1. INTRODUCTION

Granular-type porous medium is one of the most common media. Granular-type porous medium modeling with the following seepage process research has attracted significant interest in material science, geosciences, soil geology, coal coal, oil recovery, etc. for many decades. In the early 1920s, Washburn proposed that a porous body behaved as an assemblage of very small cylindrical capillaries, thus developing the understanding of Darcy’s porous medium. Then, the Lacus–Washburn equation was proposed to study the influences of seepage path diameter and liquid viscosity on the seepage process. After that, Richards simplified the irregular material particles into regular spherical particles representing the spatial configuration of porous media. Smith constructed an ideal soil particle model, where spherical particles of uniform diameter were arranged in regular tetrahedrons, and studied its infiltration process, which provided the basis for the hypothesis of the future particle-stacking porous medium model.

By 1993, researchers had tried a variety of particles of different shapes, not only the basic spherical particles but also conical, sinusoidal, ellipsoidal, and other shapes, which were considered to study the particle-packed porous medium model. However, this method required a lot of computing resources, and the calculation results were often not easy to converge. After a lot of research, the assumption that spherical particles occupied the dominant position in the porous medium modeling field was made. Cai invested a lot of effort in analytically modeling spontaneous imbibition in a porous medium and investigated the capillary rise in tortuous capillaries. With the wide application of porous medium models in soil geology, oil exploitation, penetration simulation, and other fields, researchers have tried to improve the models to represent the real structure. In 2013, Al-Dhahli and van Dijke established a three-phase porous media model of any wettability in carbonate rock, simulating the pore membrane and laminar motion processes. In recent years, researchers have considered three configurations of separation, contacting, and extrapolation between adjacent spherical particles in a porous medium and have built a two-dimensional (2D) model of particles regularly arranged. As for the particle-stacking porous medium, its inner spacial structure may change with the upward stacking pressure, leading to a different pore structure even on the same horizontal plane. Even though advanced image processing has been developed rapidly year after year, challenges still exist.

As one of the most important fossil resources in the world, coal has been used and stored widely in many industrial production fields. Due to the characteristics of self-heating, smoldering accidents take place at times in coal stacks, where water-based extinguishing agents are often used preferentially. Usually pulverized coal forms a typical granular-type porous medium structure in the natural stacking state, which is characterized as diverse apparent shapes of particles, large size distribution span, obvious gap of bonding strength between different materials, and its surface physical properties being affected by many factors. Since the coal hydrophobic surfaces
usually obstruct water-based extinguishing agents from penetrating rapidly into the coal stacks, this may result in secondary disasters.21–24 Much attention has been paid to the liquid seepage process in such granular-type porous media for years, and the influencing factors have been studied.

As for liquid imbibition and drainage process in a porous medium, the methods of numerical calculation, analytical solution, physical model test, and field test16,17,21,23 are mostly used to investigate the liquid flowing field inside the porous medium. Among the above methods, the numerical calculation method substitutes the continuously changing flow field using a series of discrete values or simple functions at small intervals or over small elements to describe the relationship between variables. It usually provides an approximate solution rather than the exact solution. The analytical solution method consists of a series of theoretical functions containing all of the variables. It can give solutions in concrete function formulas and solve the exact value for any variable. However, it is always extremely difficult and costs much to solve partial differential equations for real problems. The field test method includes full-scale, laboratory-scale, and small-scale field tests and usually requires a lot of manpower and resources. Though researchers can obtain huge amounts of raw test data and visually observe experimental phenomena with the field tests, some details are still not available due to the experimental limitation. Benefiting from the development of computer technology and improvement of finite element theory, the numerical calculation method has become one of the most important methods in this field with the advantages of low cost, low risk, and high repeatability. Besides, the numerical calculation method can help in obtaining complicated and comprehensive flow field details, which are usually difficult to obtain using other methods.

This work is expected to study the liquid seepage process in such granular-type porous media and some factors influencing analysis on liquid drainage. Considering that traditional sampling and analysis methods, such as mercury injection method (MIR),2,5,17 centrifuge method, and fluorescent agent injection method, may destroy the original structure of the porous medium, a new pulverized coal sampling device was designed and manufactured in this study. Based on the concept of the height compression ratio, an approach combining ultra-deep-field microscopy and advanced image processing technologies was proposed to rebuild granular-type porous medium models of 200 mesh pulverized coal stacks. These models were evaluated by testing the pore structure and hydraulic conductivity coefficient with real coal samples using Darcy’s constant head seepage tests. With the assistance of CFD technology, liquid seepage in coal stack porous medium under different conditions was simulated. The detailed flow field characteristics of liquid seepage process in a granular-type porous medium with the influences of the inlet head pressure, liquid viscosity, and pore size were analyzed based on these simulation results. This work aims at providing references and basis for future research on seepage in granular-type porous media and deep-seated fire prevention and disposal technologies.

