DEM simulation of overcoating particles in the planetary-overcoater for optimizing the structure of key components and processing parameters

Authors: Zeng, Miss Ning, Prof. Zhenming Lu, Gao, Mr. Ming, Lu, Mr. Anyuan, Du, Mr. Ben, Wang, Liming, Prof. Xin-lin Yan, Liu, Dr. Bing, Zeng, Miss Ning, Gao, Mr. Ming, Lu, Anyuan, Du, Mr. Ben, Wang, Liming, Yan, Prof. Xin-lin, Liu, Dr. Bing

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Abstract

The coating layer of TRISO (Tri-structural iso-tropic) coated particles serves as the first barrier to ensure the safety of high-temperature gas-cooled reactors (HTRs). The overcoating layer wrapped around the surface of coated particles can directly and effectively reduce damage to the coating layer during the fuel element production process. To optimize the key component structure and process of a newly developed planetary overcoater, the Discrete Element Method (DEM) was employed to investigate the motion of overcoating particles within the pot of the planetary overcoater. Variations in particle motion state were studied and analyzed by setting different values for the transition arc radius angle at the planetary-disk edge, planetary-disk roughness, planetary-disk rotational speed, and deflector angle, demonstrating that these factors directly affect the trajectory and motion state of overcoating particles, thereby improving overcoating process efficiency and quality through parameter adjustment. Experimental results using the optimized simulation parameters showed that the overcoated particles achieved a yield of up to 95% with uniform particle size distribution, which complies with the expected production standard of >90%.

Full Text

Preamble

DEM Simulation of Overcoating Particles in the Planetary-Overcoater for Optimizing the Structure of Key Components and Processing Parameters

Ning Zeng[1], Zhen-ming Lu[1],[2], *Ming Gao*[3]*, An-yuan Lu*[1]*, Ben Du*[1]*, Li-min Wang*[4]*, Xin-lin Yan*[5]*, Bing Liu*[2]

[1]Hubei Key Laboratory of Coal Conversion and New Carbon Material, School of Chemical Engineering and Technology, Wuhan University of Science and Technology, Wuhan 430081, China
[2]Institute of Nuclear and New Energy Technology, Tsinghua University, Beijing 100084, China
[3]China North Nuclear Fuel Co., Ltd., Baotou 014035, China
[4]State Key Laboratory of Mesoscience and Engineering, Institute of Process Engineering, Chinese Academy of Sciences, Beijing, 100190, China
[5]Institute of Solid State Physics, Vienna University of Technology, Wiedner Hauptstr. 8–10, 1040 Vienna, Austria

Corresponding author. E-mail: luzhenming@wust.edu.cn (Zhenming Lu)
Corresponding author. E-mail: bingliu@tsinghua.edu.cn (Bing Liu)

Abstract

The coating layer of TRISO (Tri-structural iso-tropic) coated particles serves as the first barrier to ensure the safety of high-temperature gas-cooled reactors (HTRs). The overcoating layer wrapped around the surface of coated particles can directly and effectively reduce damage to the coating layer during fuel element production. To optimize the key component structure and processing parameters of a newly developed planetary-overcoater, the Discrete Element Method (DEM) was employed to investigate the motion of overcoating particles within the equipment pot. By systematically varying the transition arc radius at the planetary-disk edge, planetary-disk roughness, rotational speed of the planetary-disk, and deflector angle, we studied and analyzed changes in particle motion states. These factors directly affect the trajectory and movement state of overcoating particles, thereby enabling process efficiency and quality improvements through parameter adjustment. Experimental results using the optimized simulated parameters demonstrated that overcoated particles achieved yields up to 95% with uniform particle size distribution, meeting the expected production standard of >90%.

Keywords: Planetary-overcoater, High-temperature gas-cooled reactors, Discrete Element Method, Overcoated particle, Coated fuel particle, Particle motion

1 Introduction

The coating layers of tri-structural isotropic (TRISO) coated fuel particles (CFPs) in spherical nuclear fuel elements function as the primary safety barrier for pebble-bed high-temperature gas-cooled reactors (HTRs) [1-3]. Maintaining a low failure rate during the preparation process is therefore of paramount importance [4]. To prevent crushing of the coated layers during the pressing process of nuclear fuel elements, a buffer layer of matrix graphite powder must be overcoated onto the CFPs [5-7]. This process, commonly referred to as "overcoating," occurs before pressing [6-9].

