Hindawi
Science and Technology of Nuclear Installations
Volume 2022, Article ID 1817191, 8 pages
https://doi.org/10.1155/2022/1817191

Research Article

Design, Experiment, and Commissioning of the Spent Fuel Conveying and Loading System of HTR-PM

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Received 5 February 2022; Revised 6 April 2022; Accepted 7 April 2022; Published 23 April 2022

Academic Editor: Arkady Serikov

The Chinese high-temperature gas-cooled reactor pebble-bed module, HTR-PM, began fuel loading in August 2021. The reactor refuels continuously, while the spent fuel is discharged from the core. The spent fuel conveying and loading system was designed to convey the spent fuel pebbles to the spent fuel building and load them into dry canisters for on-site interim storage. This study describes the operating principles of the main functions and introduces the experiments and commissioning tests of the system. Functional tests were carried out to indicate the items of mechanical and electrical equipment are functioning in accordance with the designed requirements. Experience learned from commissioning activities was also presented as feedback for future operation and design improvement.

1. Introduction

The high-temperature gas-cooled reactor pebble-bed module (HTR-PM) demonstration power plant, supported by the National Science and Technology Major Projects of China [1], is the first industrial-scale pebble-bed modular HTR. The inherent safety features of the reactor meet the standards of generation IV nuclear systems. The project began construction in December 2012 and entered the full commissioning phase in 2020. The cold functional tests were completed in 2021. Following the issuance of an operating license for the plant on 20 August, the reactor started fuel loading. The power plant was connected to the grid in December 2021.

The cylindrical reactor core is 3 m in diameter and 11 m in height. It consists of approximately 420000 randomly packed pebble fuels (Figure 1). The reactor is continuously refueled during operation by the fuel handling system (FHS). Spherical fuel elements unloaded from the bottom of the core are reloaded into the core. Each fuel element will pass through the core for up to 15 times on average to flatten the power distribution of the core. Once the specified burn up is reached, the spent fuel element will be discharged for storage. The spent fuel conveying and loading system (SFCLS) can continuously lift and transport the spent fuel elements unloaded from the reactor core [2] through FHS to the spent fuel storage building (Figure 2). After rechecking by a γ ray detector [3] when necessary, the spent fuel elements are loaded into the spent fuel canister inside the shielding cask [4] through the fuel loading apparatus.

In the running-in phase of reactor operation, graphite pebbles will be unloaded from the reactor core [5], and these graphite pebbles also need to be lifted and transported by the SFCLS to the spent fuel storage building and then loaded into the graphite pebble storage canister.

To prevent the radioactive gas and dust that may exist in the fuel conveying pipeline and the storage canister from being discharged into the building, blowers and a closed loop for the lifting and conveying of spent fuel elements are equipped in the SFCLS, so that the radioactive gas and dust can be pumped into the dust filter and the iodine adsorber [6] and collected.

This study introduces the design principles, experiment, and commissioning experience of the SFCLS from the

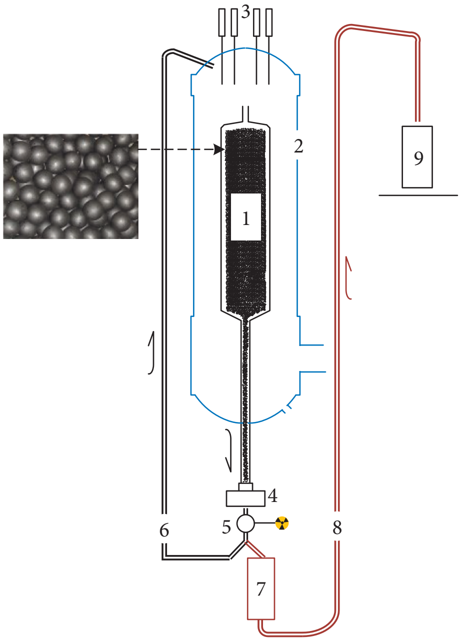

Figure 1: Online refueling of the pebble-bed HTR. 1, pebble-bed reactor core; 2, reactor pressure vessel; 3, control rod driver mechanisms; 4, scrap separator; 5, burnup measurement and switching system; 6, pipeline for fuel reloading; 7, buffering tank for spent fuels; 8, pipeline for spent fuel conveying; 9, spent fuel canister; inset, a photo of 60 mm dummy pebble bed at our test facility.

following aspects: fuel pebble conveying in the pipeline, fuel loading into the canister by the fuel loading apparatus, sealing and loading of the canister, and the monitoring and control of the system.

