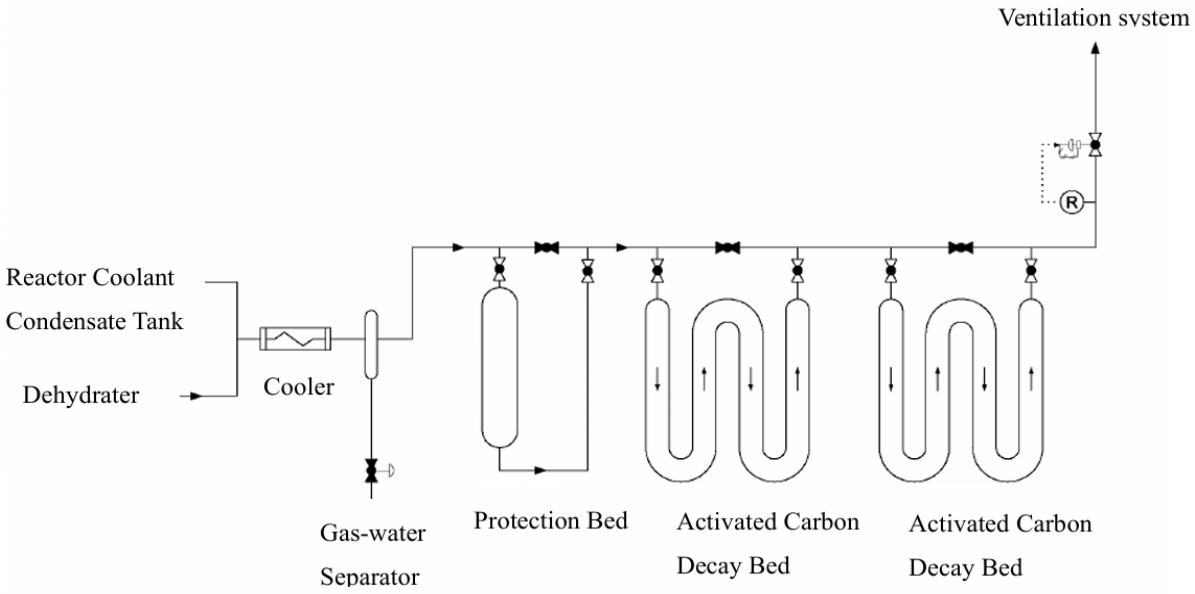

Figure 2: The flow diagram of the gas radioactive waste treatment system for the AP1000 reactor type

The nitrogen, hydrogen and inert radioactive gases from the primary circuit degasser of the VVER reactor type first pass through the hydrogen combustion system to remove hydrogen. Then, the gas enters the combiner where H2 and O2 are combined under the action of a catalyst [10]. The majority of the gas returns to the buffer tank before completing a closed-loop cycle in the system circulation loop. Some of the exhaust gas is sent to the main processing line of the radioactive exhaust gas treatment system, cooled to 35°C by a gas cooler, and then enters the collector. The gas coming out of the collector enters the aerosol filter and is then sent to the zeolite dryer for drying. The dried gas continuously passes through four activated carbon adsorbers. The treated exhaust gas is sent to the exhaust chimney through the bypass pipe of the exhaust gas compressor. The processing flow rate of this processing line is 2 to 5 Nm^3/h [11, 12]. **Figure 3** shows the process flow diagram of the radioactive exhaust gas treatment system for the VVER reactor type. **Table 1** summarizes the design of the exhaust gas treatment systems for different reactor types based on the gas flow rate processed by each processing unit and the volume of the processing unit.