With ongoing advancements in HTR technology and the necessity for large-scale nuclear fuel element production, overcoating equipment development in China has progressed through three generations: laboratory-scale onion-shaped types, commercial demonstration perforated drum-shaped types [6], and large commercial-scale non-perforated drum-shaped types [7]. However, original drum-type overcoating structures have proven insufficient for meeting growing demands of larger-scale, more automated production. Specifically, challenges have emerged in raw material feeding, product transportation, and efficient cleaning of the working chamber.

To address these issues, we have devised a novel nuclear fuel overcoating apparatus: the planetary-overcoater (PO) [10]. During the overcoating process, overcoating particles (OVPs) exhibit planetary-like movement—similar to Earth's revolution around the sun and rotation on its axis—driven by centripetal force within the working chamber. To enhance optimal design and production processes, Discrete Element Method (DEM) numerical simulation [11-20] was implemented. DEM has demonstrated effectiveness in various applications, including tablet coating in the pharmaceutical industry [17-19] and seed coating in agriculture [20]. This success prompted us to leverage the technique for optimizing critical parameters such as planetary-disk edge shape, planetary-disk roughness, rotational speed, and deflector angle, which directly influence particle trajectories and activity. These optimization outcomes can guide the design and manufacturing of essential equipment components while improving overcoating process parameters. By revealing intrinsic relationships and patterns between different parameters and OVP motion through numerical simulations, the overcoating process can be more effectively regulated to improve overcoating layer quality and nuclear fuel performance, thereby enhancing reactor operational safety.

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2 General Structure and Operating Principle of PO

The PO consists of an overcoating mainframe, matrix powder supply system, solvent conveying system, gas supply system, and gas exhaust/dust removal system. The overcoating mainframe includes an overcoating pot, planetary-disk, motor transmission, ethanol supply unit, powder feeding unit, and deflector. The PO structure is shown in Fig. 1 [Figure 1: see original paper].

The planetary-disk is mounted inside the overcoating pot, dividing the space into two parts: an upper working chamber and a lower gas chamber. An annular air gap is uniformly distributed between the outer edges of the planetary-disk and the inner wall of the overcoating pot, serving both to transmit gases from the lower gas chamber to the working chamber and to prevent dust from entering the machine interior during production. The deflector is located in the working chamber, positioned close to the inner wall of the overcoating pot.

During operation, the rotating planetary-disk creates a centrifugal effect that forces OVPs toward the working chamber wall. OVPs are also subjected to gravity, buoyancy from gas in the annular air gap, mutual pressures among particles transmitted through the overcoating pot wall, pressures due to gravity, inter-particle friction, and friction from the planetary-disk. Particles revolve primarily due to centripetal force arising from transmitted pressure while rotating on their own axis under inter-particle friction—movements analogous to planetary motions. During overcoating, OVPs are first wetted by solvents, then coated by powders in the powder feeding area. The OVPs gradually grow by absorbing powders, form spherical shapes through their "rotations," and finally reach the desired sizes.

3.1 Analysis of OVPs Dynamics

In the early overcoating stage when only minimal ethanol solution is supplied for wetting, the bonding effect between OVPs and matrix graphite powder is weak. Centripetal force causes OVPs to move along the inner wall of the overcoating pot. In the middle stage, OVPs undergo circular movement around the central axis at the edge of the planetary-disk. Initially, OVPs and graphite powders are considered physically indistinguishable particles, and we assume the planetary-disk rotates at the same speed as the particles—meaning no bouncing when particles fall onto the planetary-disk and no mutual forces among particles. A single particle is randomly selected as the research object and treated as a mass point. The force analysis is shown in Fig. 2 [Figure 2: see original paper].

In the early stage, the particle undergoes centrifugal movement, requiring centripetal force greater than inter-particle friction. When the particle moves at position r from the center of the planetary-disk, Newton's second law gives:

$$\mathbf{F} = m\mathbf{a} = \mathbf{F}_r + \mathbf{F}_{f1} + \mathbf{F}_c$$

where **F** is the total force on the particle, **F**_r the centripetal force, **F**_{f1} the friction between particle and planetary-disk, and **F**_c the Coriolis force. $_1$ represents the friction coefficient between particle and planetary-disk, while a and m denote particle acceleration and mass, respectively.