2. Design, Experiment, and Commissioning Tests

The commissioning of the SFCLS was carried out in accordance with the provisions of the commissioning outline. All commissioning tests were completed in the prenuclear commissioning phase, that is, before the first nuclear fuel loading. The tests include the test of fuel loading apparatus, test of pebble conveying under negative pressure, test of spent fuel and graphite pebble loading, test of negative pressure suction of pebbles, and pipeline blowing test. The general steps of the commissioning are shown in Figure 3.

2.1. Fuel Pebble Conveying in the Pipeline

2.1.1. Pebble Conveying under Negative Pressure by an Airflow Loop. Fuel pebbles in the 62–65 mm inner diameter vertical pipe can be pneumatically lifted under negative pressure by an airflow loop. This method was verified at the engineering test facility [1], where a total of 40000 dummy pebbles were lifted.

In the project of HTR-PM, fuel pebbles are pneumatically conveyed from FHS to the spent fuel storage building under negative pressure by an airflow loop (Figure 4). The airflow is driven by a Roots blower. The total length of the pebble conveying pipeline is approximately 70 m, in which the lifting height of the vertical section is more than 30 m. The inner diameter of the vertical pipe section is 62 mm, while that of the near-horizontal pipe sections is 62 or 65 mm.

During the commissioning phase, the conveying function of SFCLS was tested with the interaction of FHS under the control of the DCS. Pebbles discharged from FHS were continuously conveyed through the pipeline and sent into the canister below the fuel loading apparatus. The flow rate in the vertical section under the normal conveying condition is 1.3 m^3/min, and the operational flow range is 0.8–2.1 m^3/min. The stable conveying efficiency is 4–6 pebbles/min. The total conveying time for each pebble is 20–24 s. The negative pressure inside the fuel loading pipe is approximately −2–0 kPa (g).

2.1.2. Blowing of Pipeline. Graphite dust may be generated when pebbles interact with the pipe wall during conveying [7]. Sufficient gas flow is able to blow the dust, debris, and even the fragments away [8]. Therefore, air blowing of the conveying pipeline should be carried out regularly to ensure the long-term stable operation of the SFCLS. An airflow rate of up to 4 m^3/min supplied by the Roots blower for at least 1 min is employed at the end of each pebble conveying batch to clean the pipeline (Figure 5). During the commissioning phase, the air blowing function was tested. Its cleaning effect was verified by endoscopic observation in the pipeline and comparison before and after the test. Another supplementary method of blowing is the pulsed airflow released from the compressed air tank. It is also used in SFCLS for bidirectional blowing from upstream and downstream of specific positions on the pipeline.

2.1.3. Dust Filter and Iodine Adsorber. The graphite dust in the conveying pipeline is collected by the dust filter [9] before the airflow goes back to the Roots blower. The filter adopts porous sintered stainless steel filter elements manufactured in a one-side closed cylindrical form [10]. These elements are aligned in parallel to form a candle array and settled inside the pressure vessel. The airflow goes from outside the elements to the inside, leaving dust particles on the outer walls of the elements. The dedusting efficiency of the metallic filter is 99.8% for 0.3 μm graphite dust. Although dust cakes would build up on the outside of the candles, they can be detached by pulsed jet blowback, using compressed air from a tank attached to the filter.

During the commissioning phase, the metallic filter was also verified in the airflow loop by the pebble conveying test. The blowback function of the filter was also tested.