2. RESULTS AND DISCUSSION

Previously, a porous medium was regarded as cylinders with circularity, tortuosity, and other coefficients.1–3,7,13 Even for other treatments like the ideal spherical hypothesis, the irregular capillaries formed by solid particles are still simplified to cylinders. In this study, Hudot’s pore structure classification15 was adopted in the seepage process analysis in the granular-type porous medium. From the graphical statistics and analysis of the rebuilt pore structure model, the effective pore size is mainly in the range of 8–15 μm. This is the macro pore range. Liquid seepage in coal stack porous medium is consistent with Darcy’s seepage in a binary heterogeneous anisotropic porous medium, and the basic differential equation of the head function is

\[
\frac{\partial}{\partial x} \left( K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left( K_y \frac{\partial h}{\partial y} \right) + \omega = S \frac{\partial h}{\partial t}
\]

(1)

where \( h \) is the head function; \( t \) is the time; \( s; K_x \) and \( K_y \) are the hydraulic conductivities in the x and y directions, respectively, m/s; and \( s \) is the unit water storage rate, m³/s. The definite solution conditions for seepage equation are listed as follows

\begin{align*}
(1) \ & \text{initial conditions} \\
& h_{t=0} = h(x, y, 0)
\end{align*}

(2)

\begin{align*}
(2) \ & \text{boundary conditions} \\
& \text{Head boundary} \\
& h_{\Gamma_1} = h(x, y, t)
\end{align*}

(3)

\begin{align*}
(3) \ & \text{Flow boundary} \\
& -k_x \frac{\partial h}{\partial x}{|_{x=\omega}} = q(h, x, y, t)
\end{align*}

(4)

where \( \Gamma_1 \) is the first-class boundary condition, \( \Gamma_2 \) is the second-class boundary condition, and \( \omega \) is the outer normal direction of boundary \( \Gamma_2 \).

In this study, detailed micrographic information of pore structures with varied flow field parameters can significantly help in analyzing the liquid seepage process in a porous medium. Among the porous material physical properties, liquids’ physical properties, interface interactions, etc.,1,2,6–28 the influences of factors such as head pressure, liquid viscosity, and pore size on liquid seepage process in such a kind of porous medium are discussed in this study.

2.1. Effects of Head Pressure on Seepage Process. On the contact of liquid with the solid surfaces of a porous medium, the head pressure is the main driving force for liquid downward seepage. Once the liquid enters the interior pores of the porous media, additional pressure is generated simultaneously on the meniscus due to surface tension in capillaries. In spontaneous imbibition process, where the contact angle is smaller than 90°, capillary imbibing height can be calculated by combining the Laplace equation with the liquid pressure equation1,2 as

\begin{align*}
P_c &= \frac{2\sigma}{r} \quad (5) \\
P_c &= \rho gh \quad (6) \\
H_{im} &= -\frac{2\sigma}{\rho g r} \quad (7)
\end{align*}

where \( P_c \) is the additional pressure, Pa; \( \sigma \) is surface tension, N/m; \( r \) is the capillary radius, m; \( \rho \) is liquid density, kg/m³; \( g \) is gravity, m/s²; and \( H_{im} \) is capillary imbibition height, m. In this study, the contact angle is measured to be 42.72°. For a specific kind of liquid, the imbibition height totally depends on the capillary
Table 1. Seepage Simulation Results under Different Head Pressure Conditions

| liquid column height (mm) | 30   | 60   | 90   | 120  | 150  |
|---------------------------|------|------|------|------|------|
| mass flow rate Q (×10⁻⁴ kg/s) | 0.684| 1.370| 2.054| 2.868| 3.850|
| hydraulic conductivity K (×10⁻⁴ m/s) | 1.15 | 1.17 | 1.18 | 1.24 | 1.33 |
| permeability k (×10⁻¹⁵ m²) | 1.18 | 1.20 | 1.21 | 1.27 | 1.36 |
| pressure drop per unit ΔP/ΔL (Pa/mm) | 278.325| 558.085| 825.756| 1100.948| 1376.234|
| seepage velocity v (mm/s) | 2.973| 5.955| 8.925| 11.89| 14.85|

Increasing the head pressure can obviously increase the liquid seepage velocity, while the driving force is mainly from gravity in this research. As for actual deep-seated fire disposal technology, it can be referenced that increasing the initial water pressure promotes water-based extinguishing agents’ seepage in coal stacks.

2.2. Effects of Liquid Viscosity on Seepage Process.

Viscosity plays an important role in liquid transport in a porous medium and is mentioned in many classical and significant mathematical models, such as Handy model, Benavente model, Li and Horne model, and Cai model. To avoid the effect of gravity in constitutionally promoting liquid flow downward in porous medium pores, acetone, methanol and ethanol that have a similar density and different viscosities were selected as comparative fluids. Table 2 shows the simulation results of seepage properties with different liquids.

