SIMULATION ANALYSIS OF ENHANCED FLUIDIZATION LEACHING PROCESS AND GEOTHERMAL SYNERGY IN DEEP GROUND METAL MINES

by

Deqing ZHANG [a*], ***Ende WANG*** [a], ***Jinpeng LUAN*** [a], ***and Xue WANG*** [b]

[a] Northeastern University School of Resources and Civil Engineering, Shenyang, China
[b] Liaoning Geological And Mineral Survey Institute Co. Ltd., Shenyang, China

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Based on the mining of deep metal mineral resources and the current in-situ leaching mining process of uranium ore, combined with the technological characteristics of "fluidized mining of metal ore" and "deep geothermal development", an innovative concept of strengthening the fluidized leaching process of deep metal ore - geothermal co mining is proposed, A numerical simulation method was used to analyze the turbulent flow and heat transfer characteristics of a new type of heat transfer enhancement element - a swirl plate as a support between tubes. The renormalization two equation turbulence model was used for numerical simulation, and the SIMPLEC algorithm was used for pressure and velocity coupling, and the enhanced wall treatment method was used for wall treatment. The periodic changes in the cross-sectional flow field and turbulence intensity of the unit flow channel were analyzed, as well as the synergistic relationship between the flow field and temperature field on the cross-section. The corresponding variation trends of the average Nusselt number and the average synergy angle of the cross-section were compared. The experimental results show that the 270-4.25 cyclone sheet can more fully utilize the enhanced heat transfer of the spin flow, and the overall average Nusselt number is higher than 180-2.0, which is consistent with the experimental results. That is, θ_m is low where high Nu_b and θ_m is high where low Nu_b is low, indicating that the changing trend of the two is fully consistent with the field synergy principle. This paper systematically analyzes the basic theoretical bottleneck, key technical problems and future development trend in the process of geothermal joint mining of deep metal mine, and aims to provide reference for the strengthening of geothermal joint mining and geothermal joint mining of deep metal ore.

Key words: *deep mining, metal ore, fluidized mining, geothermal energy, collaborative mining*

Introduction

In 2021, the production of ten types of non-ferrous metals reached 64.543 millionns, an increase of 206.8% compared to before 2010, achieving a record high profit of 364.48 billion yuan, providing a continuous source of basic nutrients for the development of China, an industrial powerhouse, the formation of metal mineral resources requires a long geological evolution process [1]. With the continuous development and utilization of various mineral resources by the country in recent years, the shallow resources in China have almost been depleted. *Marching deeper* has become a national policy direction and consensus in the mining science

* Corresponding author, e-mail: de51qz4@163.com

field. In the next decade, more than one-third of the metal mines will have a mining depth of 1000 m, and some mines will reach 2000-3000 m. However, as the mining depth continues to increase, facing a series of practical problems related to mine ventilation, transportation, water supply and drainage, support*, etc.* caused by high ground stress, high well depth, and high well temperature, traditional mechanical models, mechanized equipment, mining techniques, and other research results applicable to shallow mining will be difficult to sustain [2]. A large number of research results show that large-scale mining of deep mineral resources with the current mining mode and method will significantly reduce the recovery rate of deep recycling and economic benefits. In the face of the current severe mining situation, the academic community urgently needs to research the mining technology and system that cater to the development of deep mining. In February 2021, the Guiding Opinions of the State Council on Accelerating the Establishment and Improvement of a Green and Low Carbon cycle Economic Development System officially put forward the concepts of *carbon neutrality* and *carbon peaking*, prompting a large number of *super super, super super, high energy consuming* enterprises to make timely transformation in line with the trend of the times. As a high energy consumption, high solid waste, and low environmental protection industry, the traditional mining industry urgently needs to set an example under the current policy guidance, achieve fluidized leaching mining of mineral resources, achieve collaborative mining of mineral resources and geothermal resources, and change the traditional large-scale mining method. This is an important part of achieving environmentally friendly mining.

Literature review

Liquid solid fluidized beds have been widely used in various fields such as chemical engineering, energy, and environmental protection due to their excellent particle mixing and heat and mass transfer characteristics. Fully understanding the dynamic characteristics of flow, transfer, and reaction in the bed after sudden changes in operating speed is of great guiding significance for the scale-up design and optimization operation of liquid-solid fluidized beds, in response to the inevitable start-up, shutdown, and variable operating conditions in the actual process [3].