When the particle reaches the transition arc at the planetary-disk edge (Fig. 3 [Figure 3: see original paper]), the forces acting on it are:

$$\mathbf{F}_r = m\omega^2 r$$

$$\mathbf{F}_{f1} = \mu_1 m\omega^2 r$$

To maintain particle movement on the planetary-disk, the condition

$$\mathbf{F}_r \geq \mathbf{F}_{f1}$$

must be satisfied. From these equations, we obtain:

$$\omega_c = \sqrt{\frac{g\cot\theta}{r}}$$

Equation 5 provides a critical condition ω_c. During overcoating, we set $\omega \geq \omega$_c to ensure complete mixing of OVPs with matrix graphite powders. This is achieved through particle movements (both OVPs and graphite powders) driven by centripetal force from cylinder rotation and gravity. High rotational speeds force particles to be thrown vertically out of the planetary-disk due to the edge arc (Fig. 3), after which they fall back onto the planetary-disk under gravity.

3.2 Collision Contact Force Analysis of OVPs

OVP flow behavior is primarily caused by mutual particle collisions. OVP movement can be calculated using Newton's second law. Particle collisions are calculated using a linear spring-damper model (Fig. 4 [Figure 4: see original paper]):

$$m_i \frac{d\mathbf{v}_i}{dt} = \sum_{j=1}^{n_c} (\mathbf{F}_{c,n,ij} + \mathbf{F}_{c,t,ij}) + m_i \mathbf{g}$$

where m and $\mathbf{v}$ represent the mass and velocity of particle i, respectively, and $\mathbf{g}$ is gravitational acceleration. $\mathbf{F}$_c,n,ij and $\mathbf{F}$_c,t,ij represent normal and tangential contact forces, respectively, and n_c is the number of contact forces on particle i applied by particle j or the wall. By analyzing these forces and collisions, we identify key factors influencing particle movement during overcoating, providing a reliable theoretical basis for equipment optimization.

3.3 Modeling of Overcoating Process

EDEM software was employed to simulate the overcoating process and visualize 3D particle flow. The software can conveniently construct three-dimensional particle models and define physical properties and shapes (spherical or irregular). Supplementary mechanical, material, and physical characteristics enable formation of the requisite particle solid model. In this research, OVPs are spherical, so a single spherical shape in the model is sufficient. The related parameters are presented in Table 1 , with values ensuring the model is grounded in realistic data.

The movement state of OVPs inside the working chamber is a critical factor affecting overcoating results [21]. Since OVPs cannot be compressed, contact among them can be described by the Hertz-Mindlin (no slip) model. The simulator grid is divided and the time step determined based on particle diameter to ensure accurate and effective simulation of particle movement states.

The simulation duration was set to 5 s, with data acquisition every 0.01 s. Colored particles were used to visualize state changes, while the analyst module extracted data such as velocity and trajectory to analyze particle movement states.

4.1.1 Planetary-Disk Edge Transition Arc Radius

OVPs in the working chamber move along the planetary-disk edge due to centripetal force. When passing through the transition arc at the edge, particles change their movement state by climbing, with climb characteristics varying depending on transition arc radius and consequently affecting particle activity differently. Three-dimensional planetary-disk models with varying transition arc radii (10 mm, 25 mm, and 40 mm) were constructed to simulate and calculate particle flow movement.

Once particles were generated by the factory module in the software, they fell onto the planetary-disk. When rotation began, friction between particles and the planetary-disk was insufficient to maintain requisite centripetal force, causing particles to move to the disk edge. To establish particle trajectories, we randomly selected three particles in the working chamber. As shown in Fig. 5 [Figure 5: see original paper], particles changed their moving trajectory from a centrifugal route to a very short, simplified curve. After reaching the transition arc, particles moved upward spirally due to force from the overcoating pot wall.

To visualize particle climbing heights in the working chamber, calculations were performed as shown in Fig. 6 [Figure 6: see original paper] for climbing height versus time. With the same angular velocity ω, the planetary-disk generates identical centrifugal force for particles (ideally), making climb height clearly dependent on arc radius (Table 2). We define maximum height as the highest value any particle can reach during the period, and climbing height as the average value for these particles over time. Particles in the working chamber with 40 mm transition arc radius showed the largest maximum height of 118.75 mm, while those with 25 mm arc radius exhibited the largest climbing height of 64.28 mm.