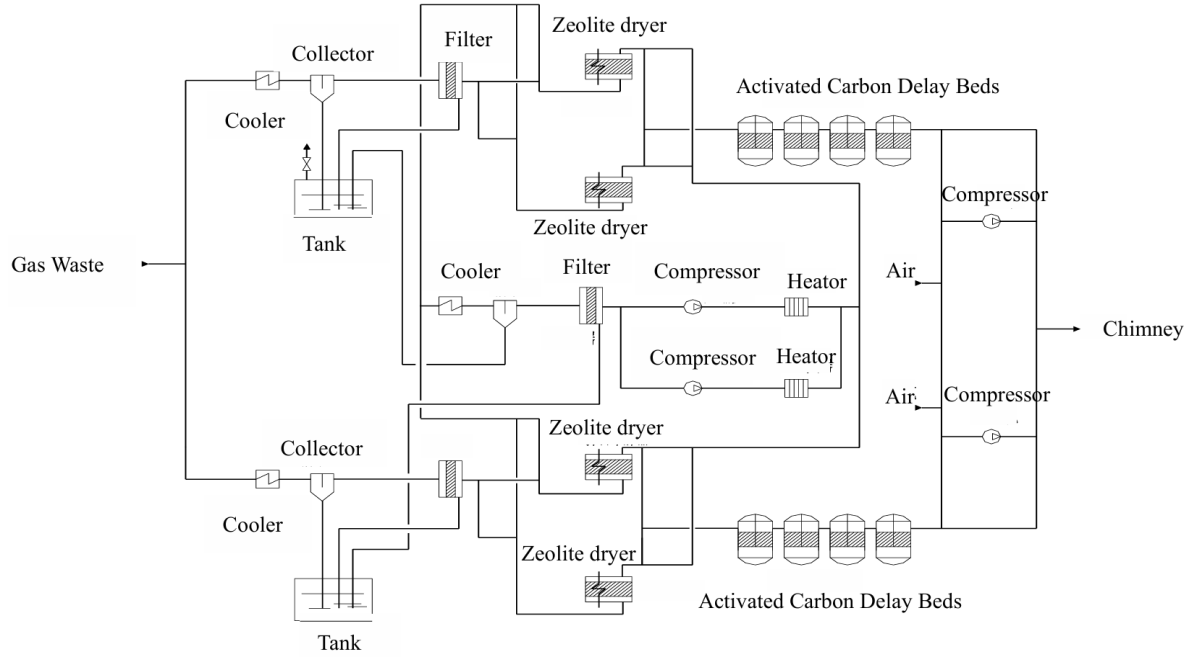

Figure 3: The flow diagram of the radioactive exhaust gas treatment system for the VVER reactor type

Table 1: Current Status of Radioactive Exhaust Gas Treatment Technology for Pressurized Water Reactors

Reactor Type	EPR	AP1000	VVER
Process	Pressurized Storage Decay	Activated Carbon Retention Decay	Hydrogen-Oxygen Combination + Activated Carbon Retention Decay
Processing Capacity	38~76Nm³/h	0.83~0.99Nm³/h	2~5 Nm³/h
Volume (Only Processing Unit)	4×60m³/Single Unit	2×2.3m³/ Single Unit	4×5m³/ Single Unit

From **Table 1**, the EPR reactor type can handle a gas flow rate of 38 - 76 Nm³/h; the gas flow rate of the AP1000 reactor type is 0.85 Nm³/h; and the VVER reactor type only processes a gas flow rate of 2 - 5 Nm³/h on the main processing line. By comparing the processing capacity, it can be seen that the compression + storage decay technology used by the EPR reactor type can handle a relatively large gas flow rate and can adapt to the exhaust gas treatment requirements under fluctuating flow rates; while the activated carbon retention decay technology used by the AP1000 reactor type and the VVER reactor type can only handle a relatively small exhaust gas flow rate. At the same time, based on the operational experience feedback from nuclear power plants [13]: when the exhaust gas flow rate fluctuates greatly, the retention adsorption effect of the activated carbon atmospheric pressure retention decay process used by the AP1000 reactor type and the VVER reactor type significantly decreases; and a large amount of activated carbon is required to handle a large flow rate of radioactive exhaust gas, which can easily lead to a large amount of waste activated carbon.

On the other hand, without considering other equipment and only considering the volume of the processing unit, it can be seen from Table 1 that the storage tank capacity of the processing unit required by the EPR reactor type to handle a large gas flow rate is 240 m³ per

single unit [14]. When there is a leak in the decay tank or related valves and other equipment, a tank transfer operation (i.e., transferring the gas in one decay tank to another decay tank through a compressor) must be performed. Therefore, the capacity of the decay tank must be conservatively considered in the design to prevent insufficient capacity. Additionally, based on the current operational experience feedback from nuclear power plants [15, 16], the compression storage decay technology used by the EPR reactor type has also exposed some problems during long-term operation, such as frequent internal leakage of diaphragm valves, damage to compressors during tank transfer operations, and complex personnel operations. Compared to the activated carbon atmospheric pressure decay technology used by the AP1000 reactor type and the VVER reactor type, the compression decay technology has relatively weaker safety.

In conclusion, each reactor type's exhaust gas treatment process has its advantages and limitations. By analyzing the current status of different pressurized water reactor nuclear power plant exhaust gas treatment technologies, summarizing the on-site operation feedback experience, and comprehensively considering the plant layout planning and economy, AHPR1000 will consider using the activated carbon retention and decay technology for the treatment of radioactive exhaust gas [17].

At the same time, in view of the design limitations of the AP1000 and VVER reactor types, AHPR1000 will consider through the process system design to enable the retention and decay technology to handle the fluctuating flow of gas from the upstream and reduce the generation of waste activated carbon.

3 Radioactive treatment unit

3.1 Upstream exhaust gas volume and characteristics

The radioactivity of the exhaust gas in pressurized water reactor nuclear power plants mainly comes from the fission products produced by the nuclear fission reaction in the reactor core, which enter the gas phase from the liquid phase due to pressure changes, forming radioactive nuclides such as krypton (Kr) and xenon (Xe) [18, 19]. The main sources of radioactive exhaust gas in AHPR1000 are the chemical and volume control system (RCV), boron recovery system (ZBR), and nuclear island condensate exhaust system (RVD). By analyzing the operation of main source systems, the exhaust gas treatment system needs to have the ability to handle fluctuating flow rates of 1.2 to 20 Nm^3/h. The source terms of the primary circuit exhaust gas mainly refer to the EPR reactor type. From the conservative source terms of the primary circuit inert gas, Kr-85 has the longest half-life of 3905.5 days, and its decay rate is extremely small in a short period of time, making it difficult to remove; however, its proportion is the smallest, only 0.13%. Among the exhaust gas source terms, Xe is the main contributor to the total activity concentration, accounting for 84.3% of the total activity concentration. Among the Xe elements, the longest half-life is Xe-133, with a half-life of 5.2 days. Therefore, the reduction effect of the exhaust gas radioactivity level mainly depends on the decay effect of Xe-133.