The Mu *et al*. [4] proposed an improved process for treating low grade nickel ice using chlorination roasting water leaching, which is an intermediate product obtained from ore flotation and high temperature smelting. The results indicate that the particle size ranges from 75-80 μm. The matte particles with a chlorination time of 2 hours, a chlorination agent to matte mass ratio of 2:1, and a chlorination temperature of 350 °C can simultaneously extract 93.6% Ni, 91.7% Cu, and 88.2% Co. The chlorination roasting process was determined by differential thermal analysis, thermogravimetric analysis (DTA-TG), X-ray diffraction (XRD) and thermodynamic analysis of chlorination reaction. Li *et al.* [5] used roasting leaching experiment, pore structure measurement, SEM and XRD explore the evolution of surface pore structure and its influence on leaching performance. Under the condition of ventilation rate of 0.6 m^3 per hour and roasting at 650 °C for 2.0 hours, the optimal size of pores was obtained. Under these conditions, approximately 92.55% of the gold can be recovered. As the temperature further increased to 850 °C, the porous structure observed by SEM became more dense. The formation of $CaSiO_3$ and $CaSO_4$ in the pores leads to pore shrinkage. Lyashenko *et al.* [6], V studied traditional mining techniques and techniques that combine underground block leaching (UBL) to extract metals from rocks and ores, and used explosives to preliminarily crush them in devices installed in mines. One of the most problematic areas is the difficulty in achieving the given crushing quality, as well as the height and loosening factors required to store ore in the chamber for subsequent metal leaching, while also considering the control of the energy of rock ore explosion damage.

In view of this, the author closely follows the urgent needs of deep resource exploitation and geothermal development, and based on the aforementioned concepts of *fluidized mining of metal mines* and *co-ordinated co mining of geothermal energy*, puts forward a concept of deep mining technology suitable for deep resource fluidized mining - efficient utilization of geothermal energy, and discusses theoretical gaps, key technologies and potential development directions, the relevant research can provide new ideas and new schemes for promoting the green mining of deep metal mines and the efficient utilization of geothermal energy.

Simulation analysis of enhanced fluidization leaching process and geothermal synergy in deep ground metal mines

Fluidized leaching technology for deep ground metal mines

In the process of transitioning from shallow to deep mining, limited by geological environmental conditions such as high ground stress, high well depth, and high ground temperature, on-site manual operation of machines can cause the following three problems:

– The safety uncertainty of the mining operation process has increased. Due to incomplete research on the deep underground mechanical system, theoretical calculations and engineering practices have repeatedly shown that traditional mechanical support methods are difficult to maintain the stability of deep underground space, and the safety of production operations is worrying.
– The operating costs of mines are constantly increasing. Due to issues such as increased environmental temperature, yielding of support materials, leakage of pressurized water, and longer ventilation-lines, it is inevitable to spend more funds to control and prevent a series of unfavorable factors for production.
– The working environment is further deteriorated. Limited by the high well depth, the mine ventilation system, water supply and drainage system, *etc*. will face great challenges. The working environment of workers and equipment is deteriorated. There are a large number of available geothermal energy resources within the mining depth of mineral resources. With the increase of depth, the deep environmental temperature increases significantly. The average geothermal gradient near the surface is 30 K/km, and the increasing gradient decreases to 1 K per km after entering the deep [4].

Petroleum is a liquid resource that exists underground and is often developed by drilling vertical and horizontal wells. It has the characteristics of ultra-deep, ultra-high temperature, and ultra-high pressure. Currently, the country has achieved the development of drilling at depths of 8500 m, indicating that the country has overcome most of the difficulties in ultra deep drilling technology due to the limitations of deep geological conditions, the ultra-high well depth of petroleum mining is a difficult depth to match for traditional open-pit and wellbore mining methods. However, the fluidized mining method of petroleum provides a good idea for the development of deep metal mineral resources. The advantages of this method are obvious:

– Maintaining ecosystem balance. This process does not require the entire ore body to be transported to the ground, minimizing damage to the underground original rock structure and surface ecological environment;
– Save investment and operational costs. This process does not require the stripping of large volumes of overlying rocks during development, and does not require the use of large-scale production, transportation equipment, and a large amount of human resources during production and operation, minimizing production costs to the greatest extent.
– Improved production safety. Pipe line transport is adopted for the production of this process, so the workers do not need to enter the deep ground with harsh environment for mining operations, which reduces the probability of fatal injury accidents.