High particle climbing capability is desirable for extensive interactive movement among particles, which also benefits particle activity. However, spherical particle movement suffers from the Brazil Nut Effect, where small particles preferentially accumulate at the bottom of the working chamber and large particles at the upper level. This bias destroys uniform wetting of OVPs of different sizes with matrix graphite powder. Extensive interactive movement among particles can mitigate the Brazil Nut Effect to some extent and improve overcoating homogeneity for OVPs of different sizes.

Particle velocity distributions for different planetary-disk transition arcs r were derived and displayed in Fig. 7 [Figure 7: see original paper]. As shown in Table 3 , the average particle velocity v for $r = 10$ mm is highest with the greatest variance, whereas v for $r = 40$ mm is lowest with the smallest variance. Both v and variance values for $r = 25$ mm are similar to those for $r = 40$ mm.

Particle distribution on the planetary-disk during overcoating was investigated using maximum spreading width d as a parameter (Table 4). A small d—where particles mainly accumulate at the planetary-disk edge rather than on the plate—may be unfavorable for wetting, as liquids such as ethanol spray primarily onto the plate rather than particle surfaces. This causes graphite powders to stick mostly to the plate, heavily reducing product yield. Experiments show that d for $r = 25$ mm is the largest.

Based on these results, $r = 25$ mm—with good particle climbing ability, reasonable particle velocity distribution v , and large particle spread d—is considered the optimal parameter for the planetary-disk.

4.1.2 Planetary-Disk Roughness

The driving force for particle movement on the planetary-disk comes from friction between the planetary-disk surface and particles, inter-particle friction, and particle gravity. It is therefore necessary and reasonable to consider plate surface roughness as an impact parameter for device design. We studied various dynamic friction coefficients for the plate surface in EDEM software. A linear relationship can be established between the dynamic friction coefficient and the force provided to particles, causing changes in particle movement states.

We set the transition arc radius r to 25 mm and friction coefficient f to 0.01, 0.05, 0.1, and 0.5 for the study. As shown in Fig. 8 [Figure 8: see original paper], varying f from 0.01 to 0.5 decreased the velocity distribution width from 0–8 m/s to 0–4 m/s, accompanied by reduction in maximum particle velocity.

Nevertheless, average particle velocity increased with f (see Table 5). This can be interpreted as follows: with smaller f, velocity distribution is broader and particles with lower speeds dominate. When f increases due to greater roughness, particle velocities increase. Particles may accumulate at the planetary-disk edge if friction is insufficient to provide requisite centripetal force for circular movement with an appropriate radius. The driving force for tangential movement comes from inter-particle friction, while centripetal force is provided by particles against the edge wall of the planetary-disk. In this condition, although velocity distribution is small, velocities are relatively dispersed among particles.

With decreasing f (minimizing surface roughness), force transmission from the planetary-disk to particles becomes difficult due to low friction, especially when particle accumulated layers exceed one layer. This leads to a large portion of particles having low speeds. However, because overall particle speeds are relatively low, the centripetal force needed for circular movement is small, which avoids particle accumulation at the planetary-disk edge to some extent. Additionally, the transition arc can provide necessary force for particle movement, explaining why velocity distribution is relatively wide for small f.

Figure 9 [Figure 9: see original paper] shows particle proportions within certain speed ranges under various plate surface roughness values (i.e., f). Proportions of low speeds for f ranging from 0.05 to 0.5 are low. For $f = 0.1$, the proportion with velocity exceeding 1 m/s is 74%, representing the largest value. Together with reasonable velocity distribution and particle activity, we consider $f = 0.1$ the optimal parameter for surface roughness.

4.2.1 Angle of the Deflector

Without external interference, OVPs move planetarily in the working chamber and accumulate at the inner wall (edge) of the planetary-disk, forming a particle flow with certain height. Constrained by narrow space and insufficient inter-particle interactions, the overcoating process is significantly impeded and the overcoating layer may become non-uniform. To improve particle interactions, we installed a deflector in the working chamber. The deflector can alter particle flow, causing particles to move in different directions for enhanced activity.

Clearly, deflector angle influences particle movement state. We set this angle to 30°, 35°, 40°, and 45° in simulations to obtain optimal values for high particle activity.