Before the air in the pipeline goes back to the blower, it needs to be further purified by the iodine adsorber to retain any airborne radioactive iodine [11]. The iodine adsorber is installed downstream of the metallic filter and upstream of the air discharge outlet of the SFCLS. The iodine adsorber is equipped with a build-in high efficiency particulate air (HEPA) filter and a type II iodine adsorber unit. The HEPA

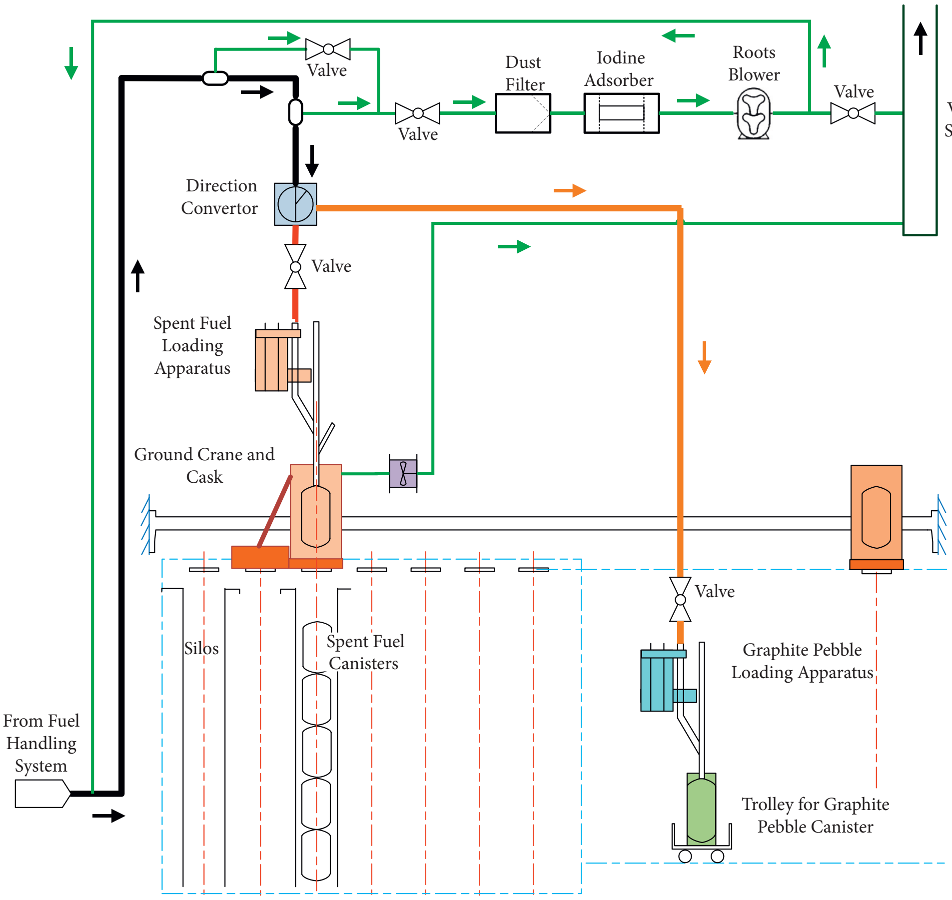

Figure 2: Schematic P&ID diagram of the SFCLS (not to scale).

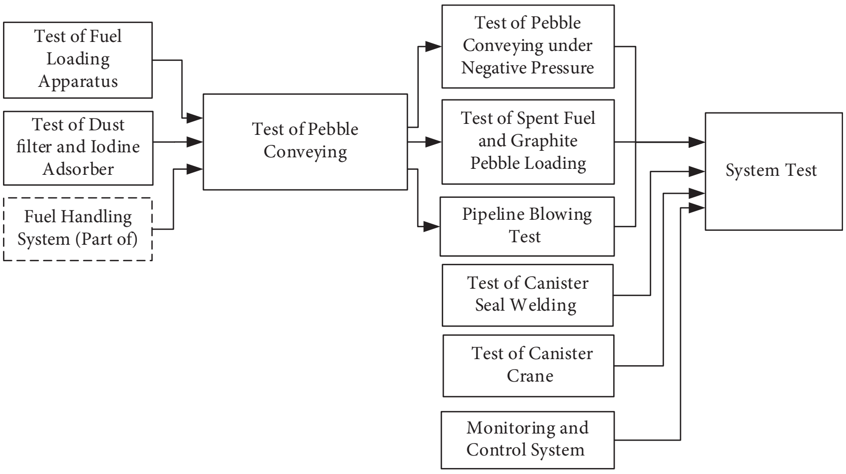

Figure 3: Flow diagram of the commissioning of SFCLS.

filter is set upstream to further purify the gas in the pipeline and protect the iodine adsorber unit. The adsorber unit is installed downstream and is used to adsorb iodine and its compounds in the airflow.