Conception of enhanced fluidized leaching process – geothermal collaborative coextraction process

– Conceptual background

Collaborative mining means that the relationship between the environment and resource mining should be handled harmoniously by some technical means to minimize the impact of adverse factors on mining activities, or even make use of the adverse effects to generate benefits. The fluidized leaching mining technology of metal ore and the geothermal energy mining technology have much in common, and their common points are:

- the target resource is located below 1000 meters above the surface,
- target resource has extremely high mining and utilization value, and
- the target resource needs to be extracted through drilling and fluidization.

The difference lies in that in-situ leaching mining requires injecting corrosive solutions such as strong acids and alkalis into the ore body, and then extracting the rich solution containing metal ions to the surface through production wells for further processing. Geothermal energy mining is to obtain energy by means of heat exchange or direct extraction of aqueous solution. Deep mineral resources and geothermal energy resources have the same geographical environment and are both important strategic resources that have a direct and indirect impact on the national economy and the people's livelihood. Therefore, the collaborative mining of the two has become one of the main research arguments to solve the problems of low efficiency of a single mining model and high drilling production costs. Previously, experts and scholars had proposed various ideas for mining geothermal collaborative mining. Based on the in-situ leaching mining method, the author proposed a concept for strengthening the fluidized leaching process and geothermal collaborative mining process, hoping to provide new ideas for subsequent research of this type.

– Conceptual implementation method

At present, many scholars have conducted extensive research on the enhancement of leaching process under heap leaching conditions. From a comprehensive perspective of the occurrence characteristics of deep metal minerals, the pore structure of the ore body is unclear, the selection of leaching solution lacks uniqueness, the solution seepage parameters are difficult to control, the selection of leaching bacteria, the proliferation activity of bacteria and the synergistic effect between bacteria, pH value changes, unstable reaction temperature, imbalance between oxygen supply and demand in biological chemical reactions, and the generation and mechanism of passivation substances, it is the main factor hindering the efficient implementation of metal ion leaching reactions at present. The strengthening process of fluidized bed leaching of deep metal mines is reflected in the control of the aforementioned factors. Through intelligent equipment and automated process flow, real-time monitoring of various high impact factors in the reaction process is carried out, and strict control is exercised over the suitability of leaching solution, bacterial species, and reaction environment for mineral leaching. In order to solve the problem of low economic, social, and environmental benefits in such mines, this concept comprehensively plans the three time and spatial dimensions of engineering exploration, engineering operation, and engineering reclamation, in order to build a modern mine that knows the root of resource storage, energy-saving and efficient resource utilization, and environmentally friendly resource stripping. With the increase of people's development depth of deep metal mineral resources, the temperature of the ore body increases [8]. When the surrounding rock temperature reaches 50 °C, the minimum threshold of geothermal energy utilization has been met. At this time, geothermal energy can be used in an appropriate way. This concept is based on in-situ leaching mining technology and proposes an enhanced fluidized leaching process for deep metal mines – geothermal co mining process. The process flow is shown in fig. 1.

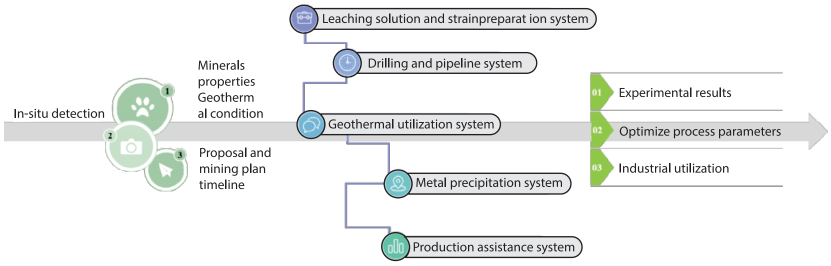

Figure 1. Flow chart of enhanced geothermal collaborative co-mining process for fluidized leaching of deep ground metal mines

The production and operation process is shown in fig. 2, and the main process steps are briefly described:

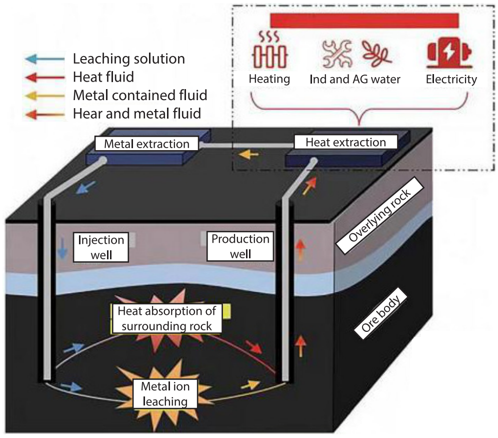

Figure 2. Schematic diagram of enhanced geothermal co-mining process for fluidized bed leaching of metal ore

