36th Annual International Pittsburgh Coal Conference

Research Progress in Dry Beneficiation

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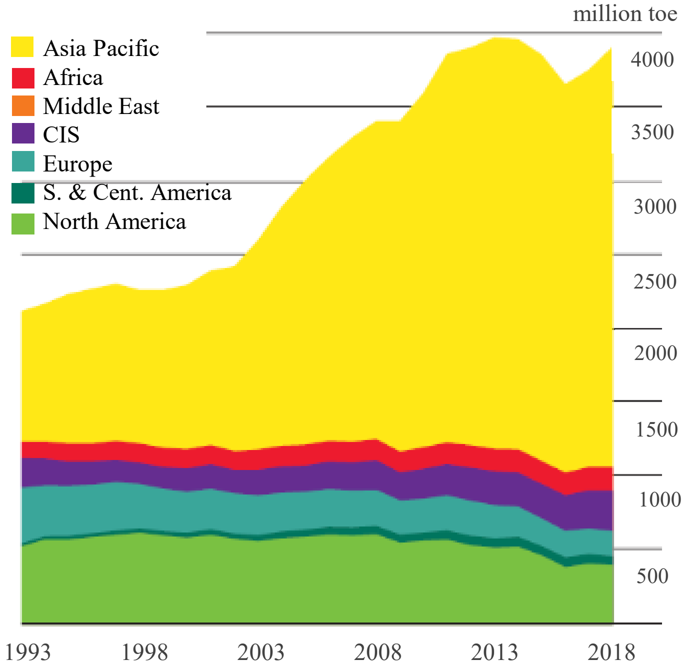
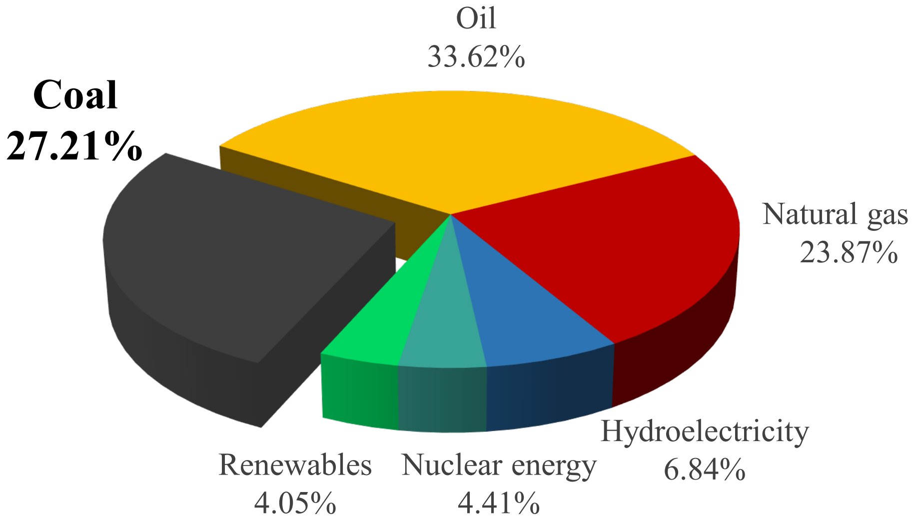
1. Technical background

Global primary energy

- In 2018, world coal production was 3.92 billion toe, which increased of 4.3%.
- Coal consumption was 3.77 billion toe, which increased of 1.4%, accounting for 27.2% of the world's primary energy consumption.



Coal production around the world (1993-2018)

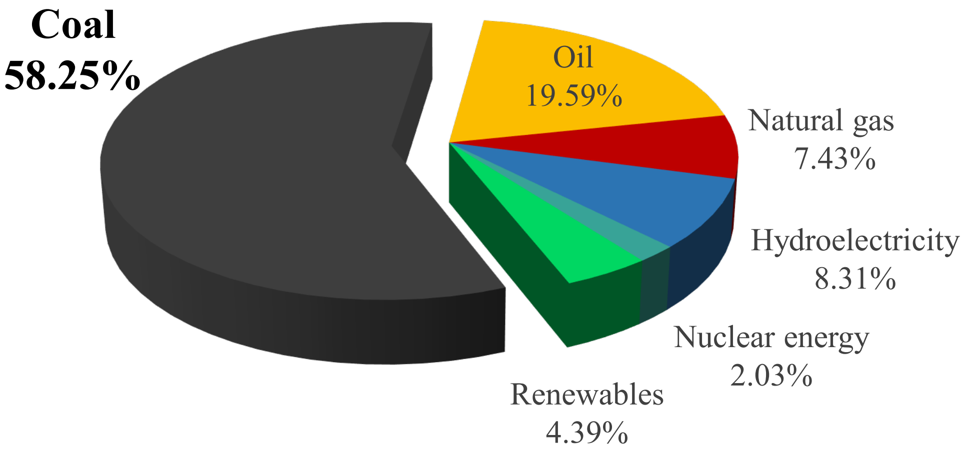


Primary energy consumption structure in 2018

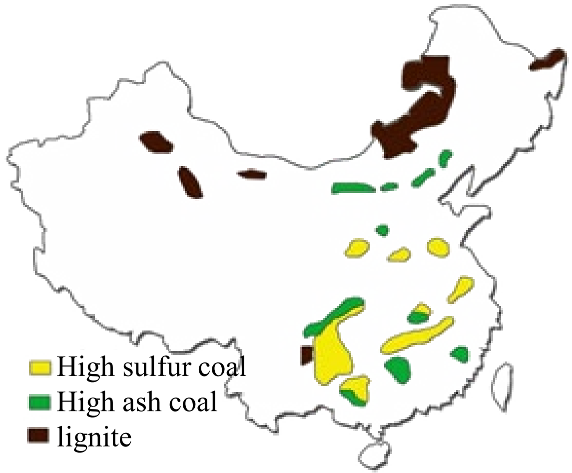
BP Statistical Review of World Energy 2019

Coal is the main energy source in China

- In 2018, China's coal production was 1.829 billion toe, accounting for 46.69% of the world's coal production.
- China's coal consumption was 1.907 billion toe, accounting for 58.25% of China's primary energy consumption, accounting for 50.55% of the world's coal consumption.