During the commissioning phase, the aerosol penetration of the HEPA filter was verified to be no greater than 0.05% of the upstream concentration at rated airflow, using dioctylphthalate (DOP) as the aerosol material. The iodine adsorber unit was also tested with refrigerant-11. Its gas penetration was verified to be no greater than 0.05%.

2.2. Spent Fuel Loading Apparatus. The spent fuel loading apparatus in SFCLS was designed to safely and reliably load

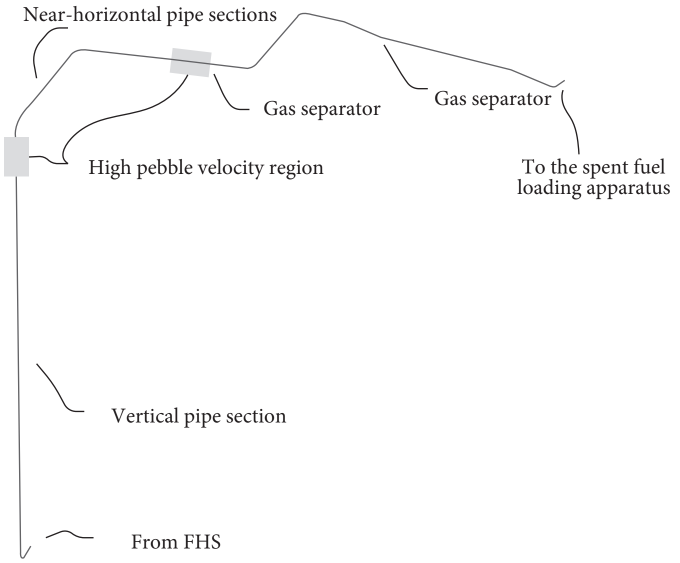

Figure 4: Schematic drawing of the pebble conveying pipeline.

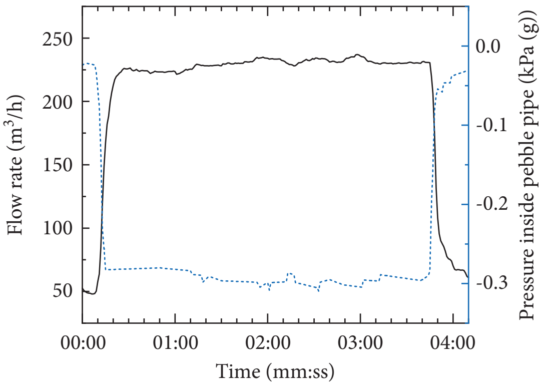

Figure 5: Flow rate and pressure inside pebble conveying pipe versus time during air blowing by the Roots blower.

Table 1: Main parameters of the spent fuel loading apparatus.

Total weight	4.5 t
Power rate of the drive motor	3 kW
Lifting or lowering time of the fuel loading pipe driven by the drive motor	120–150 s
Lifting or lowering speed of the canister plug gripper with the piston in the vertical air cylinder	1-2 m/min
Pressure of compressed air	0.5–0.8 MPa (g)

fuel pebbles into the canister and retrieve them out of it when needed. Its main parameters are given in Table 1. It is located at the end of the pebble conveying pipeline. It consists of a fuel loading pipe, a canister plug gripper, and corresponding driving mechanisms, as shown in Figure 6. The fuel loading pipe can be raised and lowered through the openings of the floor and to the top of the shielding cask by the radiation-resistant drive motor and the screw mechanism. Inside the pipe, the canister plug gripper is installed and driven by a vertical air cylinder. When the bottom end of the fuel loading pipe is lowered and meets the mouth of the canister inside the shielding cask, the gripper can seize and pull out the plug, so that fuel pebbles can be sent into the canister through the pipe. The radiation-resistant motor and pneumatic mechanisms were employed due to the radiation environment near the pebble conveying pipeline [12].