– Preliminary exploration and experimentation: ① determine the area of the ore body, drill injection wells and production wells, ② inject the leaching solution and leaching bacteria used in the experiment. After the leaching solution fully reacts with the ore body, extract the rich solution containing metal ions and thermal energy to the surface, and analyze the leaching and thermal energy replacement effects, ③ repeat process ② to eliminate errors, and ④ based on reliable results obtained from multiple experiments, conduct early pre feasibility and feasibility studies to develop reliable solutions for later industrial production.
– Production system construction. The production system includes leaching solution and bacterial preparation system, drilling and pipe line transportation system, geothermal utilization system, metal precipitation system, and production auxiliary system. ① The leaching solution and bacterial strain preparation system ensures sufficient leaching production operation process. The main process steps are summarized:
– Preliminary exploration and experimentation: ① determine the area of the ore body, drill injection wells and production wells, ② inject the leaching solution and leaching bacteria used in the experiment. After the leaching solution fully reacts with the ore body, extract the rich solution containing metal ions and thermal energy to the surface, and analyze the leaching and thermal energy replacement effects, ③ repeat process ② to eliminate errors, and ④ based on reliable results obtained from multiple experiments, conduct early pre feasibility and feasibility studies to develop reliable solutions for later industrial production.
– Production system construction: The production system includes leaching solution and bacterial preparation system, drilling and pipe line transportation system, geothermal utilization system, metal precipitation system, and production auxiliary system: ① The leaching solution and strain preparation system ensures the provision of sufficient parameters such as leaching solution temperature and mineral leaching rate, by treating a series of leaching solutions and leaching bacteria, and recycling the lean solution without metal ions, ② the

drilling and pipe line transportation system ensures that the leaching solution can reach the ore body and there is no leakage during the liquid transportation process, ③ the geothermal utilization system is used to extract thermal energy from the solution, which can be achieved by constructing high efficiency heat pipe components, high efficiency heat pump components, or a mixture of the two, ④ the metal precipitation system is used to extract metal ions from the rich solution, and ⑤ the production auxiliary system is used to ensure the smooth operation of various systems, including system modules such as power system, hydraulic system, monitoring system*, etc.*

– Production and operation process: ① Use blasting or Fracking in the well to create pores and fissures, expand the contact area and path between solution and ore, and provide a preparatory environment for efficient leaching, ② transport the prepared leaching solution and bacterial strains to the ore body through pipe lines, and adjust the real-time monitoring parameters through the production auxiliary system temperature monitoring module to ensure the good operation of the leaching process, ③ the high temperature and high metal concentration leaching solution is extracted through a production well. Firstly, its thermal energy is extracted through a geothermal utilization system, and then mineral components are extracted through a metal precipitation system. Finally, the lean solution is transported to the leaching solution and bacterial preparation system, and after concentration and purification, it is stored and used continuously, ④ repeat steps ② and ③.

Model establishment and field collaboration methods

Numerical simulations were conducted to investigate the flow and heat transfer characteristics of supports spaced between smooth tube bundles of 19 mm × 1.5 mm. The vortex plate is made by twisting a short metal plate through a certain angle, and the defined angle of twisting is the rotation angle α, torsion $Y = p/b$ (where b is the width of the swirl plate and p is the pitch), as shown in fig. 3. Two types of swirl plates α 180 ° and 270 °, respectively, with Y being 2.0 and 4.25, named 180-2.0 and 270-4.25. The longitudinal flow tube shell heat exchanger used in industrial applications has a larger shell diameter, and the heat exchange tube lay-out area accounts for the majority of the shell. The flow and heat transfer of the shell side fluid mainly occur in the lay-out area. In addition, longitudinal flow heat exchangers generally use square lay-out pipes, and based on symmetry, four heat exchange tubes are taken to form a *unit flow* channel. For large shell side longitudinal flow heat exchangers, most areas are in the fully developed stage of flow and heat transfer, and the fluid-flows axially through multiple inter tube supports, exhibiting periodic and fully developed flow. Therefore, in 3-D numerical calculations, the *periodic unit flow channel* is used as the calculation area, with a unit flow channel length of 525 mm and a pipe center distance of 25 mm.