3.2 Activated carbon adsorption performance test

The adsorption of inert gas on activated carbon is physical adsorption. The atomic diameters of Xe and Kr and the relative relationship with the pore size of activated carbon make them easy to enter the micro-pores of activated carbon and difficult to escape. According to research, the adsorption performance of Kr and Xe on the same type of activated carbon has a good correlation - that is, activated carbon with good adsorption performance for Kr also has good

adsorption performance for Xe [20]. The dynamic adsorption coefficient *K*d is an important parameter reflecting the adsorption capacity of activated carbon for inert gas, and its calculation formula is as follows [21]:

$$K_d = \frac{F \times T_d}{M} \quad (1)$$

(1) Where K_d - dynamic adsorption coefficient, Ncm³/g; F - carrier gas flow rate, Ncm³/min; M - activated carbon mass, g; Td - average retention time, min.

3.2.1 Inert Gas Retention Test

Three activated carbon samples meeting the recommended physical property criteria were selected based on relevant literature [22], and their physical parameters were subsequently measured. The detailed physical properties of the samples are presented in **Table 2**.

Table 2: Physical Properties of Activated Carbon Samples

Indicator Type	Unit	Recommended Value	Sample 1	Sample 2	Sample 3
Strength	%	≥97	99.1	98.4	98
Particle Size Distribution	%	≥90	95.6	92.0	91
Ash Content	%	≤4	2.8	3.9	4.0
Moisture Content	%	≤5	2.0	0.8	2.1
Apparent Density	g/mL	0.4-0.6	0.48	0.42	0.40

To determine the dynamic adsorption coefficients of krypton (Kr) and xenon (Xe), a test bench was established for the inert gas retention test. **Figure 4** illustrates the flow diagram of the activated carbon retention performance test system, while **Figure 5** presents a three-dimensional picture of the test bench setup.

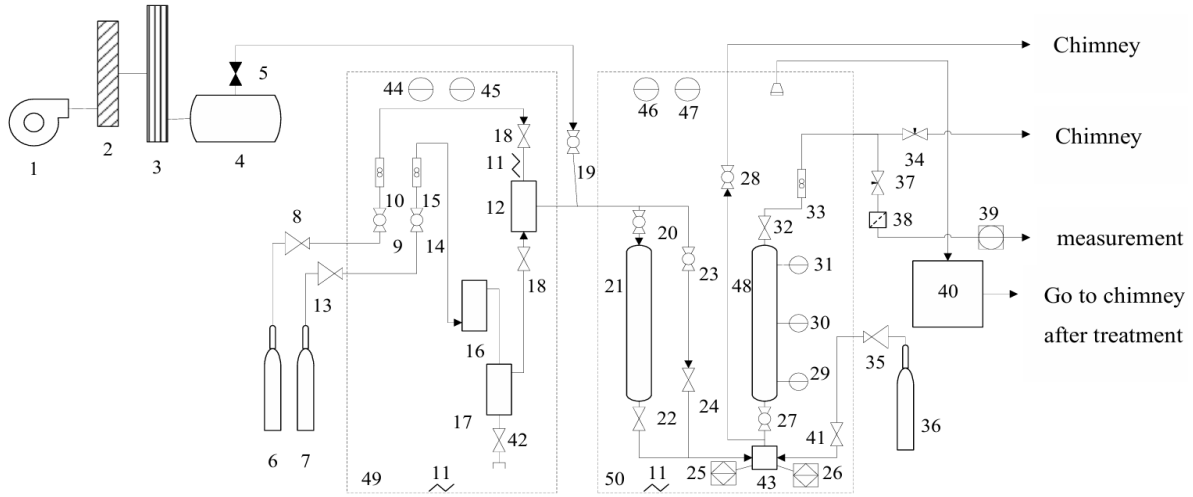

Figure 4: The flow diagram of the activated carbon retention performance test system

(1 – Compressed air; 2 – Oil removal module; 3 – High-efficiency filtration module; 4 – Buffer tank; 5, 8, 13, 35 – Pressure reducing valve; 6, 7 – Nitrogen; 9, 14 – Flow control valve; 10, 15, 33 – Flowmeter; 11 – Heater; 12 – Mixer; 16 – Humidifier; 17 – Gas-water separator; 18, 22, 24, 32, 41 – Globe valve; 19, 20, 23, 27, 28 – Ball valve; 21 – Protective bed; 25 –