Some assumptions made in the following analysis are stated: (a) liquids and gases behind the imbibing waterfront are both continuous phases, (b) the pressure gradient in the gas phase is negligible both in front of and behind the imbibing waterfront, and (c) the additional pressure gradient over any increase of length provides the driving force for overcoming viscous forces in that same increased length. In the steady-state simulation, the mass flowing velocity is the net mass flux per second when liquids drain through the flow field region. In the plot of the square of the mass flowing velocity versus viscosity, as shown in Figure 2, the square of the mass flowing velocity is inversely proportional to the liquid viscosity, thus in line with the Handy model for liquid drainage process in a porous medium

\[ Q^2 = \frac{2\mu k \phi A^2 S_w}{\mu_w L} \]  

where \( Q \) is the mass flow rate, kg/s; \( P_c \) is additional pressure, Pa; \( k \) is the effective permeability, m²; \( \phi \) is the porosity; \( A \) is the cross-sectional area of the sample, mm²; \( S_w \) is the fractional water content of the pore spaces; \( \mu_w \) is the liquid viscosity, Pa·s; \( t \) is time, s; \( v_w \) is the flowing velocity, m/s; \( x \) is the flow position; \( \Delta \rho \) is the density difference for liquid and air; and \( g \) is the gravity, m/s². The fitted \( Q^2-\mu^{-1} \) curve can be described mathematically as

\[ Q^2 = (-80.63 \pm 11.70) + (111.05 \pm 5.56) \times \mu^{-1} \]  

where \( R^2 = 0.9975 \) and the slope represents the proportional relationship between the square of flow rate and reciprocal viscosity. It is noted that Handy model is proposed to describe the spontaneous imbibition, the intercept with minus in the front explains that Handy model neglects the gravity effect. Additionally, in a hypothetical case of liquids with infinite viscosity, the viscosity term approaches 0 and only a negative constant term is left in \( Q^2 \). This limiting approximation is radius in the case of a balance between the capillary force and gravity, while in liquid seepage process, the additional pressure can promote liquid penetration downward in the porous medium. The liquid head pressure and additional pressure are the main driving force for the liquid penetrating the porous medium bed. Then, in flowing seepage formulas and equations, the gravity term and additional pressure term share the same calculating signs.

Based on the verified granular-type porous medium models, simulations with pressure conditions of 294.3, 588.6, 882.9, 1177.2, and 1471.5 Pa upon the coal sample surfaces were carried out corresponding to liquid heights of 30, 60, 90, 120, and 150 mm. The simulation liquid was set as water. Simulation results of the mass flow rate \( Q \), hydraulic conductivity \( K \), permeability \( k \) under different head pressure conditions are listed in Table 1. \( K \) and \( k \) are almost the same for the same medium structure and infiltrating liquid, while the pressure drop per unit length along the seepage direction is nearly proportional to the head pressure. As a result of the effect of the hydraulic gradient, \( Q \) shows an approximately linear increase with the inlet head pressure.

The pressure distribution in pores of coal stacks under different head pressures followed similar rules. Except for the different pressure gradient values, the colored area distribution was roughly the same in Figure 1. The pressure value at specific locations seems to be proportional to the liquid column heights. According to Darcy’s Law

\[ Q = KSJ \]  

\[ Q = \frac{k\Delta PA}{\mu L} \]  

where \( Q \) is the seepage volume velocity, m³/s; \( K \) is the hydraulic conductivity, m/s; \( A \) is the cross-sectional area, m²; \( J \) is the hydraulic gradient; \( k \) is the permeability, m²; \( \Delta P \) is the pressure drop, Pa; \( \mu \) is the liquid viscosity, Pa·s; and \( L \) is the length of seepage path, m. The seepage mass flow rate is proportional to the hydraulic gradient, which changes proportionally with pressure drops in the pores, thus explaining that the curve of mass flow rate versus inlet pressure conforms to the linear distribution. The maximum flowing velocity proportionally relates to the hydraulic gradient. This is because the main driving force mainly depends on the water head, while the flowing resistance consists of frictional and local resistance. For the same flow field physical model, the same pore resistance coefficient results in the approximately same energy dissipation. According to Bernoulli’s principle, the remaining water head converts into kinetic energy for accelerating the liquid flow.

The fluctuation of \( K \) and \( k \) of water under different inlet pressures was controlled under 2.0%, which indicated the good adaptability and robustness for different driving pressures in this work.
unrealistic and explains that only liquids with head pressure bigger than a certain pressure, which is called critical penetration pressure here, can penetrate into the porous medium.

Additional pressure due to the gas–liquid interfacial interaction influences liquids flowing in pores greatly.

According to Newton’s inner friction law and law of conservation of momentum, the effects of viscous shear stress on flowing fields increase with liquid viscosity. Along the flowing paths, the higher viscous shear stress can greatly deform fluid flowing, thus increasing the velocity gradient near the wall and causing more turbulence eddy dissipation in the

Figure 1. Pressure distribution in the porous medium under different inlet pressure conditions.
flowing field. Under the same flowing path conditions, viscosity causes vortices to be generated in fluids, and the flowing velocity decreases with the turbulence eddy dissipation.

From the seepage velocity distribution of the three liquids in Figure 3, the bulk velocity and the maximum flowing velocity both decrease with increasing liquid viscosity. In the areas framed by black frames, flowing velocity and velocity gradient decrease with increasing viscosity, and the velocity contour gradually becomes sparse. This means that the overall permeability performance weakens with increasing viscosity.