Simulations show that when the planetary-disk starts moving, numerous particles pass through the deflector, most of which are stopped and remain in the area between the planetary-disk bottom and deflector. This leads to low particle activity and vortex formation due to particle collisions. As shown in Fig. 10 [Figure 10: see original paper], red represents faster particles while blue represents slower particles. Most particles in the working chamber are red, indicating generally high OVP activity at this time. Due to friction between particles and wall, particles near the working chamber wall have lower velocities (green). This result is corroborated by Figures 11 [Figure 11: see original paper] and 12. After 2 seconds, particle movement stabilizes and forms a traceable trajectory. When = 30° and 35°, the number of particles staying between the planetary-disk bottom and deflector is negligible. When exceeds 35°, many green and blue OVPs appear in that area and the number of stationary particles increases. Furthermore, these particles have low velocities, resulting in reduced activity and high risk of vortex formation, which decreases overcoating efficiency. Conversely, when is too small, the deflector may not efficiently affect particle flow, impairing the mixing process.

Figures 11 and 12 show particle distributions across velocity ranges for different values. When = 35°, the proportion of particles with velocity less than 0.5 m/s is smallest and particles exhibit the highest activity. Therefore, = 35° is considered the optimal parameter for the device.

4.2.2 Planetary-Disk Rotation Speed

The rotation speed ω of the planetary-disk must also be optimized as it is crucial for particle movement state. Low ω generates insufficient centripetal force, reducing compression of the overcoating layer and leading to decreased bulk density. While low bulk density may benefit effective buffering between OVPs and prevent layer breakage in subsequent stages, optimal balance is required.

Using the optimal parameters mentioned above, various rotation speeds ($\omega =$ 100, 150, and 200 rpm) were simulated for particle movement in the working chamber. As shown in Fig. 13 [Figure 13: see original paper], at $\omega = 100$ rpm, particles form a layer at the plate bottom traveling in circles at low speed. More green particles (low speed) are visible in Fig. 13a, verified by Fig. 14 [Figure 14: see original paper] and Table 7 . Since this is the area for liquid and powder spraying, these particles can be overcoated first with matrix graphite powder and grow to large sizes, leading to a “Matthew Effect.” The net results could be low product yield and a relatively large proportion of oversized OVPs.

Particle distributions across velocity ranges were derived and shown in Fig. 14 and Table 7. Results show that increasing ω increases centripetal force, which enhances average particle velocity. At $\omega = 150$ rpm, the proportion of particles in each velocity range is relatively even and the overcoating effect is very good. The proportion of particles with speed less than 0.5 m/s is smallest and particle activity is high. Therefore, $\omega = 150$ rpm is considered the optimal parameter for the device.

4.3 Variation of Particle Movement State During Overcoating Process

Once particles are overcoated with graphite powder in the working chamber, particle size increases while OVP density decreases. To simulate OVP movement states, we assumed two types of particles with different densities and sizes as shown in Table 8 . To ensure movement states match real conditions, the simulator grid was divided according to minimum particle diameter to guarantee correct simulation of each particle's movement state. Since generating two particle types in the Particle Factory module requires time, simulation duration was extended from 5 s to 7 s, with data collection every 0.01 s.

Using the Grid Bi Group module in EDEM software, we divided the mixing region in the working chamber into a 20 mm × 20 mm × 20 mm grid, as shown in Fig. 15 [Figure 15: see original paper]. We then applied the "mixing measurement" method [22] to count particle numbers in each grid, calculating the "mixing index" [23] to indicate mixing degree. Results are shown in Fig. 16 [Figure 16: see original paper].

The mixing index formula is:

$$M = \frac{S_0 - S}{S_0 - S_R}$$

where S_0 and SR denote variance for complete separation and random mixing, respectively. p is the proportion of one particle type in the total, and N represents the average number of particles per grid. The variance S of random mixing in the chamber is calculated as:

$$S = \frac{1}{N} \sum_{i=1}^{N} (p_i - p)^2$$

where N is the number of cells occupied by total particles in the computational domain, and p represents the proportion of one particle type in grid i.

Generally, a complete mixing state can be achieved for the two particle types after some time (Fig. 16). With increasing rotation speed ω, the mixing index increases, reaching a maximum of 0.997 after 6 s at $\omega = 150$ rpm. For $\omega = 200$ rpm, the mixing index reaches 0.9977 after 7 s, indicating that sufficiently high rotation speeds enable complete mixing over time. To maintain low bulk density while achieving high mixing index, we selected a relatively low ω of 150 rpm.