Pressure sensor; 26 – Temperature and humidity sensor; 29, 30, 31 – Pressure/temperature sensor; 34, 37 – Needle valve; 36 – Inert gas source; 38 – Filter membrane; 39 – Inert gas measurement system; 40 – Dust removal and purification system; 42 – Drain valve; 43 – Mixing measurement tank; 44, 45 – Pressure display instrument; 46 – Humidity display instrument; 47 – Temperature display instrument; 48 – Activated carbon test bed; 49, 50 – Equipment integrated constant temperature cabinet/instrument display panel)

Figure 5: The picture of the test bench setup

The test conditions were set to a temperature of 20 °C, a gas flow velocity of 0.116 cm/s, a pressure of 0.014 MPa (g), and a relative humidity of 5.0%. A known concentration of inert gas was introduced into the system using the pulse injection method, and the downstream effluent concentration was continuously monitored and recorded. The retention time was defined as the time interval between the entry and exit of the inert gas pulse peak through the activated carbon bed. Based on the recorded data, the actual retention time and corresponding dynamic adsorption coefficients of Kr and Xe were calculated.

The dynamic adsorption coefficients of Kr and Xe for the three activated carbon samples at 20 °C are summarized in **Table 3**.

Table 3: Dynamic Adsorption Coefficients of Activated Carbon Samples

Name	Dynamic Adsorption Coefficient of Kr(Ncm^3/g)	Dynamic Adsorption Coefficient of Xe(Ncm^3/g)	Adsorption Coefficient Ratio
Sample 1	61.7	1188.8	19.3
Sample 2	55.7	1012.6	18.1
Sample 3	52.4	800.3	15.3

The results indicate that Sample 1 exhibits the highest dynamic adsorption capacities for both Kr and Xe, with values of 61.7 Ncm^3/g and 1188.8 Ncm^3/g, respectively, demonstrating superior adsorption performance compared to the other samples.

3.2.2 Operational Parameter Influence Test

The adsorption of inert gases on activated carbon is primarily attributed to intermolecular van der Waals forces [23]. Adsorption occurs when inert gas molecules come into contact with suitable surface vacancies on the activated carbon, which is an interfacial phenomenon. When the dipole or quadrupole moments of the adsorbate molecules are linearly arranged, the molecular free energy is significantly reduced. Consequently, variations in operational parameters such as pressure, temperature, humidity, and flow rate can influence the dynamic adsorption coefficient (*K*d) of activated carbon [24].

To evaluate the impact of operational parameters on the adsorption performance of activated carbon, a bench-scale test was conducted using Sample 1. The selected variable parameters included gas flow rate, temperature, and pressure, while the control variable method was applied during the experimental design. Based on the exhaust gas source characteristics listed in Table 2, Xe was identified as the primary contributor to radioactivity. Therefore, the dynamic adsorption coefficient of Xe on activated carbon was measured to assess its adsorption performance.

(1) Influence of Gas Flow Rate on Adsorption Performance

Figure 6 presents the dynamic adsorption coefficient of Sample 1 for Xe under varying gas flow conditions at a constant temperature and pressure. The results indicate that within a certain range of gas flow rate, the adsorption coefficient remains relatively stable.

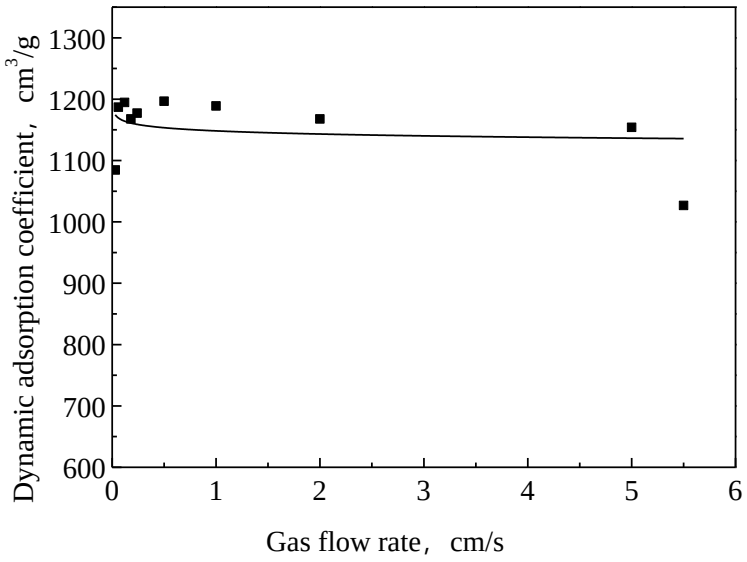

Figure 6: The influence of gas flow rate on the adsorption performance

(2) Influence of Temperature on Adsorption Performance

The adsorption performance test was conducted under an inlet pressure of 0.014 MPa and a gas flow rate of 0.24 cm/s. The dynamic adsorption coefficient of Xe on activated carbon was measured across a temperature range of 10–50 °C. As shown in **Figure 7**, the test results reveal a linear relationship between logK_d and temperature, indicating that the adsorption coefficient decreases with increasing temperature.