A full-scale prototype machine was made and verified at the engineering test facility in the HTR-PM engineering laboratory [1]. Verification tests were carried out for over 280 cycles. In each cycle, all mechanical actions were performed successfully. Pebbles could enter the canister through the fuel loading pipe of the apparatus.

During the commissioning phase, the final apparatus for the power plant was tested under the control of the

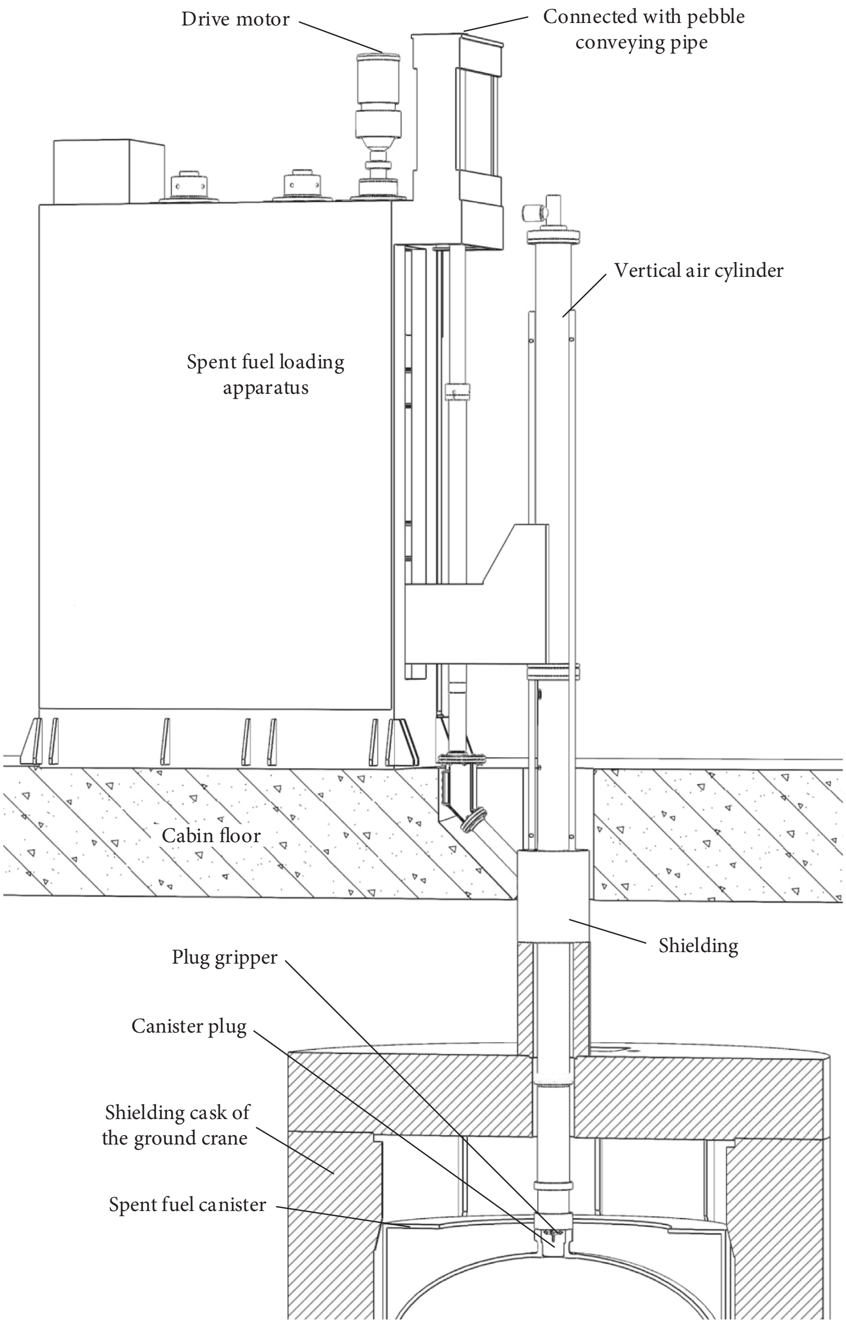

Figure 6: Schematic drawing of the spent fuel loading apparatus.

distributed control system (DCS). All mechanical actions were performed successfully. All action commands were executed successfully and all status signals are normally received.