5 Analysis of Experimental Results

To validate the optimal parameters from DEM simulation, experiments were conducted using these parameters: $r = 25$ mm, $Ra = 1.6$, $= 35°$, and $\omega =$ 150 rpm. Tungsten carbide clad particles with sizes and densities similar to real nuclear fuel particles were used. The initial mean particle size was 0.92 mm, with target size after overcoating of 1.2–1.6 mm diameter.

OVPs were classified by size, shape-sorted, and analyzed for product yield across three tests. Results are listed in Table 9 , showing very high values. Size classification yields exceeded 96 wt% across batches, shape sorting yields exceeded 99 wt%, and total yields exceeded 95 wt% with an average of 96.33 wt%, meeting the anticipated production standard of >90%. Figure 17 [Figure 17: see original paper] demonstrates OVP characteristics: spherical shapes, uniform sizes, and lack of noticeable deformities. The particle size distribution after classification is displayed in Fig. 18 [Figure 18: see original paper], following a normal distribution with most particles between 1.3–1.4 mm, accounting for over 60% of the total. Experimental results using optimized simulated parameters showed OVPs achieved a product qualification rate up to 95% with uniform particle size distribution, aligning well with expected production standards.

6 Conclusion

An in-depth DEM simulation and analysis of OVP movement states in the PO has been conducted to optimize the overcoating process. The study demonstrated that key equipment and process parameters—including planetary-disk edge transition arc radius, planetary-disk roughness, planetary-disk rotational speed, and deflector angle—exert considerable influence on OVP trajectories and overcoating layer uniformity. Data analysis revealed optimal parameters: planetary-disk edge transition arc radius of 25 mm, planetary-disk surface roughness of 1.6, deflector angle of 35°, and planetary-disk rotational speed of 150 rpm. Optimizing these parameters significantly improved OVP activity and overcoating layer uniformity in the chamber.

Experimental results using optimized parameters demonstrated that OVPs achieved a product qualification rate up to 95% with uniform particle size distribution, meeting anticipated production standards. This study provides effective technical support for OVP production and offers theoretical basis and practical guidance for equipment design and application. With rapid HTR development and increasing safety requirements for various reactor types, demand for accident-tolerant nuclear fuel (ATF) with TRISO particles is increasing significantly, and PO technology will have broader application prospects through continuous innovation and optimization. Further research should focus on exploring potential for larger-scale production and achieving full automation of PO for industrial applications.

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Author Contributions

All authors contributed to study conception and design. Material preparation, data collection, and analysis were performed by Ning Zeng, Zhen-Ming Lu, Anyuan Lu, Ben Du, and Ming Gao. The first draft was written by Ning Zeng, and all authors commented on previous versions. All authors read and approved the final manuscript.

References

1. M.L. Liu, R.Z. Liu, B. Liu et al., Preparation of the coated nuclear fuel particle using the fluidized bed-chemical vapor deposition (FB-CVD) method. Procedia Eng. 102, 1890-1895 (2015). https://doi.org/10.1016/j.proeng.2015.01.3
2. Z.Y. Zhang, Y.J. Dong, Q. Shi et al., 600-MWe high-temperature gas-cooled reactor nuclear power plant HTR-PM600. Nucl. Sci. Tech. 33, 101 (2022). https://doi.org/10.1007/s41365-022-01089-9
3. D. She, B. Xia, J. Guo et al., Prediction calculations for the first criticality of the HTR-PM using the PANGU code. Nucl. Sci. Tech. 32, 90 (2021). https://doi.org/10.1007/s41365-021-00936-5
4. K. Verfondern, H. Nabielek, J.M. Kendall, Coated particle fuel for high temperature gas cooled reactors. Nucl. Eng. Technol. 39, 603-616 (2007). https://doi.org/10.5516/NET.2007.39.5.603
5. Z.M. Lu, W.K. Zhang, J. Zhang et al., Research on manufacture technology of spherical fuel elements by dry-bag isostatic pressing. Nucl. Sci. Tech. 33, 101 (2022). https://doi.org/10.1007/s41365-022-01110-1
6. Z.M. Lu, J. Zhang, Y.M. Wang et al., Study on the main process of coating particles for HTGR fuel elements. At. Energy Sci. Technol. 46, 665-668 (2012). (in Chinese)
7. X.W. Zhou, Z.M. Lu, J. Zhang et al., Preparation of spherical fuel elements for HTR-PM in INET. Nucl. Eng. Des. 263, 456-461 (2013). https://doi.org/10.1016/j.nucengdes.2013.07.001