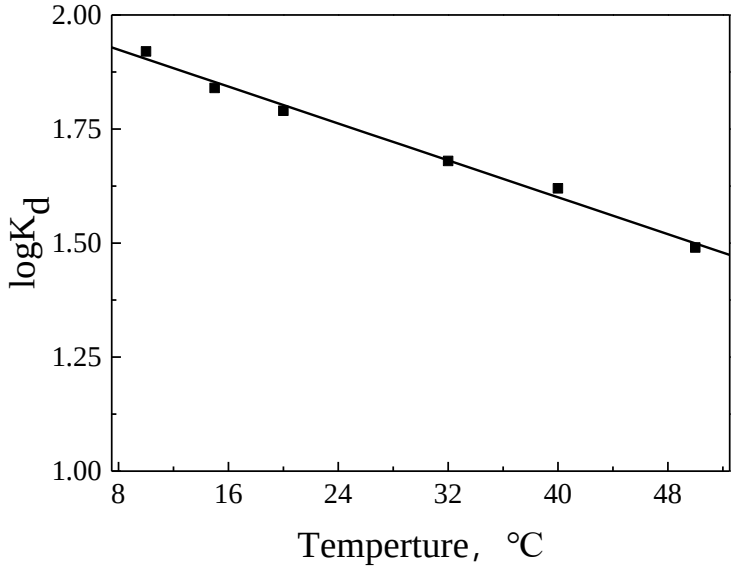

Figure 7: The influence of temperature on the adsorption performance

(3) Influence of Pressure on Adsorption Performance

The dynamic adsorption coefficient of activated carbon for Xe was measured using Sample 1 under varying pressures (0–0.8 MPa(g)), at a constant temperature of 20 °C and gas flow rate of 0.24 cm/s. The results, illustrated in **Figure 8**, demonstrate that operating pressure has a positive effect on the dynamic adsorption coefficient—higher pressure enhances the adsorption capacity. However, as pressure approaches 0.8 MPa, the rate of improvement in dynamic adsorption performance diminishes.

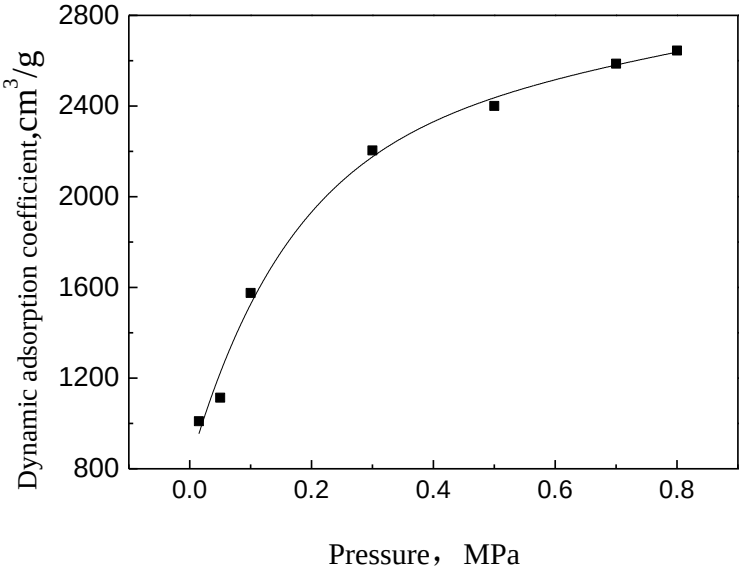

Figure 8: The influence of pressure on the adsorption performance

Additionally, according to previous research [25, 26], the presence of high-boiling-point substances significantly affects the adsorption process. When the relative humidity of the gas stream is high, activated carbon preferentially adsorbs water vapor, which reduces its capacity to adsorb inert gases. Specifically, when the relative humidity exceeds 20%, the dynamic

adsorption coefficient decreases markedly. Therefore, a relative humidity below 20% is typically maintained to prevent the deactivation of activated carbon.

3.3 Design of Activated Carbon Pressurized Retention Decay System

In engineering applications, maintaining the activated carbon delay bed at a temperature of 10°C over an extended period would result in significant energy consumption and reduced economic efficiency [27]. Therefore, for AHPR1000, the retention decay system for activated carbon primarily adopts a pressurized design to enhance the adsorption performance of the activated carbon, reduce the required quantity of activated carbon, and consequently minimize the generation of spent activated carbon.

Based on research findings regarding the adsorption performance of activated carbon and the characteristics of upstream exhaust gas from AHPR1000, the operational parameters for the radioactive exhaust gas treatment system have been established as follows: operating temperature of 20°C, pressure of 0.7 MPa (g), humidity below 20%, and a flow rate of 20 Nm^3/h. Under these conditions, the adsorption capacities of Sample 1 for Kr and Xe are 139.5 Ncm^3/g and 2594.7 Ncm^3/g, respectively.

The system is designed with four delay beds connected in series for the retention and decay of inert gases. In the event that any one of the delay beds requires activated carbon replacement, it can be isolated and bypassed. Assuming each delay bed is filled with 5 m^3 of activated carbon and the density of Sample 1 is 0.48 g/cm^3, the total mass of activated carbon (M) across the four delay beds is calculated to be 9600 kg.