2.3. Sealing of the Spent Fuel Canister. The spent fuel canister is sealed with a circumferential weld between the opening and the plug by gas-tungsten arc welding. The welding machine is installed in the room above the canister. The weld head can be lowered and lifted through the hole in the floor by a servo motor. At the end of the weld head, the flexible positioning rod can be automatically aligned with the

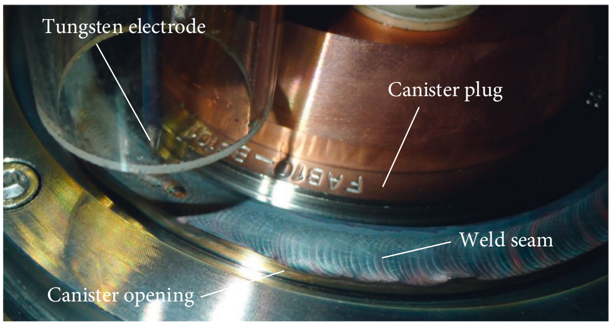

Figure 7: Close-up of the welding torch and the seam during testing.

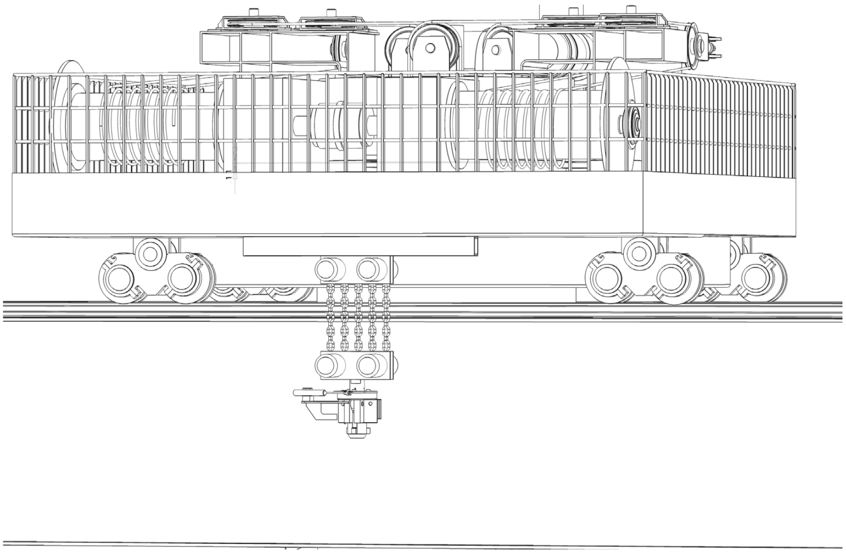

Figure 8: Schematic drawing of the ground crane.

opening of the canister. The welding torch and a radiation-resistant camera next to it rotate around the rod during the welding process. The weld can be observed in real time. Argon with a purity of over 99.99% was used surrounding the tungsten electrode as a shield gas to protect the weld seam (Figure 7).

During the commissioning phase, mockups of the canister opening and the plug were welded with the welding machine. The surface of the welds showed no indication of defects. The longitudinal sections of the welds showed that the weld penetration depth of the entire circumference was no less than 2 mm.

2.4. Loading of the Spent Fuel Canister. The spent fuel canister is carried by the ground crane [13] in the building from the spent fuel loading position to the welding position and then hoisted down into the silo (Figure 8).

2.5. Monitoring and Control. The SFCLS is mainly monitored and controlled by nonsafety DCS [14]. Approximately 100 digital signals, several analog signals, and pulse signals are sent to DCS acquisition units from the field. Approximately 90 control signals are sent out from DCS. The digital signals are dry contact signals of 24 VDC or 220 VAC. Point-to-point hardwiring is preferred for most connections, since it is safer and more reliable than the digital communication paths. All functions based on those signals can be realized at the operator workstations of the power plant.