Figure 4 shows the turbulence eddy dissipation distribution of the three liquids in the coal stack porous medium. The viscosity of acetone and methanol is small, resulting in a smaller eddy current dissipation of 700 and 1200 m²/s³, respectively; for ethanol with higher viscosity of 1.2 mPa·s, the eddy dissipation, which is about 4700 m²/s³, is obvious and larger than the two other liquids. At the same position in Figure 4, large eddy dissipation gradient takes place much more easily in the case of liquids with high viscosity.

As a liquid flows in the inner pores, the viscosity of the fluid would lead to eddy currents, causing eddy current energy dissipation. When the liquid viscosity increases, the shearing effect of viscous shear stress on the flow field is more obvious, fluid flowing deformation strengthens, and the eddy current energy dissipation caused by fluid eddy currents also increases.

Figure 5a shows the local streamlines of the velocity profile of acetone in the selected flow field region in Figure 4, and eight monitoring points are marked along the streamlines. In the

| Table 2. Seepage Properties’ Simulation Results with Different Liquids |
|-----------------|-----|-----|-----|
|                 | acetone | methanol | ethanol |
| liquid viscosity $\mu$ (mPa·s) | 0.32 | 0.60 | 1.15 |
| liquid density $\rho$ (kg/L) | 0.7845 | 0.7918 | 0.7890 |
| surface tension $\sigma$ (mN/m) | 18.8 | 20.14 | 21.97 |
| mass flow rate $Q$ ($\times 10^{-5}$ kg/s) | 16.4 | 9.86 | 4.54 |
| hydraulic conductivity $K$ ($\times 10^{-6}$ m/s) | 2.76 | 1.66 | 0.762 |
| permeability $k$ ($\times 10^{-13}$ m²) | 2.82 | 1.70 | 0.781 |

Figure 2. Square of mass flowing velocity versus reciprocal viscosity.

Figure 3. Flow field velocity profile for the three liquids.
cases of methanol and ethanol, monitoring points are set at the same positions. The turbulent eddy dissipation rate versus viscosity is plotted and fitted using polynomial functions, as shown in Figure 5b. The slope represents the variation trend of turbulent eddy dissipation with viscosity, and it changes faster with higher viscosity. It should be noted that this phenomenon is not so obvious at narrow flow fields, as the slopes of fitting curves at points 1 and 8 are relatively smaller. The slopes at points 3 and 4 are larger than that at points 2, 5, and 6, indicating that the turbulent eddy dissipation varies faster away from the flow field boundary than near the boundary.

2.3. Effects of Pore Size on Seepage Process. Pore size not only limits the flowing boundary conditions but also influences the moving capillary front, thus influencing liquid drainage processes significantly. Poiseuille\textsuperscript{30,31} assumed a constant flow of incompressible viscous fluid in a horizontal tube and introduced a volume flow proportional to the fourth power of the pipe radius, which is known as Poiseuille’s Law\textsuperscript{2,13,32}

$$Q = \frac{\pi r^4 \Delta P}{8\mu L}$$  \hspace{1cm} (13)

$$R = \frac{8\eta L}{\pi r^4}$$  \hspace{1cm} (14)

where \(Q\) is the mass flow rate, \(kg/s\); \(r\) is the pipe radius, \(mm\); \(\Delta P\) is the pressure difference through the pipe, \(Pa\); \(\mu\) is the viscosity, \(Pa\cdot s\); \(L\) is the flowing length, \(mm\); and \(R\) is the flow resistance. However, in an actual granular-type porous medium, the substantially complicated inner pore structure can be deformed by many factors. Jian Shen investigated the difficulty of water to escape from the well-developed microspores due to strong gas–water interfacial tension in the microspores and attributed it to larger pores, resulting in lower interfacial tension. From the Laplace equation, larger pores with diameters greater than 1000 nm in this study can lead to lower additional pressure, while the interfacial tension on the air–water–coal three-phase line is basically unchanged.

Porosity generally describes the structural characteristics of certain kinds of porous media from a macro perspective. As for granular-type porous medium stacks, the particle diameter distribution can directly affect its inner pore structure, which is shown as porosity. As one of the main structural parameters of a granular-type porous medium, the pore size has a great influence on fluid seepage processes. Figure 6 shows the velocity vector profile of simulation results, in which water was set as the seepage liquid and the inlet pressure was 294.3 Pa. Along the fluid flow direction \(a \rightarrow b \rightarrow c\), points \(a\), \(b\), and \(c\) were selected as reference points. When the fluid flows through \(a\) and \(c\), the pore diameter becomes smaller, increasing the fluid velocity and wall shear stress around locations \(a\) and \(c\) and affecting the fluid seepage process in the porous medium.