Energy consumption structure in China



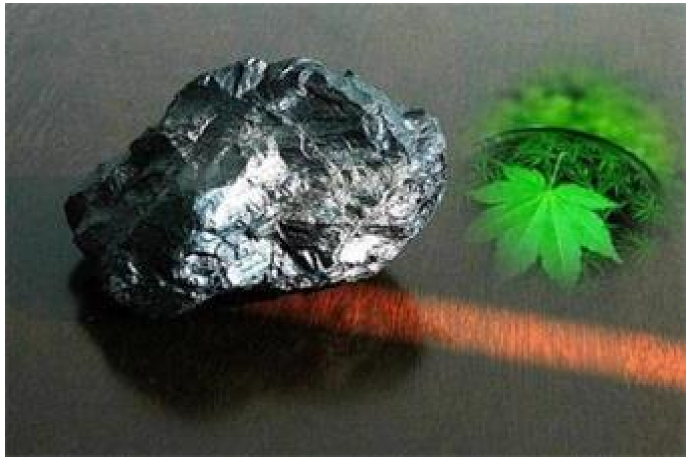
Distribution of low-quality coal

☐ Coal preparation is the source of clean coal technology

Significance of coal preparation:

- **Remove impurities such as ash and sulfur from coal effectively.**
- **Improve quality.**
- **Promote clean utilization of coal.**

✓ Coal preparation provides clean raw materials for electric power, metallurgy, chemical industry and other fields.



☐ Development of coal preparation industry in China

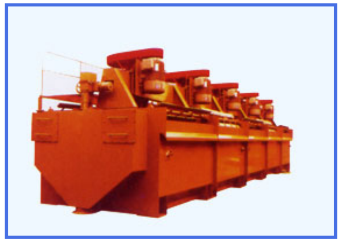
- The **raw coal selection rate has reached 71.8%.**
- The number of coal preparation plants has reached more than 2300.
- New technologies, new equipment and new processes.

Dense medium cyclone (Max Φ=1600mm)

Shallow groove separator(Max B=7925mm)

Coarse slime separator (Φ=3.65m)

Jigger (B=5000mm+)



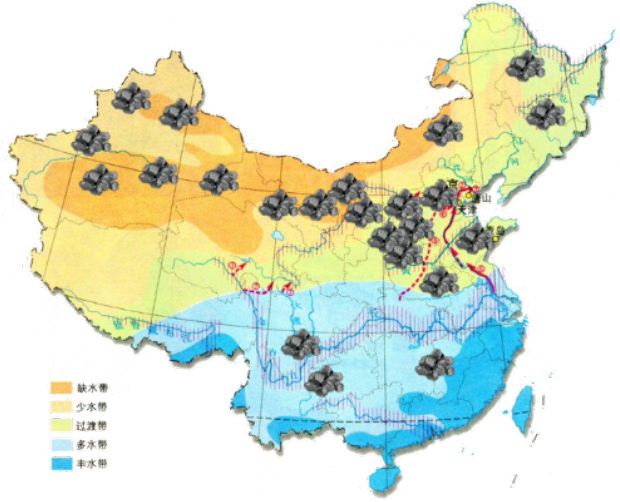
Flotation machine (Max=120m³)

Cyclonic micro-bubble flotation column separation (Max Φ=5500mm)

☐ Importance of dry coal preparation technology

- Coal preparation is mainly wet process, which needs to consume a large amount of water resources.
- More than 2/3 of coal is distributed in drought and water-scarce areas in Western China.

There is an urgent demand for efficient dry coal preparation technology



Distribution of coal and water resources in china

Drought and water-scarce areas

☐ Main dry coal preparation technology

Technical name	Feed particle-size	Separation effects
Compound dry separation	< 80mm	Quantitative efficiency > 90%
Wind jigging/shaking table	75-6 mm	E > 0.20 g/cm^3
Air dense medium fluidized bed	80-6 mm	E = 0.05-0.08 g/cm^3
Photoelectric separation	300-25 mm	Rate of discharging refuse > 90%
Fluidized bed with external force field	6-0.5 mm	E = 0.06-0.10g/cm^3
Triboelectric separation	< 1 mm	The recovery rate of combustible matter > 70%

2. Current technical status of dry coal preparation

1. Dry coal preparation technology of air dense medium fluidized bed

Separation medium

Wet process: Water → Water + Dense medium

Dry process: Air → Air + Coal fines → Air + Dense medium

Air → Traditional dry coal preparation

Air + Dense medium → Air dense medium fluidized bed

◆ **The gas-solid separation system is unstable and it is difficult to achieve accurate separation of coal in limited space and time.**

- Under the action of compressed air, a gas-solid fluidized bed with even and stable density is formed in the air-dense medium fluidized bed with magnetite powder and pulverized coal as the aggravating substance. Coal is separated by density.