There are also some host industrial control computers for integrated apparatuses that can be monitored and controlled in more detail, such as the fuel loading apparatus and the welding machine. Enabling commands are sent to the host computers by DCS to provide operation permission.

All the functional tests of mechanical equipment were carried out with monitoring and control by DCS. Moreover, interlock control functions were also tested. Fault status signals were simulated and action signals were given. It is verified that fault actions do not take place.

3. Commissioning Experience

3.1. Pebble Velocity. The necessary rate of airflow supplied to the pipe for pebble conveying varies with different pipe inclinations. These inclined pipe sections, with typical angles of 6–10 to the horizontal plane, need a lower rate of flow than the vertical pipe. Pebbles lifted to the top of the vertical pipe in the reactor building continue travelling through the inclined pipe sections to the spent fuel storage building. To keep the velocity of the pebble in a safe range, the airflow is diverted out of the inclined pebble pipe sections into the branch gas pipes by gas separators (Figure 4). Valves were introduced in the branch gas pipes for flow control. During the commissioning phase, to determine the opening angles of these valves, the pebble passing detectors [15] were installed at specific locations along the pipeline to measure the maximum pebble velocities. According to the pipe route, these installation locations include the top of the vertical pipe section, the highest point of each inclined pipe section before an elbow, and the entrance of the gas separator. The measured maximum velocity is typically 4.0–5.9 m/s, which is lower than the safe limit of 8.8 m/s.

3.2. Negative Pressure in the Pebble Conveying Pipe. A connecting pipe between the air pipe and the vent stack was set at the outlet of the Roots blower. Thanks to this connection, the zero gauge pressure point is near to the blower outlet. Therefore, the whole pebble conveying pipe downstream of the blower outlet is almost under negative pressure. When the fuel loading pipe is raised off the canister, the negative pressure inside the pipe can avoid airborne effluent leakage to the air in the cabin and ensure the safety of radiation protection in the building. The air sucked from the cabin into the pipe will pass through the dust filter, the iodine adsorber, the Roots blower, the connecting pipe, enter the vent stack, and be discharged into the atmosphere at high altitude under radiation monitoring.

A ball valve was introduced in the connecting pipe between the blower outlet and the vent stack for flow control. The valve opening determines the flow rate of the air exhausted to the vent stack and therefore the equal flow rate of the air sucked into the fuel loading pipe.

During the commissioning phase, the opening range of this valve is determined to be 20–50%. When the valve opening is increased, the total flow rate provided by the Roots blower also needs to be increased. The flow rate can be adjusted by adjusting the blower frequency, owing to the adopted variable frequency adjustable speed converter-fed motor. In this way, a sufficient flow rate for pebble conveying could be provided while the negative pressure could be kept.

3.3. Electric Ball Valve Troubleshooting. Electric ball valves are employed in the spent fuel and graphite pebble conveying pipes of SFCLS to switch the airflow. When the valves are open, pebbles should pass through successfully. During the commissioning phase, one of the valves did not fully open in place in some cases, causing pebbles to stop. An endoscope was employed by inserting the camera into the pipe through a flange opening nearby. The opening position of the valve was then readjusted. It is suggested that openings such as flanges should be configured near the valves in the pebble conveying pipes as backup entrances for the endoscope when troubleshooting.

4. Conclusions

The spent fuel conveying and loading system of HTR-PM receives pebble elements from the fuel handling system and stores them in the spent fuel canisters. According to our design, pebbles are conveyed in the pipeline by pneumatic force and loaded into the canister by the fuel loading apparatus. The canister is sealed by a welding machine and loaded into the dry silo by the ground crane. Experiments were carried out to verify the engineering design. It is shown that the system design achieves the target functions. Functional tests were carried out at the plant site during the commissioning phase. It is shown that under the designed operating conditions, the machines and instruments can run safely under the control and monitoring of the control system and achieve the expected functions and performance. The commissioning tests provided valuable experience for the subsequent operation of the reactor and design optimization of future pebble-bed gas-cooled reactors.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the National Science and Technology Major Project of China (ZX069).