![Figure 4. Turbulent eddy dissipation profile for the three liquids.](image)

![Figure 5. Relationship between viscosity and turbulent energy dissipation.](image)
As shown in Figure 7, fluid turbulence kinetic energy at locations a and c increases. Pore diameter gradually becomes larger from a to b, with eddy current causing the fluid to leave the boundary surfaces and eddy resistance increasing energy dissipation. When the liquid flows from b to c, the flowing direction cannot change immediately due to the moment of inertia, resulting in the separation of the boundary layer and the generation of eddy current. At the same time, the narrower pore diameter can increase the viscous shear stress caused by liquid viscosity. Increasing eddy resistance and shear stress strengthens energy dissipation, causing the pressure potential energy to decrease. From the pressure distribution shown in Figure 8, the flowing pressures at locations a, b, and c are 246.5, 243.6, and 238.4 Pa, respectively. As a result, apparently, $\Delta P_{bc} > \Delta P_{ab}$.

From the velocity profile in Figure 9, fluids under the same driving pressure have different flow velocities in pores of different sizes. According to the Washburn equation1
\[ v = \frac{P(r^2 + 4er)}{8\mu L} \]  

(15)

where \( v \) is the flowing velocity, m/s; \( P \) is the fluid pressure, Pa; \( r \) is the capillary radius, mm; \( \varepsilon \) is the boundary slip coefficient; \( \mu \) is the liquid viscosity, Pa·s; and \( L \) is the flowing length, mm.

In Figure 9, the fluid flows faster in the right pore than in the left one because the right pore is larger, where the velocity gradient in the fluid is also much larger. As a result, fluid turbulence is more intense in the right pore, intensifying liquid flowing.

Pore shape deformation can increase wall stress applied to the fluid, as shown in Figure 10, and the flow resistance term due to wall shear stress increases. More pressure potential energy is used to counteract the resistance dissipation in the right-side pores. The additional pressure due to the contact of liquids with the capillary inner surface also creates obstruction effects. According to the Laplace equation, as the pore diameter decreases, the additional pressure and flow resistance term increases. Therefore, the pressure below the pore on the right is smaller than that at the same height on the left, as shown in Figure 11.

Larger pores may result in lower gas−water interfacial tension, thus weakening the water blocking effect. Therefore, water can easily drain through the macro- and mesopores. Furthermore, immobile water content is positively related to microspore volume and negatively related to total pore volume. This suggests that water is difficult to drain out through the well-developed microspores due to the strong gas−water interfacial tension in microspores.

3. CONCLUSIONS

Pulverized coal stacks have typical granular-type porous structure and risks of smoldering fire due to their self-heating property. For further research on the prevention and disposal technology for deep-seated fire, a lot of efforts were made in this study in rebuilding a granular-type porous medium model and analyzing liquid seepage characteristics. The research findings also provide technology support and theoretical references to liquid dynamics in a granular-type porous medium and relevant fields.

In this study, an approach to reconstruct 2D granular-type porous medium models was proposed; the ultra-deep-field microscopy and a series of advanced image processing technologies were applied to capture the original particle-stacking structure in as much detail as possible. Verified by Darcy’s constant head seepage tests, the rebuilt granular-type porous medium model represents the permeability performance of granular-type porous medium with the maximum error of 8.56 and 8.34%, respectively, for hydraulic conductivity \( K \) of permeability \( k \). Followed by systematic research of liquid seepage process in the porous medium, the effects of head pressure, liquid viscosity, and pore size were discussed and illustrated with detailed flowing field parameters in the simulation. Some conclusions were summarized as follows.

In liquid seepage process, additional pressure and upper liquid static pressure were the main driving forces for liquids penetrating the porous medium bed. In seepage analytical equations, the gravity and additional pressure shared the same calculating signs. For a granular-type porous medium such as pulverized coal stacks, the mass flow rate was linearly related to the inlet driving pressure, which conforms to Darcy’s seepage law. Only liquids with head pressure bigger than the critical value could penetrate into the porous medium. The liquid pressure distribution profile in the porous medium under different driving pressures could be similar to each other, and the pressure value at critical turbulent regions could be linearly related to the driving head pressure. Liquid viscosity was the
cause of shear stress and plays an important role in the liquid seepage process, even in low-velocity seeping processes. Turbulent eddy currents due to higher liquid viscosity could influence the flowing state and then aggravate eddy dissipation in the fluid. In research regions, acetone and methanol resulted in a smaller eddy current dissipation of 700 and 1200 m$^2$/s$^3$, respectively. For ethanol with higher viscosity of 1.2 mPa·s, the eddy current dissipation reached up to about 4700 m$^2$/s$^3$, which was nearly seven times greater than that of acetone. Plotting the turbulent eddy dissipation—viscosity at flow field points, the turbulent eddy dissipation rate fitted with viscosity was better using polynomial functions than linear ones. More pressure potential energy and kinetic energy were consumed in the case of high-viscosity liquids, resulting in decreasing permeating velocity. As one of the most important structural parameters, pore size directly influenced the momentum and energy transfer, thus changing the liquid seeping process. Larger pores could reduce shear stress in the flow field. The additional pressure at the front end of the fluid in pores of the porous medium was decreased, lowering the fluid flow resistance, and thus increasing the fluid kinetic energy and the seepage flowing velocity.

Additionally, there are still many other factors playing important roles, such as particle size distribution, pore structure, water-based extinguishing agents, etc., in liquid seepage in granular-type porous media. The influences of these factors will be studied in further research combining a few capillary experiments. The proposed approach of rebuilding granular-type porous medium models still needs to be developed for specific practical problems to improve its applicability. The relevant work will be studied in the future.