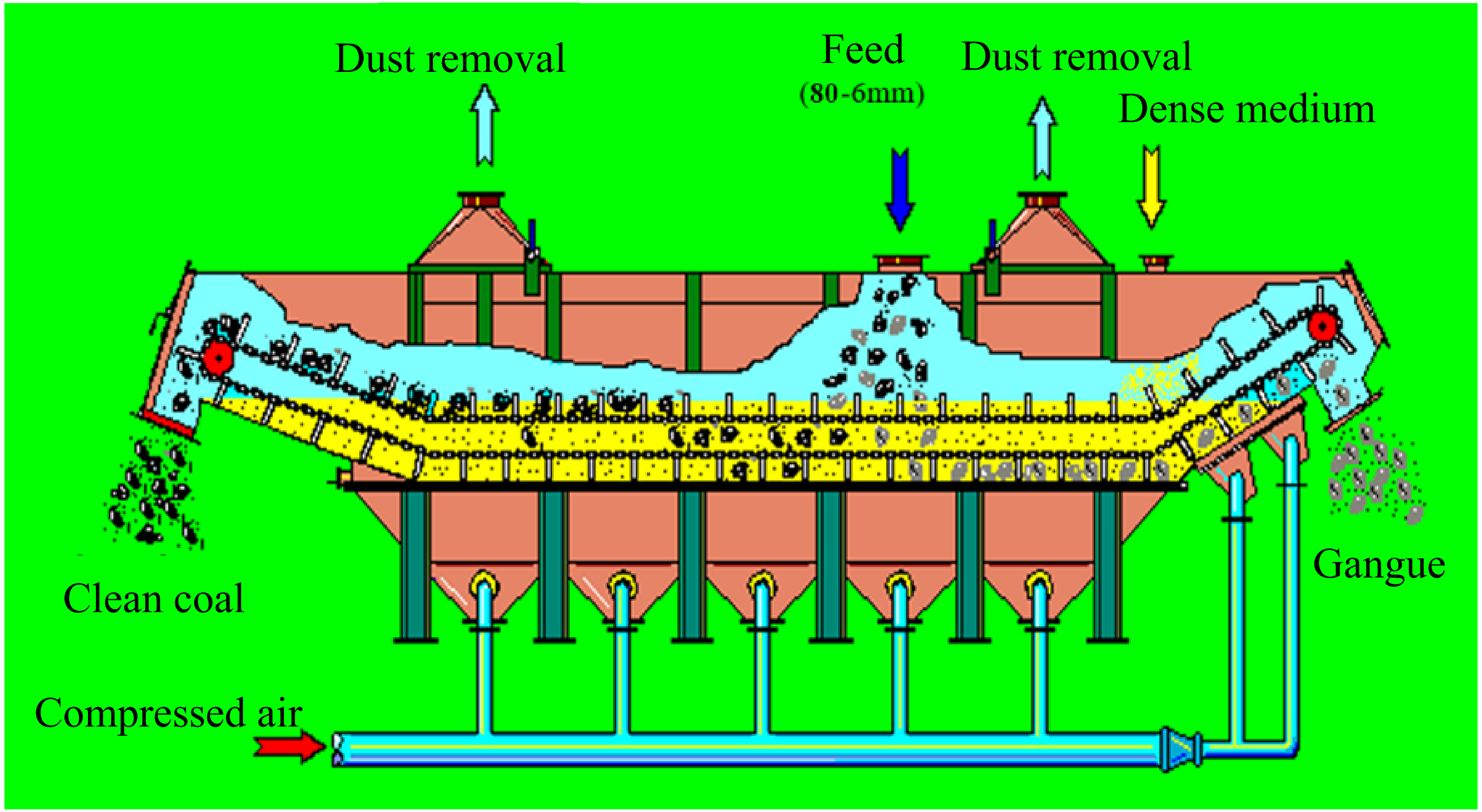


Diagram of dry separation in air dense medium fluidized bed

▼Key technical problems

- Even stability of bed density;
- The low viscosity and high fluidity bed medium;
- Wear resistance and blockage resistance of air distributor;
- The adjustability of medium solids gradation and bed density.
- Structural parameters optimization of new generation separator;
- Reliability of modular dry dense medium coal preparation system.

Bubbling fluidized bed
Agglomeration, large bubble, unstable bed, serious particle backmixing

Separation fluidized bed
Quasi-dispersive, microbubbles, stable bed, even particle dispersion

1.1 The dry separation theory of gas-solid fluidization

▼Steady state regulation of dense phase separation fluidized bed

- A theory of two-stage air distribution with high pressure and low fluidization number was put forward.

$$C_P = (\Delta P_D^2 + \Delta P_B^2)/[(\Delta P_D + \boxed{\Delta P_B})\boxed{\Delta P_D}]$$

Pressure drop of air distributor

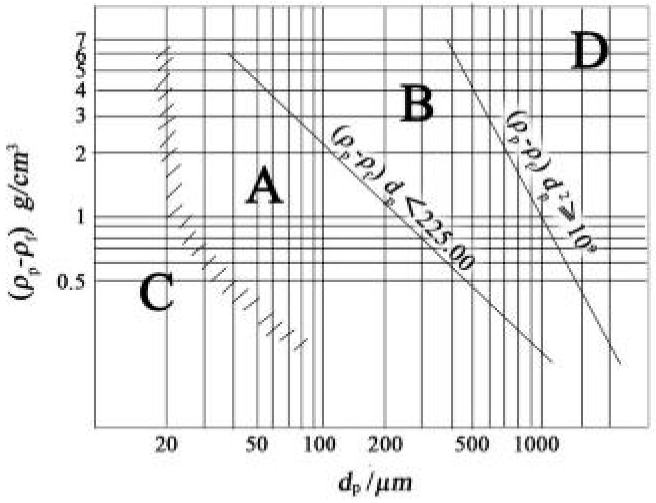
Pressure drop of bed

- A calculation model of critical fluidized state equation was established.