Using Equation (1), the retention times for Kr and Xe can be calculated as follows:

$$T_{d,Kr} = \frac{K_{Kr} M}{F} \tag{2}$$

$$T_{d,Xe} = \frac{K_{Xe} M}{F} \tag{3}$$

Accordingly, the retention times for Kr and Xe in the radioactive exhaust gas treatment system of AHPR1000 are determined to be 2.8 days and 51.9 days, respectively. Based on the analysis of the upstream exhaust gas source terms presented in Table 2, it is concluded that the reduction in radioactivity primarily depends on the decay of Xe-133. The retention time of Xe by activated carbon (51.9 days) is approximately ten times the half-life of Xe-133. According to engineering experience, after ten half-lives, the radioactivity has decayed to less than 1/1000 of its original level [28, 29]. Therefore, the pressurized retention decay system utilizing activated carbon in AHPR1000 can effectively reduce the radioactivity level of the exhaust gas.

4 Exhaust Gas Treatment Design Scheme

4.1 Process Design Flow

The radioactive hydrogen-containing exhaust gas generated from AHPR1000 is collected by the RVD system and subsequently converges into the main pipeline. It then passes through a gas-water separator to remove any moisture present in the gas stream. The dried exhaust gas enters the buffer tank, where its pressure is stabilized. Following this, the gas flows through a hydrogen-oxygen analyzer, which measures the concentrations of H_2 and O_2 in the pipeline.

If the hydrogen concentration exceeds the threshold level, nitrogen is introduced into the

system to dilute the gas mixture. The hydrogen-oxygen analyzer continuously monitors the hydrogen and oxygen content and automatically adjusts the injection rate of air or oxygen accordingly. When the H_2 concentration drops below 3%, the gas is directed into the hydrogen-oxygen reactor, where a catalytic hydrogen-oxygen recombination reaction occurs. Since this reaction is exothermic, the resulting gas stream is cooled in a gas cooler before being passed through another gas-water separator to remove condensate. The hydrogen-oxygen analyzer also monitors the gas composition after the reactor to assess reactor performance and verify the effectiveness of the recombination process.

The gas is then compressed by a compressor to a pressure of 0.7 MPa(g). The compression process increases the gas temperature, which is subsequently reduced using a compressed gas cooler. After cooling, the gas passes through a gas-water separator to remove any condensate formed during the cooling process. The compressor serves as the primary driving force for the entire exhaust gas treatment system. Following dehumidification, excess gas is recirculated back to the inlet of the buffer tank via a control valve, forming a closed-loop system. This ensures that the gas flow entering the protection bed remains constant at 20 Nm^3/h.

The protection bed is designed to further dehumidify the gas and remove chemical impurities, thereby enhancing the adsorption efficiency of the downstream activated carbon beds. Temperature and relative humidity monitoring systems are installed downstream of the protection bed to ensure that the gas entering the delay bed maintains a temperature of 20°C and a relative humidity below 20%. The gas then flows through four series-connected delay beds, where Kr and Xe are adsorbed by activated carbon. The treated exhaust gas undergoes radioactivity monitoring before being discharged into the ventilation system of the nuclear auxiliary building via a pressure-reducing valve.

Under conservative operating conditions, the radioactivity levels of the treated exhaust gas are calculated and categorized based on operational parameters, except for Kr-85, which is difficult to remove, the radioactivity of other inert gases has been effectively reduced. The total radioactivity after treatment accounts for only 1.33% of the annual emission of airborne radioactive effluents. Therefore, the design of the radioactive exhaust gas treatment system meets the required treatment efficiency, ensuring that gaseous emissions comply with regulatory standards. A schematic diagram of the process flow is presented in **Figure 9**.

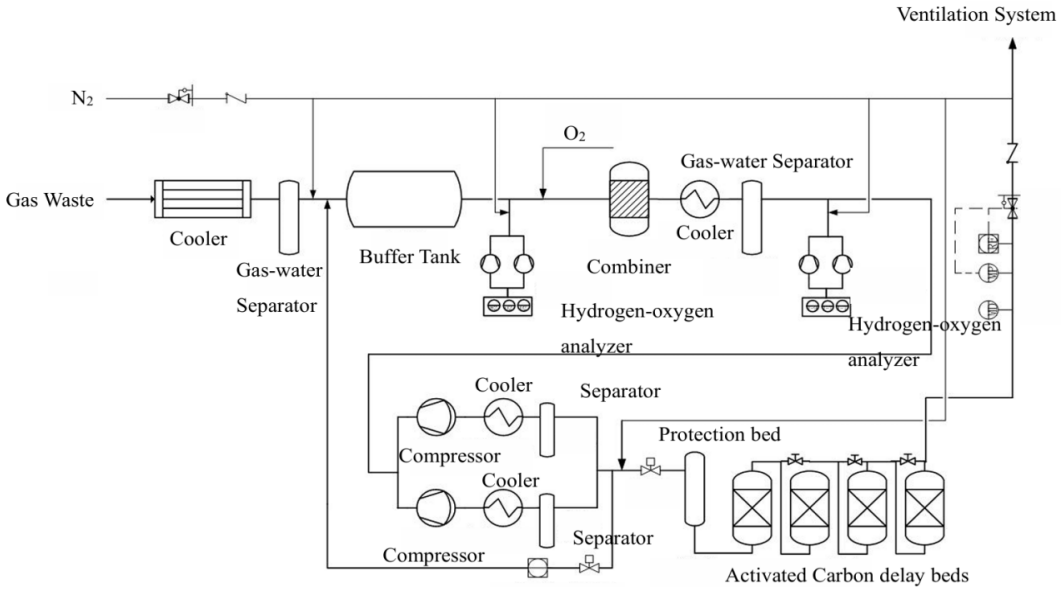

Figure 9: The flow diagram of the Radioactive waste treatment system for the AHPR1000 reactor type