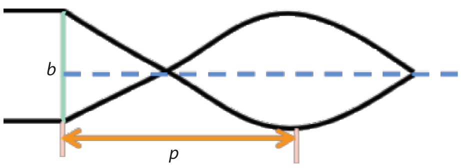

Figure 3. Swirl plate

Although the field synergy principle of convective heat transfer was originally proposed for steady 2-D laminar oundary-layer flow, it has been extended to turbulent flow through extensive empirical research. The 3-D field synergy relationship equation:

$$\frac{\text{Nu}}{\text{Re}\,\text{Pr}} = 0.25\iiint_{\Omega} \bar{U}\nabla\bar{T}\,\text{d}\bar{V} \tag{1}$$

$$\bar{U}\nabla\bar{T} = \left|\bar{U}\right|\left|\nabla\bar{T}\right|\cos\theta \tag{2}$$

The synergy angle θ is the angle between $\bar{U}$ and $\nabla\bar{T}$, and the local average synergy angle θ_{m} adopts the integral median angle:

$$\theta_{\mathrm{m}} = \arccos\frac{\sum\left|\bar{U}\right|\cdot\left|\nabla\bar{T}\right|\cos\theta_k \mathrm{d}V}{\sum\left|\bar{U}\right|\cdot\left|\nabla\bar{T}\right|\mathrm{d}V} \tag{3}$$

The subscript k represents the local location of the calculation area and m represents the average of a certain area.

Mathematical models and numerical methods

Simplify and assume the model as: ① the fluid is a steady-state flow with constant physical properties and no internal heat source, ② the fluid is incompressible, ③ both flow and heat transfer have been fully developed, and ④ regardless of the increase in heat transfer area caused by the support [9]. According to the periodic unit channel model, the general control equations of mass, momentum and energy of single-phase incompressible fluid steady flow:

$$\mathrm{div}\left(\rho U \Phi\right) - \mathrm{div}\left(\Gamma_{\Phi} \mathrm{grad}\Phi\right) = 0 \tag{4}$$

where ρ is the density, U – the fluid velocity vector, Φ – the general variable, and Γ_{Φ} – the generalized diffusion coefficient. Periodic full development refers to the periodic variation of flow and heat transfer characteristics in the mainstream direction with the geometric period of the flow channel. If the length of a geometric period in the flow channel is S, then there is a relationship between velocity U, periodic pressure drop Δp, and 1-D temperature Φ:

$$U\left(\vec{\mathrm{r}}\right) = U\left(\vec{\mathrm{r}} + S\right) = U\left(\vec{\mathrm{r}} + 2S\right) = ... \tag{5}$$

$$p\left(\vec{\mathrm{r}}\right) - p\left(\vec{\mathrm{r}} + S\right) = p\left(\vec{\mathrm{r}} + S\right) - p\left(\vec{\mathrm{r}} + 2S\right) = ... \tag{6}$$

$$\Phi\left(\vec{\mathrm{r}}\right) = \Phi\left(\vec{\mathrm{r}} + S\right) - \Phi\left(\vec{\mathrm{r}} + 2S\right) = ... \tag{7}$$

Boundary conditions: ① the pipe wall and support wall surface meet the non-slip boundary condition, ② during the experiment, the constant wall temperature condition of the heating tube wall was ensured, so the tube wall is a constant wall temperature boundary condition, and the inter tube plane of the unit flow channel is a symmetric boundary, and ③ the heated fluid in the flow channel is air, and the inlet and outlet adopt periodic boundaries. The grid division adopts a split grid and densifies the swirling area downstream of the wall and swirling plate, the distance between the grid nodes near the wall surface and the 1-D, Y^+, is controlled between 1-5. Since the renormalization (RNG) κ-ε two equation turbulence model can more effectively predict the effects of transient flow and streamline curvature than the standard κ-ε model, the RNG κ-ε model is used for the turbulence model, SIMPLEC algorithm is used for pressure and velocity coupling, and the enhanced wall treatment method is used for the wall treatment.

Calculation results and analysis of field synergy principle

Comparison of heat transfer performance

Figure 4 compares the average Nusselt number of the unit flow channel walls of the swirl plate and the hollow ring under different Reynolds number conditions. The swirl plate and the hollow ring support have both enhanced the heat transfer between the tube bundles, and the strengthening effect increases with the increase of Reynolds number. The Nusselt number of the hollow ring is higher than that of the unsupported material, but the heat transfer enhancement effect is weaker than that of the vortex plate, and this difference gradually increases with the increase of Reynolds number. The heat transfer enhancement effect of the 270-4.25 vortex plate is better than that of the 180-2.0 vortex plate.