  - **Equation of critical fluidization:**

$$\mathrm{Re}'_{mf} = [-C_1 + (C_1^2 + C_2 Ar)^{0.5}]/[1-\exp(-13.775\Delta P^{-0.2945})]$$

$$C_1 = 42.86(1-\varepsilon_{mf})/\psi \qquad C_2 = 0.5714\psi\varepsilon_{mf}^3$$

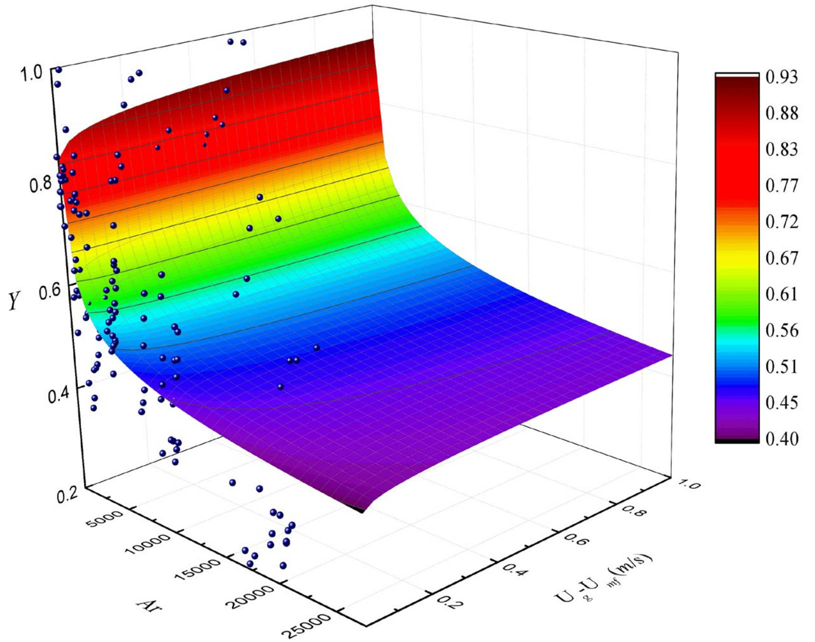


Geldart particle classification diagram

- A computational correlation of the two-phase theoretical correction parameters were constructed. The Geldart Class B particle fluidization two-phase theory was calibration corrected.

- **Correction parameters of gas-solid two-phase theory :**

$$Y = 0.9286\frac{H - H_{mf}}{H}\left[\frac{(H + 4A_D^{0.5})^{1.4} - (4A_D^{0.5})^{1.4}}{H(U_g - U_{mf})^{0.8}} + 1\right]$$



Gas-solid two-phase theory correction parameter fitting

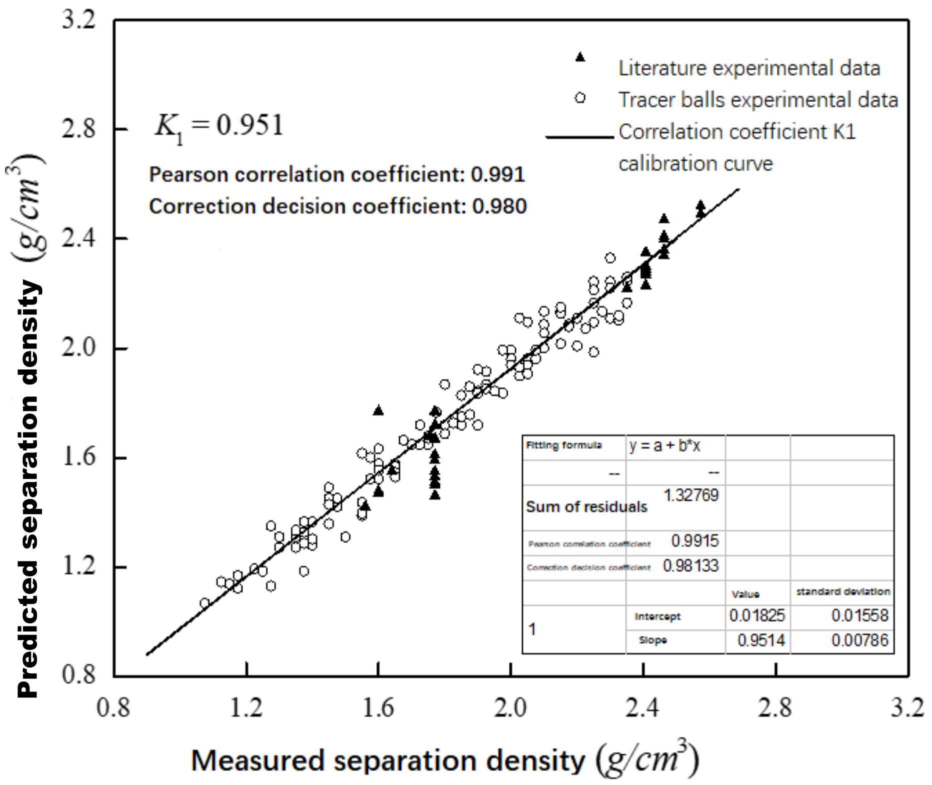
● Prediction model for separation density of fluidized bed was established.

- **Model for density axial distribution :**

$$\overline{\rho}_{\text{bed}} = (1-\varepsilon_{mf})(\rho_p - \rho_g)\times \left(1-\frac{Y}{1+1.3(h+4A_D^{0.5})(U_g-U_{mf})^{-0.8}}\right)+\rho_g$$

- **Prediction model for separation density :**

$$\rho_{\text{sep}} = K_1\left[(1-\varepsilon_{mf})(\rho_p-\rho_g)\left(1-\frac{Y}{1+1.3(H/2+4A_D^{0.5})(U_g-U_{mf})^{-0.8}}\right)+\rho_g\right] + K_2\left[18\mu_f U_g\left(1+\frac{3}{16}d_p\rho_f U_g/\mu_f\right)^{0.5}/gd_p^2\right]$$