References

[1] Z. Zhang, Y. Dong, F. Li et al., “The Shandong Shidao Bay 200 MW e High-Temperature Gas-Cooled Reactor Pebble-Bed Module (HTR-PM) Demonstration Power Plant: an Engineering and Technological Innovation,” *Engineering*, vol. 2, no. 1, pp. 112–118, 2016.

[2] J. Zhang, J. Guo, F. Li, and Y. Sun, “Research on the fuel loading patterns of the initial core in Chinese pebble-bed reactor HTR-PM,” *Annals of Nuclear Energy*, vol. 118, pp. 235–240, 2018.

[3] S. Yin, L. Zhang, and H. Wang, “Research on detection scheme of pebbles in fuel handling system pipelines in pebble-bed HTGR based on γ-ray measurement,” *Applied Radiation and Isotopes*, vol. 171, Article ID 109619, 2021.

[4] S. Sun, H. Li, and S. Fang, “The optimization of radiation protection in the design of the high temperature reactor-pebble-bed module,” *Science and Technology of Nuclear Installations*, vol. 2017, Article ID 3984603, 15 pages, 2017.

[5] J. Zhang, F. Li, and Y. Sun, “Physical analysis of the initial core and running-in phase for pebble-bed reactor HTR-PM,” *Science and Technology of Nuclear Installations*, vol. 2017, Article ID 8918424, 6 pages, 2017.

[6] R. Du, Z. Zhang, and F. Jiang, “Simulation-aided design of the negative-pressure exhaust system in HTGR nuclear power plants,” *Nuclear Engineering and Design*, vol. 343, pp. 43–56, 2019.

[7] B. Wu, Y. Li, H.-S. Zhao, S. Liu, B. Liu, and J.-H. Wang, “Wear behavior of graphitic matrix of fuel elements used in pebble-bed high-temperature gas-cooled reactors against steel,” *Nuclear Engineering and Design*, vol. 328, pp. 353–358, 2018.

[8] J. Wang, Y. Zhang, Y. Li, B. Wu, and H. Wang, “Experimental study on the transport performance of damaged fuel element in HTR-PM,” in *Proceedings of the 9th International Topical Meeting on High Temperature Reactor Technology (HTR 2018)*, Warsaw, Poland, 2018.

[9] J. Wang, B. Wang, B. Wu, Y. Li, and H. Wang, “Filtration Technology Research of Graphite Dust Produced in Spent Fuel Transportation Process in HTR-PM,” in *Proceedings of the International Conference on Nuclear Engineering*, London, UK, 2018.

[10] S. Li, J. Baeyens, R. Dewil, L. Appels, H. Zhang, and Y. Deng, “Advances in rigid porous high temperature filters,” *Renewable and Sustainable Energy Reviews*, vol. 139, Article ID 110713, 2021.

[11] Q. Sun, W. Peng, P. Li, F. Xie, and S. Ding, “Study on the representativeness of airborne effluent sampling in the stack of a high-temperature gas-cooled pebble-bed modular reactor,” *Annals of Nuclear Energy*, vol. 165, Article ID 108680, 2022.

[12] S. Fang, J. Cao, W. Li et al., “Shielding design and dose evaluation for HTR-PM fuel transport pipelines by QAD-CGA program,” *Science and Technology of Nuclear Installations*, vol. 2021, pp. 1–6, 2021.

[13] J. Wang, X. Liu, B. Wang, Y. Li, and B. Wu, “Design of the ground crane and shielding cask for the spent fuel canister of HTR-PM,” in *Proceedings of the International Conference on Nuclear Engineering*, Chiba, Japan, 2015.

[14] Q. Jia, X. Huang, and L. Zhang, “A design of human-machine interface for the two-modular high-temperature gas-cooled reactor nuclear power plant,” *Progress in Nuclear Energy*, vol. 77, pp. 336–343, 2014.

[15] Z. Han, H. Zhou, H. Zhang, and D. Du, “A detecting method for spherical fuel elements in pebble-bed HTGR using eddy current detection,” *NDT & E International*, vol. 79, pp. 81–91, 2016.