4. MATERIAL

Based on the background of the development of deep-seated fire prevention and disposal technology, pulverized coal (He Nan, China) was selected as the experimental material, and water was set as the seepage liquid in this study. Coal stacks are typical easily self-heating substances and have a particle-stacking porous structure under gravity effect. The research findings of fluid flowing characteristics in coal stacks can be applied not only to promoting deep-seated fire disposal research but also to general soil geology and fluid dynamics fields. Considering that the porosity is always regarded as the characterization parameter of granular-type porous media, it can be assumed that coal samples with the same porosity have substitutable spacial structures in this work. In the actual industrial process, the pulverized coal stacks generally contain a wide particle size distribution ranging from millimeters to micrometers. To carry out seepage tests successfully, the permeabilities of the 200 mesh and 400 mesh pulverized coal were compared in this study. Deionized water and a sodium dodecylbenzenesulfonate (SDBS) solution of 0.05 wt % were prepared, and their viscosities and surface tensions were measured and are listed in Table 3.

Table 3. Viscosity and Surface Tension of Water and SDBS Solution

|          | viscosity (mPa·s) | surface tension (mN/m) |
|----------|------------------|------------------------|
| deionized water | 2.98             | 72.75                  |
| SDBS solution of 0.05 wt % | 1.01             | 49.5                   |

"The indoor temperature was 20–25 °C.

Figure 12 shows an equivalent amount of 200 mesh and 400 mesh pulverized coal samples in two Petri dishes, respectively.

The sample surfaces were flattened with a pressure of about 281.73 Pa. Both water and SDBS solution were dropped on the left and right side of the coal sample, respectively. The liquid drops on the 400 mesh coal sample surface were wrapped into spherical shapes; however, they penetrated completely when dropped on the 200 mesh coal sample surface.

To observe the liquid wetting pulverized coal surface, equal amounts of 200 mesh and 400 mesh pulverized coal were added in two beakers and flattened on the surfaces, as shown in Figure 13. SDBS solution was poured into the breakers slowly and carefully to prevent the liquid flow from damaging the surface. After a while, the 200 mesh pulverized coal surface was wetted and the SDBS solution penetrated quite a bit. But for the 400 mesh pulverized coal, large deformation occurred on the surface, and the liquid was wrapped by pulverized coal and formed a sticky paste. Thus, the 200 mesh pulverized coal was selected as the seepage test material and modeling object, as liquid could penetrate through it.

4.1. Porosity and the Height Compression Ratio. The porosity of pulverized coal stacks varies with the coal type and particle size distribution, stacking pressure above the sample, and many other factors. Based on the spherical particle hypothesis, the whole uniform structure of the porous medium can be studied using small-area samples. Porosity was calculated by the following equation

$$\phi = \left(1 - \frac{V_s}{V}\right) \times 100\%$$  

where $\phi$ is the porosity; $V_s$ is the real solid volume, m$^3$; and $V$ is the sample apparent volume, m$^3$. However, the traditional sampling methods, such as the mercury injection method
(MIR), centrifuge method, and fluorescent agent injection method, may destroy the sample structure and therefore cannot represent the porosity-changing porous medium. Meanwhile, for the real large-scale granular-type porous medium stacks, porosity changes with the stacking pressure above. The pore structure varies along the vertical stacking direction and thus cannot be regarded as uniform in the whole studying area.

To avoid damaging the original spacial structure of the coal granular-type porous medium, a new modeling and simulating method was proposed in this study. We assume a cube of negligible weight and wall thickness, and the bottom area is \( S \) and the height is \( H \). Filling the cube with pulverized coal, the following equations can be obtained

\[
V_s = (1 - \phi) \times V = (1 - \phi) \times SH
\]

\[
M = \rho_s \times (1 - \phi) \times V = \rho_s \times (1 - \phi) \times SH
\]

where \( V \) is the apparent volume of coal sample, \( \text{mm}^3 \); \( V_s \) is the real solid volume of coal sample, \( \text{mm}^3 \); \( \rho_s \) is the real solid density, \( \text{g/mm}^3 \); \( \phi \) is the original porosity; and \( M \) is the total mass of the coal sample, g. Compacting the coal sample to a height of \( H' \) with a uniform load \( F \) on the surface, the apparent volume is \( V' = SH' \); then, the porosity can be calculated as

\[
\phi' = \frac{V' - V}{V'} = \frac{SH' - (1 - \phi) \times SH}{SH'} = 1 - (1 - \phi) \times \frac{H}{H'}
\]

Now, we define the height compression ratio, \( \alpha \), as the ratio of the compacted height to the original height, that is

\[
\alpha = \frac{H'}{H}
\]

Substituting eq 6 in eq 5, we get eq 7

\[
\phi' = 1 - \frac{1 - \phi}{\alpha}
\]

\[
\alpha = \frac{1 - \phi}{1 - \phi'}
\]

The porosity of the compacted sample, \( \phi' \), is only inverse proportionally related to the height compression ratio, \( \alpha \). Considering that the ratio \( \alpha \) is mostly determined by the sample height, the porosity of the granular-type porous medium can be adjusted by compacting the sample heights. For the same kind of granular-type porous medium, the assumption that different sample stacks with the same height compression ratio can be considered to have substitutable spacial structures is proposed. Based on this assumption, the pulverized coal samples in the following micrographics and Darcy’s seepage tests are considered to have substitutable porosities and pore structures.