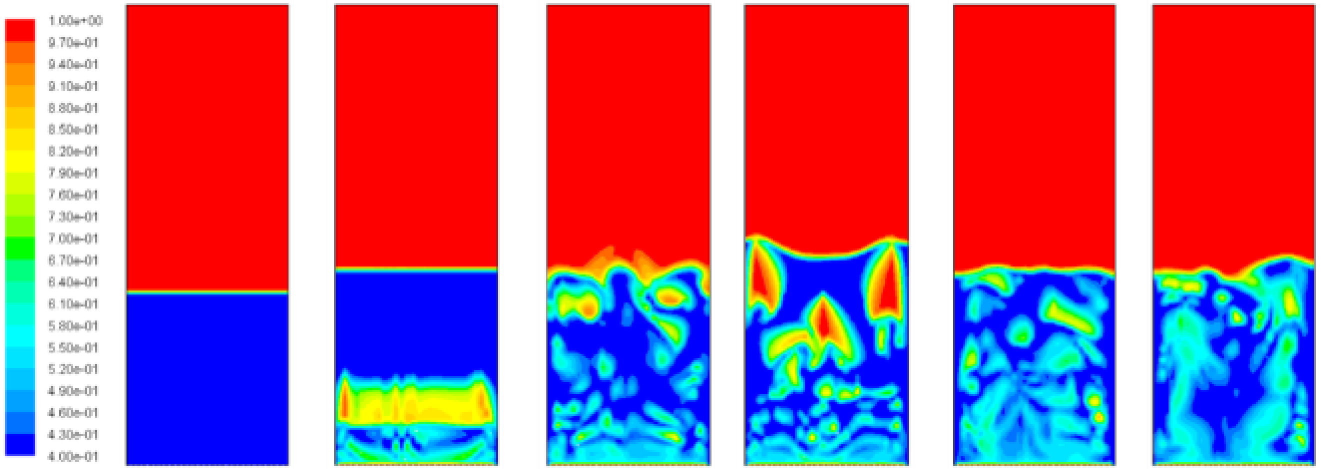
Calibration of the correlation coefficient K_1 of the separation density model

▼Numerical simulation and multi-scale analysis of gas-solid fluidized bed

- The calculation model of bubble size was established based on the Euler-Euler model.

- **Gas-solid drag coefficient:**

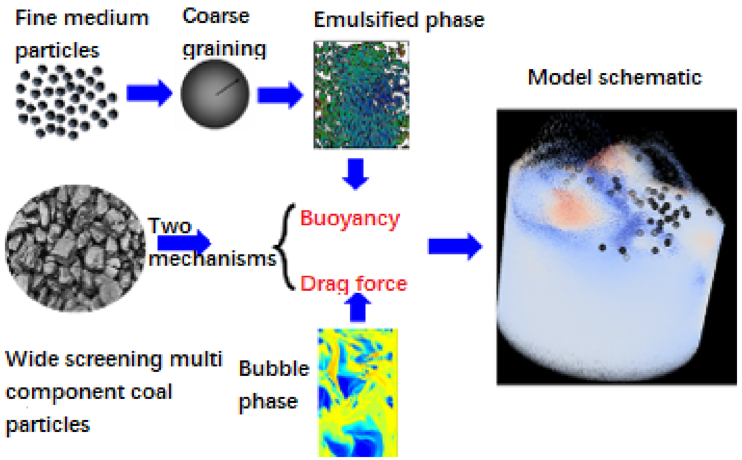
$$\beta_{gi}=150\frac{(1-\varepsilon_g)\varepsilon_i\mu_g}{\varepsilon_g(d_i\phi_i)^2}+1.75\frac{\rho_g\left|\vec{u}_g-\vec{u}_i\right|\varepsilon_i}{d_i\phi_i}\quad \varepsilon_s>0.05\qquad \beta_{gi}=\frac{3}{4}C_d\frac{\varepsilon_g\left|\vec{u}_g-\vec{u}_i\right|\rho_g(1-\varepsilon_g)}{d_i}f(\varepsilon_g)\quad \varepsilon_s\le 0.95$$

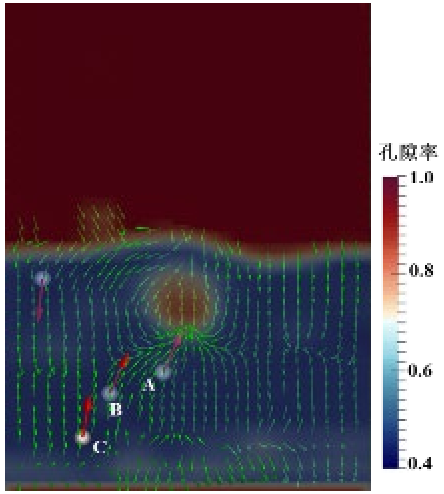


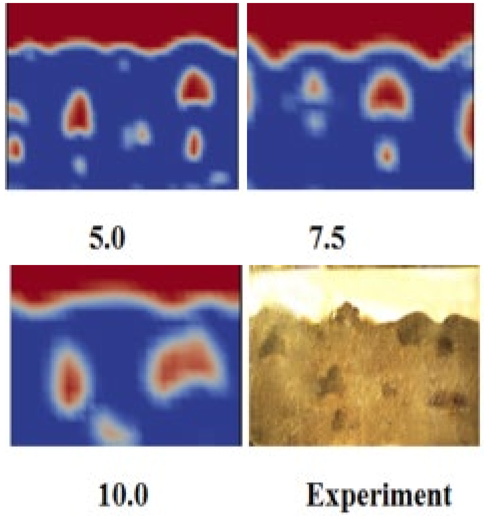
Bubble movement in separation fluidized bed

● The coarse fraction discrete model was used to numerically simulate the dense-phase gas-solid fluidization process.

● The EMMS-DPM-DEM multi-scale numerical model was established to simulate the coal separating process.







EMMS-DPM-DEM model coupling diagram　Bubble-particle interaction　Bubble evolution

A dense-phase and high-density gas-solid separation fluidized bed has been formed, which revealed the mechanism of coal separation by density steps distribution and provides theoretical support for efficient dry coal separation.