8. Z.M. Lu, W.K. Zhang, J.H. Li et al., Investigation on validation of scale-up manufacture technologies of overcoating particles for HTR fuel elements. Ann. Nucl. Energy. 182, 109614 (2023). https://doi.org/10.1016/j.anucene.2022.109614
9. P.J. Pappano, M.P. Trammell, M.R. Rogers, Development of a TRISO particle overcoating and compacting process for the VHTR. Trans. Am. Nucl. Soc. 94, 687-688 (2006).
10. Z.M. Lu, A.Y. Lu, W.K. Zhang et al., A method and device for overcoating nuclear fuel microspheres, CN Patent 202310690258.8, 17 May 2024.
11. S.Y. He, J.Q. Gan, D. Pinson et al., A discrete element method study of monodisperse mixing of ellipsoidal particles in a rotating drum. Ind. Eng. Chem. Res. 59, 12458-12470 (2020). https://doi.org/10.1021/acs.iecr.9b06623
12. H.Q. Ma, Y.Z. Zhao., Modelling of the flow of ellipsoidal particles in a horizontal rotating drum based on DEM simulation. Chem. Eng. Sci. 173, 320-334 (2017). https://doi.org/10.1016/j.ces.2017.07.017
13. N. Gui, J.R. Fan, J.S. Gao et al., Particle mixing study in rotating wavy wall tumblers by discrete element method simulation. Ind. Eng. Chem. Res. 53, 13087-13097 (2014). https://doi.org/10.1021/ie501409f
14. W.R. Ketterhagen, J.S. Curtis, C.R. Wassgren et al., Predicting the flow mode from hoppers using the discrete element method. Powder Technol. 195, 1-24 (2009). https://doi.org/10.1016/j.powtec.2009.05.002
15. M.L Liu, Z.M. Lu, B. Liu et al., DEM simulation of particle mixing for optimizing the overcoating drum in HTR fuel fabrication. AIP Conf. Proc. 1542, 726-730 (2013). https://doi.org/10.1063/1.4812034
16. L.S. Lu, S.S. Hsiau, DEM simulation of particle mixing in a sheared granular flow. Particuology 6, 445-454 (2008). https://doi.org/10.1016/j.partic.2008.07.006
17. L. Li, I. Kemp, M. Palmer, A DEM-based mechanistic model for scale-up of industrial tablet coating processes. Powder Technol. 363, 585-596 (2020). https://doi.org/10.1016/j.powtec.2020.01.087
18. P. Boehling, G. Toschkoff, S. Just et al., Simulation of a tablet coating process at different scales using DEM. Eur. J. Pharm. Sci. 95, 198-212 (2016). https://doi.org/10.1016/j.ejps.2016.08.018
19. Z.H. Liu, H.Q. Ma, L.Y. Zhou et al., DEM-DDM investigation of the tablet coating process using different particle shape models. Ind. Eng. Chem. Res. 62, 829-840 (2022). https://doi.org/10.1021/acs.iecr.2c04030
20. X.J. Ma, M. Liu, Z.F. Hou et al., Numerical simulation and experimentation of pelletized coating of small grained forage seeds. Trans. Chinese Soc. Agric. Eng. 39, 43-52 (2023). https://doi.org/10.11975/j.issn.1002-6819.202211002 (in Chinese)

21. X.W. Zhou, Z.M. Lu, J. Zhang et al., Research and manufacture of spherical fuel element for HTR-PM demonstration project. At. Energy Sci. Technol. 48, 1228-1233 (2014). (in Chinese)

22. P.W. Cleary, M.D. Sinnott. Assessing mixing characteristics of particle-mixing and granulation devices. Particuology 6, 419-444 (2008). https://doi.org/10.1016/j.partic.2008.07.014

23. L. Xu, X.K. Wu, M.L. Liu et al., Studying on the upper limit of the coarse-grained DEM model for simulating mixing processes in a rolling drum with complex wall boundary. Adv. Powder Technol. 35, 104307 (2024). https://doi.org/10.1016/j.apt.2023.104307

Note: Figure translations are in progress. See original paper for figures.