4.2. Particle Size Distribution. The morphological and surface characteristics of the coal samples were observed using a field-emission scanning electron microscope (S4800, Hitachi, Ltd., Japan) at 3.0 kV, as shown in Figure S1 in the Supporting Information (SI). It is obvious that the pulverized coal particles are characterized as diverse apparent shapes of particles and large size distribution span from the scanning electron microscopy (SEM) images of the coal samples.

The particle size distribution was measured with a laser particle size analyzer (BT-9300, Bettersize Instruments Ltd., China). In a five-point sampling method, an appropriate amount of pulverized coal was added to deionized water to make a suspension, which was then dispersed with an ultrasonic cleaner. The suspension was placed in the circulation cell and the opacity was controlled in the range of 15–20 for measurement. The above operations were repeated to obtain a stable measurement result, as shown in Figure S2 in the SI. The pulverized coal sample has a D50 of 34.67 \( \mu \)m and a specific surface area of 255.4 \( \text{m}^2/\text{kg} \).

4.3. Real Solid Density. Drainage method was used to measure the real solid density of the pulverized coal stacks. SDBS solution with a mass fraction of 0.05\% was prepared in a measuring cylinder and the original volume was denoted as \( V_1 \). The pulverized coal was weighed and the original weight was denoted as \( M_1 \). Then, some amount of the pulverized coal was added into the measuring cylinder and the weight of the remaining coal sample was measured and denoted as \( M_2 \). When the pulverized coal was completely submerged in the solution, the liquid volume was marked as \( V_2 \). The real solid density was calculated as

\[
\rho_s = \frac{M_1 - M_2}{V_2 - V_1}
\]

The above process was repeated 12 times, and then the trimmed mean value of the real solid density obtained was \( \rho_s = 1.108 \times 10^3 \text{ g/m}^3 \).

5. METHODOLOGY

5.1. Coal Stack Sample Preparation. The coal-compacting device consists of the viewing window, sample container; 3, supporting frame; 4, ball screw; 5, handle; 6, adapting piece; 7, compacting plate; and 8, pulverized coal sample.

Figure 14. Coal-compacting device. 1, viewing window; 2, sample container; 3, supporting frame; 4, ball screw; 5, handle; 6, adapting piece; 7, compacting plate; and 8, pulverized coal sample.

Table 4. Structure Parameters of the Coal Sample Before and After Compacting

|               | before compacting | after compacting |
|---------------|-------------------|------------------|
| coal solid volume \( V_s \) (\text{mm}^3) | \( 4.429 \times 10^4 \) | \( 3.234 \) |
| \( H \) (mm)  | 47.0              | 34.8             |
| apparent volume \( V_{a} \) (\text{mm}^3) | \( 1.175 \times 10^4 \) | \( 8.70 \times 10^4 \) |
| porosity \( \phi \) (%) | 62.31            | 49.09            |
container, supporting frame, ball screw, handle, adapting piece, and compacting plate, as shown in Figure 14. The sample container provides an internal space of $50 \text{ mm} \times 50 \text{ mm} \times 50 \text{ mm}$. The coal sample compression ratio is adjusted by turning the ball screw. The viewing window is detachable for accessing the micrograph of coal samples.

The coal sample was placed in the compacting container and the coal sample surface was flattened. The coal sample was compacted from $H_1 = 47.0 \text{ mm}$ to $H_2 = 34.8 \text{ mm}$ by adjusting the ball screw, and the height compression ratio was calculated using eq 6 as $\alpha = 74.04\%$. According to eq 2, the original porosity was calculated as $\phi_1 = 62.31\%$ and the compacted porosity $\phi_2 = 49.09\%$. Table 4 shows the structure parameters of the coal sample before and after compacting.

Figure 15 shows the section image from the vertical direction of the compacted coal sample. The whole sectional area was $50.0 \text{ mm} \times 27.2 \text{ mm}$, and the microscopy effective scanning area was set as $1.44 \text{ mm} \times 1.07 \text{ mm}$ with a magnification ratio of 2000. The regions marked as 1 to 5 in Figure 15 were selected to take micrographs of coal stack porous medium to ensure loading uniformity. As shown in Figure 16, the micrograph from region 5 was selected as the research region in this study.

### 5.2. Porous Medium Micrograph Processing.

The original micrographs of compacted coal stacks were binarized with MATLAB. The threshold was set as 0.38 to adjust the porosity to 51.18\%, which was close to the calculated value. Figure 17a shows the vectorized solid boundary of the rough 2D coal model with the required porosity.