1.2 New generation of dry dense medium fluidized bed separator

- **Adjustment range of separation density 1.2-2.2g/cm^3.**
- **Separation accuracy E = 0.05-0.08.**
- **Quantity efficiency > 90%.**

Key technology innovation：

- Assembled wear-resistant anti-blocking air distribution technology
- Dense medium internal circulation
- Grading technology of binary medium solids with a wide size range
- Independent double drive discharging method

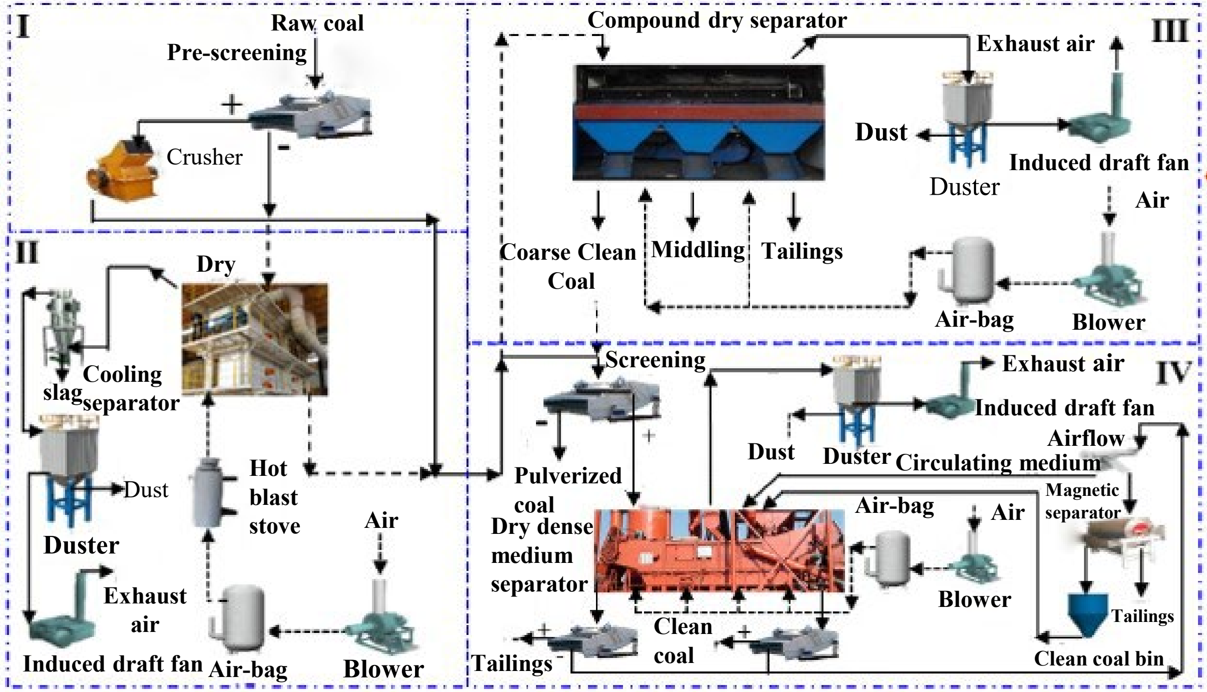
1.3 Modular high-efficiency dry coal preparation process system

The dry coal preparation process system is composed of four modules as below.

- (I) Raw coal preparation module
- (III) Roughing module and quality improvement module
- (II) Moisture control module
- (IV) Choiceness module

Raw coal preparation

Moisture control



Roughing and quality improvement

Choiceness processing

Modular dry coal preparation technology

- A series of high-efficiency dry coal preparation equipment, such as steady-state control of medium circulation and medium purification and recovery, have been developed.

- A modular and efficient dry coal preparation system was established for raw coal preparation, drying, separation, medium purification and recovery, density steady-state control, air supply and dust removal, product transportation and integrated assembly.

Modular high efficiency dry coal preparation system

- In 2014, **the world's first modular dry dense medium fluidized bed coal preparation plant was built.**
- **Advantages of modular high efficiency dry coal preparation technology:**

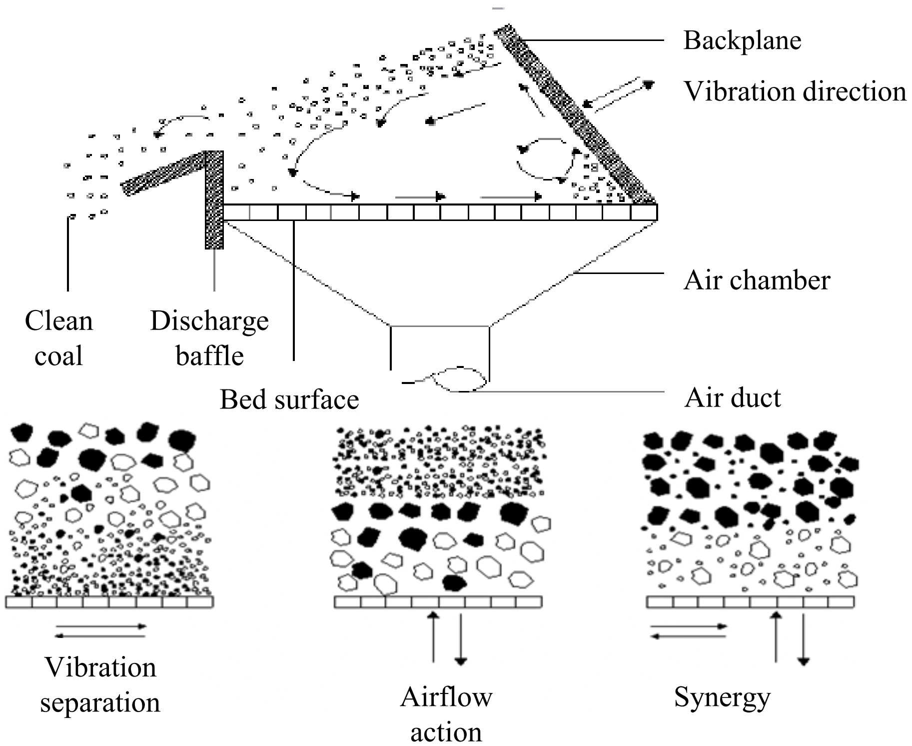
- No use of water high
- Low energy consumption
- Separation accuracy
- Strong adaptability
- Simple process
- No environmental pollution