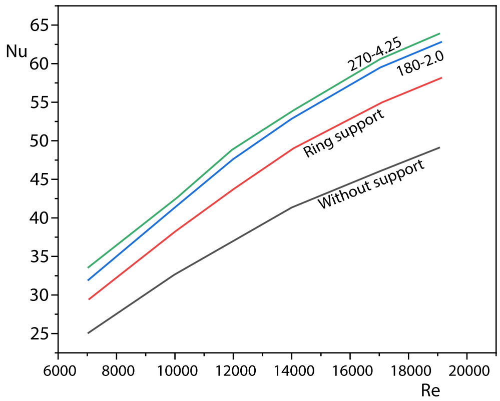

Figure 4. Comparison of Nusselt numbers

Correspondence between the average Nusselt number, Nu_b, and the average synergy angle, θ_m, of the cross-section

Figures 5 and 6 show the local average Nusselt number on the cross-section, Nu_b.

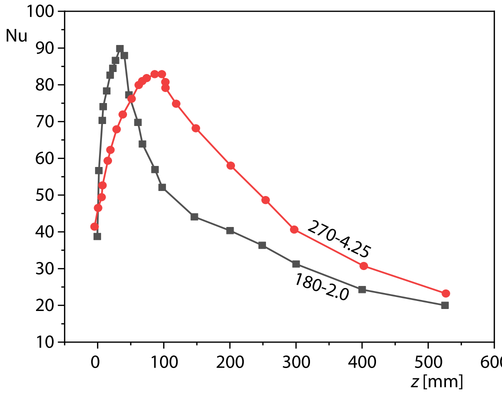

Figure 5. Distribution of Nu_b along the *z*-axis

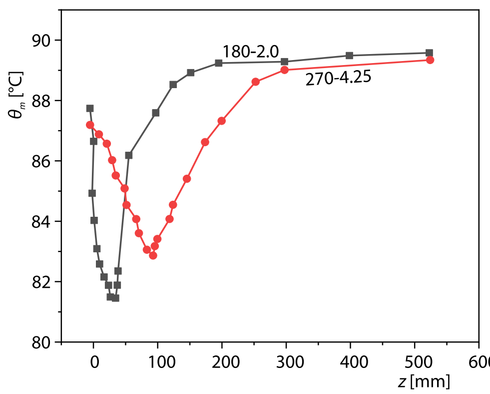

Figure 6. Corresponding change trend of average synergy angle θ_m

The variation pattern of the average synergy angle of θ_m along the flow direction. From fig. 5, it can be seen that, Nu_b is higher in the area with swirling blades and exhibits a maximum value. Due to the large degree of distortion of the 180-2.0 vortex plate, the increase in Nusselt number is faster than that of the 270-4.25 vortex plate. After leaving the swirl plate, the Nusselt number of both types of swirl plates gradually decreases, but the reduction speed of Nu_b in the 270-4.25 swirl plate is slower than that in the 180-2.0 swirl plate [10]. This is because the former has a smaller torsion ratio and the heat transfer enhancement effect of swirl is gradually enhanced, so the attenuation of spin flow will also be slow. Therefore, the 270-4.25 vortex plate can more fully utilize the enhanced heat transfer effect of spin flow, and the overall average Nusselt number is higher than 180-2.0, which is consistent with the experimental results. The variation pattern of the average synergy angle in fig. 6 is exactly opposite to the variation pattern of Nusselt number, that is, where Nu_b is high, θ_m is low, and where Nu_b is low, θ_m it is high, indicating that the variation trend of the two completely conforms to the principle of field synergy.

Conclusion

Marching deeper into the Earth is an important instruction from the Secretary and also the necessary path for metal mineral mining conducting in-situ fluidized mining of deep metal mines is a disruptive mining technology based on leaching solution as the medium, providing new ideas for deep resource mining. Geothermal energy, as a renewable and clean energy source, has broad application prospects. Based on the energy conversion of deep geothermal fluid, the author innovatively explores the concept of strengthening the fluidization leaching process and geothermal collaborative mining process. From the perspectives of fluidization of dense solid minerals, intelligent perception of deep resources, seepage control of solution, and energy exchange of deep geothermal fluid, the author proposes the difficulties and potential breakthroughs faced by the development of this process, through the analysis of the principle of field synergy, it was found that the fundamental mechanism of enhancing heat transfer by swirling fins is the effective improvement of the synergistic effect between velocity and temperature fields.

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