To ensure the continuity of the flow field, dead pores, cross lines, glitches, and cutting edges needed to be smoothed, as shown in Figure 17b,c. Then, the flow field domain in coal sample pores was generated from the solid boundaries, as shown in Figure 18.

### 5.3. Discretization of 2D Coal Stack Porous Medium.

Three meshing schemes with different element sizes were applied in a grid independence test and evaluated with the hydraulic conductivity $K$. Darcy experiments with the same boundary conditions were conducted, and the experimental value of $K$ was tested to be about $1.697 \times 10^{-10} \text{ m/s}$. The comparison results of the grid independence test are shown in Table 5.

The element size of 0.001 mm is applied in the following study. Figure 19 shows the 2D discrete model of the coal stack porous medium.

### 5.4. Verification for Granular-Type Porous Medium Model.

Darcy’s seepage test was carried out to verify the granular-type porous medium model mentioned above. As shown in Figure 20, the constant head seepage test device consists of a peristaltic pump, a seepage test section, water outlets, and a measuring cylinder.

Briefly, 200 mesh pulverized coal with $M' = 15.281 \text{ g}$ was placed in the seepage test section, and the recorded column height was $H_1' = 27.3 \text{ mm}$. According to the compression ratio $\alpha' = 73.91\%$, the coal sample was compacted to a height of $H_2' = 20.2 \text{ mm}$. The original and compacted porosity was obtained as $\phi_1' = 61.58\%$ and $\phi_2' = 48.02\%$, respectively. Thus, pulverized coal samples for seepage tests and simulation were considered to have similar porous spacial structures. Liquid column heights of 30, 50, and 60 mm were set upon the coal sample as boundary conditions, respectively, to perform the seepage tests and numerical simulation. The hydraulic conductivity $K$ and permeability $k$ were calculated according to Darcy’s law (eqs 8 and 9). The comparison between the seepage test and simulation results of hydraulic conductivity $K$ and permeability $k$ are shown in Table 6.

From Table 6, the simulation results were in good agreement with the experimental data, indicating that the method proposed in this article could be an alternative to the on-site sampling method to build coal stack porous medium.
models and that the simulation results were reliable and could be used for flow field analysis.

**ASSOCIATED CONTENT**

## Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.0c02241.

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**Table 5. Comparison Results of the Grid Independence Test**

| element size (mm) | number of cells | minimum mesh quality | maximum mesh quality | maximum aspect ratio | $K$ ($10^{-6}$ m/s) | error of $K$ (%) |
|-------------------|-----------------|----------------------|----------------------|----------------------|---------------------|------------------|
| 0.001             | 845 570         | 0.23                 | 0.99                 | 17.07                | 1.73                | 1.76             |
| 0.0014            | 559 555         | 0.18                 | 0.99                 | 21.50                | 1.94                | 14.51            |
| 0.002             | 456 535         | 0.06                 | 0.99                 | 28.08 divergence due to poor mesh quality |

**Table 6. Comparison between the Seepage Test and Simulation Results**

| height of the liquid column (mm) | $K$ ($10^{-6}$ m/s) | $k$ ($10^{-13}$ m$^2$) |
|----------------------------------|---------------------|------------------------|
| test results                     | 1.73 1.79 1.94 1.77 | 1.83 1.99               |
| simulation results               | 1.65 1.68 1.77 1.69 | 1.72 1.82               |
| relative error (%)               | 4.62 6.15 8.56 4.52 | 6.01 8.34               |

Figure 18. Smoothing operation for the rough solid boundary in the porous medium.

Figure 19. Discrete 2D model of the coal stack porous medium.

Figure 20. Darcy’s constant head seepage test. 1, water supply pipe; 2, peristaltic pump; 3, overflow tank; 4, overflow pipe; 5, iron support; 6, water inlet; 7, constant head section; 8, piezometer tube; 9, pulverized coal sample; 10, drain pipe; and 11, measuring cylinder.
Description of physical characterization of pulverized coal: SEM images of 2000 mesh pulverized coal; particle size distribution of 200 mesh pulverized coal (PDF)

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Notes
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■ NOMENCLATURE

$A$ cross-sectional area, $m^2$;
$g$ gravity, $m/s^2$;
$H_{im}$ capillary imbibition height, $mm$;
$h_c$ the head function;
$K$ the hydraulic conductivity coefficient, $m/s$;
$k$ the permeability, $m^2$;
$L$ the flowing length, $mm$;
$P_a$ additional pressure, $Pa$;
$\Delta P$ the pressure difference, $Pa$;
$Q$ the mass flow rate, $kg/s$;
$R$ flow resistance;
$r$ capillary radius, $mm$;
$S_i$ the unit water storage rate, $m^3/s$;
$S_w$ the fractional water content;
$V$ sample volume, $mm^3$;
$v$ the flow rate, $mm/s$;

Greek symbols
$\alpha$ height compaction ratio;
$\rho$ the fluid density, $kg/L$;
$\rho_p$ the real particle solid density, $kg/m^3$;
$\phi$ porosity;
$\sigma$ surface tension, $N/m$;
$\mu$ liquid viscosity, $Pa\cdot s$;
$\varepsilon$ boundary slip coefficient.

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