Parameters	Index
Processing Capacity, t/h	40-60
Feed Size, mm	6-100
Separation Accuracy, g/cm^3	0.05-0.08
Separation Density, g/cm^3	1.3-2.2
Quantitative Efficiency, %	>90
Medium Consumption, kg/t	<1
Power Consumption, kw·h/t	1.5-3.5

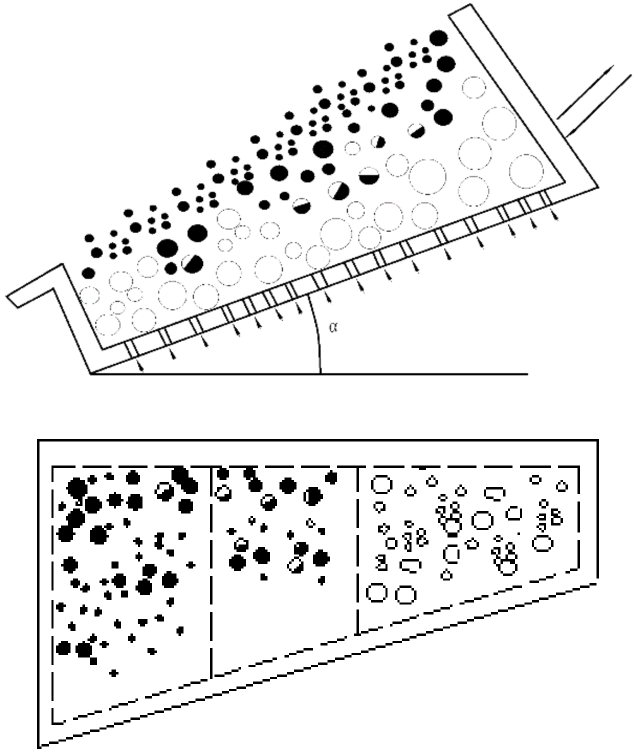
2. Large compound dry separation technology

Synergistic effects
- Vibration
- Air drag
- Autogenous medium
- Buoyancy effect

→ **Realize the separation according to density**



Schematic diagram of particle motion



Particle distribution on the surface of bed

- The strengthening method of separation process was put forward, which improved the separation accuracy of fine coal and reduced the lower limit of separation particle size.

Force model of coal particle:

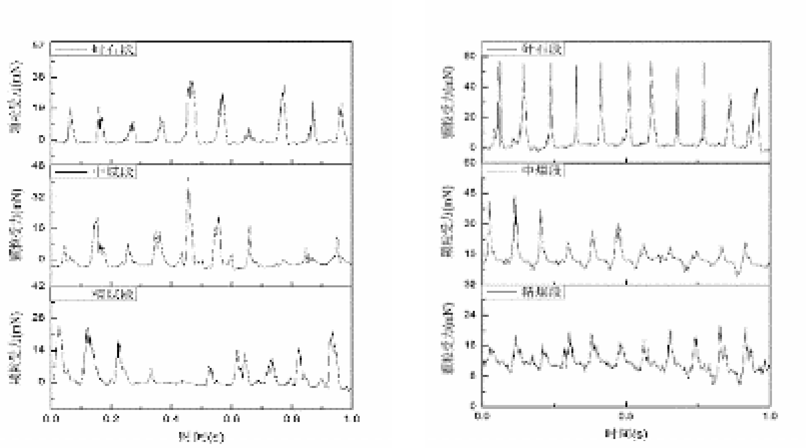
$$F_x = C_D d^2 (v_{in} - v_x)^2 \rho_{in} - mg \sin\beta - \mu\left(mg\cos\beta - \rho_g \frac{\pi}{6} d^3 g - \frac{\pi}{8} C_D d_e^2 \rho_f (U - v)^2\right)$$

$$F_y = \left(\frac{1}{8}\pi C_D d_e^2 \rho_f (U - v)^2 - \frac{1}{6}\pi d_e^3 \rho_g g\right)\sin a + \lambda \rho_e g V_e \omega^2 f \sin\phi - \tan\phi F_S$$

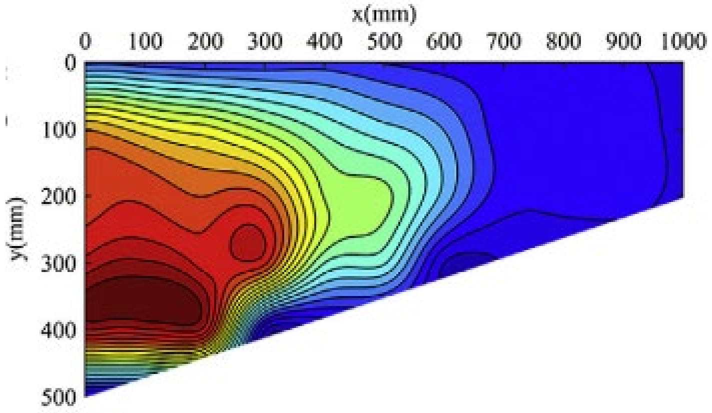
$$F_z = \left(\frac{1}{8}\pi C_D d_e^2 \rho_f (U - v)^2 - \frac{1}{6}\pi d_e^3 \rho_g g\right)\cos a - \tan\phi F_S$$

Dissipation model of energy in the bed:

$$Q_{\mathrm{d}} = \left(\frac{2}{\pi}\right)^{1/2} \frac{6}{\pi d^3} \frac{\eta(1+\eta+\eta^2-\eta^3)}{(1-\eta^3)} T \frac{2\overline{V}^2}{T/m + \overline{V}^2}$$