4.2 Comparison of Treatment Effects

The exhaust gas treatment system designed for AHPR1000 was compared with the primary treatment processes used in current domestic pressurized water reactor (PWR) nuclear power plants. The comparison focused on key parameters such as gas flow rate, decay unit configuration, decay volume, retention time for Kr and Xe, and explosion prevention measures. The results are summarized in **Table 4**.

Table 4: Comparison of Processing Technologies and Capabilities of AHPR1000 and Other Reactor Types

Reactor Type	EPR	AP1000	VVER	AHPR1000
Process	Pressurized Storage Decay	Activated Carbon Atmospheric Retention Decay	Hydrogen-Oxygen Recombination + Activated Carbon Atmospheric Retention Decay	Hydrogen-Oxygen Recombination + Activated Carbon Pressurized Retention Decay
Operating Pressure	0.65MPa	0.014MPa	0.02MPa	0.70 MPa
Decay Unit	Storage Tank (Pressurized)	Activated Carbon (Atmospheric)	Activated Carbon (Atmospheric)	Activated Carbon (Pressurized)
Decay Unit Volume	240m³/ Single Unit	4.6m³/ Single Unit	20m³/ Single Unit	20m³/ Single Unit
Kr,Processing Time	45d	2.2d	3.6d	2.8d
Xe,Processing Time	45d	38.6d	70.8d	51.9d
Explosion Prevention Measures	Nitrogen Purge	Nitrogen Purge	Hydrogen-Oxygen Recombination Device	Hydrogen-Oxygen Recombination Device

4.2.1 Equipment Floor Area

Based on the processing flow rates and decay unit volumes of EPR, AP1000, VVER, and AHPR1000, the equipment areas under equivalent flow conditions were calculated and compared. The respective floor areas per unit flow rate were 3.08 m², 4.65 m², 4.00 m², and 1.00 m². The results are illustrated in **Figure 10**.

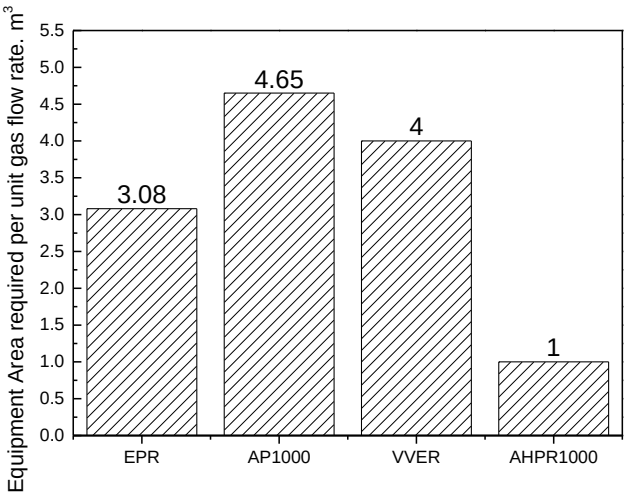

Figure 10: The equipment areas required per unit gas flow rate in different reactor types

Figure 10 illustrates the equipment area required per unit gas flow rate for different reactor types. It is evident that AHPR1000 occupies significantly less floor space per unit flow rate compared to other reactor types. Specifically, the area required is only 25% of that of the VVER reactor using atmospheric activated carbon adsorption, 67.5% less than the EPR decay tank volume, and 78.5% less than the AP1000 loading capacity per unit flow rate. Therefore, AHPR1000 demonstrates a clear advantage in terms of space efficiency.

4.2.2 Exhaust Gas Treatment Effect

Based on the activated carbon adsorption performance data: the Xe adsorption coefficient of AHPR1000 is 2594.7 Ncm³/g, Kr adsorption coefficient is 139.5 Ncm³/g; which exhibits significantly higher adsorption performance compared to other reactor types. Under pressurized conditions, the Xe and Kr adsorption coefficients of AHPR1000 are approximately 9.3 and 10 times higher, respectively, than those of the VVER reactor, and approximately 7.6 and 7.3 times higher than those of the AP1000 reactor. Therefore, AHPR1000 demonstrates superior performance in terms of activated carbon adsorption and inert gas removal efficiency.

4.2.3 Generation of Waste Activated Carbon

Based on the adsorption capacity of activated carbon used in AP1000 and VVER reactors, the required filling amounts were calculated as 2302.46 kg and 30343 kg, respectively. Assuming a replacement cycle of five years, the annual generation of waste activated carbon is estimated at 0.46 t/a and 6.07 t/a. The comparison of waste activated carbon generation among different reactor types is illustrated in **Figure 11**.

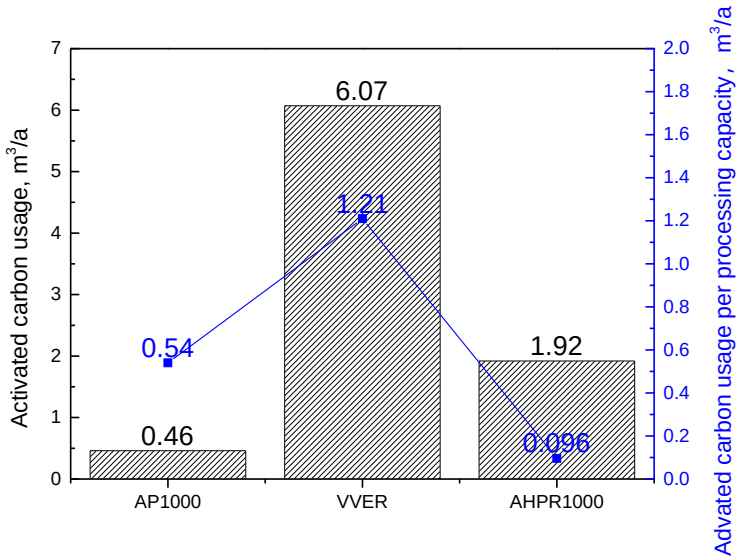

Figure 11: The usage of activated carbon in different reactor types

As shown in **Figure 11**, AHPR1000 generates less waste activated carbon per unit processing volume compared to AP1000 and VVER reactors that also employ activated carbon retention and decay processes. Furthermore, based on unit processing flow rate, AHPR1000 requires the least amount of activated carbon per unit flow, indicating superior performance.

Additionally, the HPR1000 and AP1000 reactor types primarily rely on nitrogen purging for explosion prevention, which does not eliminate the risk of explosion and fire at the source. In contrast, AHPR1000 and VVER reactor types incorporate hydrogen-oxygen recombiners into their exhaust gas treatment systems to reduce hydrogen content, thereby enhancing overall

system safety.

In conclusion, a comparative analysis of the radioactive exhaust gas treatment systems of EPR, AP1000, VVER, and AHPR1000 reveals that the "pressurized retention decay of activated carbon" technology employed in AHPR1000 effectively handles fluctuating upstream gas flows. By enhancing the adsorption performance of activated carbon, the system reduces both the amount of activated carbon required per unit flow and the associated equipment footprint and waste generation. Moreover, the integration of hydrogen-oxygen recombiners in AHPR1000 significantly improves explosion prevention capabilities, thereby enhancing overall system safety.

5 Conclusions

Based on the characteristics of upstream exhaust gas and the treatment requirements for radioactive exhaust gas, AHPR1000 have been designed with an optimized treatment process and enhanced explosion-proof measures, resulting in a comprehensive design scheme for the radioactive exhaust gas treatment system. By comparing this system with exhaust gas treatment technologies used in different reactor types, the following conclusions have been drawn:

1) In AHPR1000, radioactive exhaust gas is first collected and directed into a buffer tank to stabilize pressure. Following hydrogen removal in the hydrogen-oxygen composite unit, the gas undergoes treatment via activated carbon pressurized retention decay technology before being discharged through the building's ventilation system to the chimney. Compared with exhaust gas treatment systems in various reactor types, this process offers advantages such as a compact footprint, effective exhaust gas treatment performance, and reduced generation of waste activated carbon. Furthermore, the optimized explosion-proof design enhances overall system safety, demonstrating significant operational benefits.

2) Through a performance test bench, commercially available activated carbon was evaluated, and the optimal type for unit design was selected. The system's operational parameters were determined as follows: temperature at 20 °C, pressure at 0.7 MPa(g), humidity below 20%, and flow rate at 20 Nm^3/h. Under these conditions, the adsorption capacity of activated carbon for Kr is 139.5 Ncm^3/g and for Xe is 2594.7 Ncm^3/g. These values are significantly higher than those of activated carbon used in AP1000 and VVER reactor types. Additionally, the retention times of Kr and Xe within the treatment unit are 2.8 days and 51.9 days, respectively, which exceed those of EPR and AP1000 reactor types.

3) AHPR1000 have improved the explosion-proof design by incorporating a hydrogen-oxygen composite unit to remove hydrogen. Through comprehensive analysis and comparison, the hydrogen-oxygen composite process has been established as: "buffer tank → hydrogen-oxygen composite unit → activated carbon pressurized retention decay unit." Hydrogen and oxygen analyzers are installed upstream and downstream of the composite unit to automatically adjust the air/oxygen injection to an appropriate stoichiometric ratio. Continuous monitoring of hydrogen and oxygen content ensures complete reaction and verifies the efficiency of the hydrogen-oxygen composite process. This design effectively mitigates the risk of hydrogen explosions and reduces the emission of radioactive exhaust gas.

Author's Profile

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