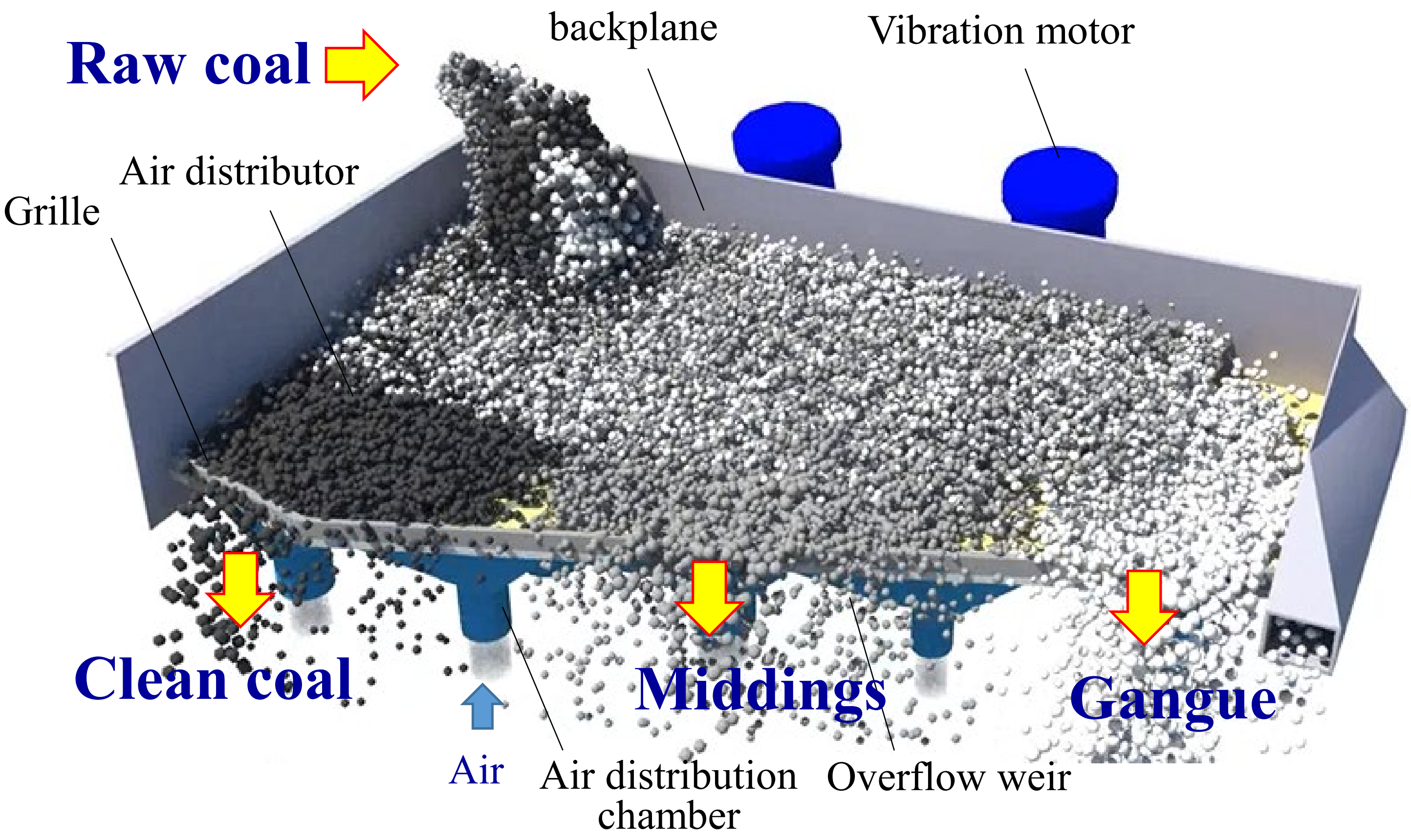


Force on coal particles in separation bed



Coal particle density distribution in separation bed

- **The regulation mechanism of air volume and pressure was put forward, and stable ladder-like distribution air distribution on large bed was realized.**



Structure and separation process of compound dry separator

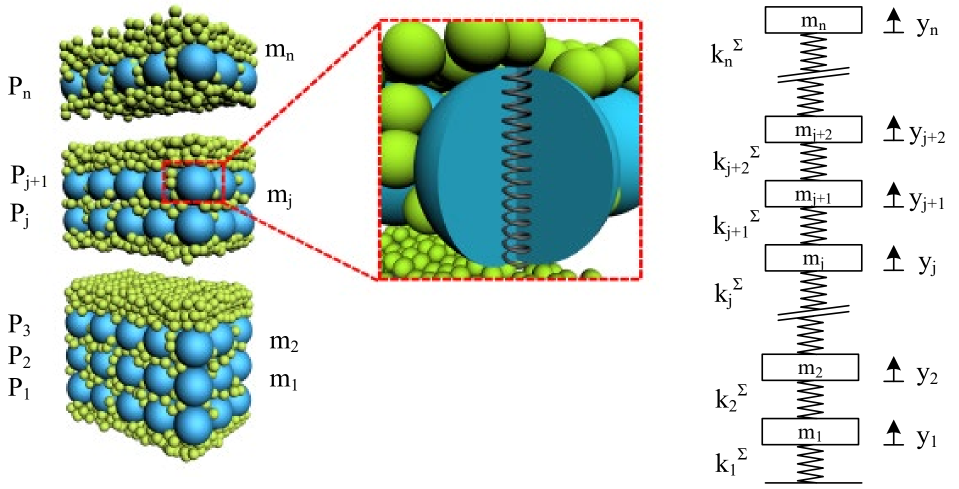
- **A large-scale compound dry separation machine with the processing capacity of 480-600 t/h and quantity efficiency higher than 90% has been developed. The large-scale dry separation and upgrading of coal has been realized.**

Parameters	Index
Processing Capacity, t/h	480-600
Quantity efficiency, %	> 90

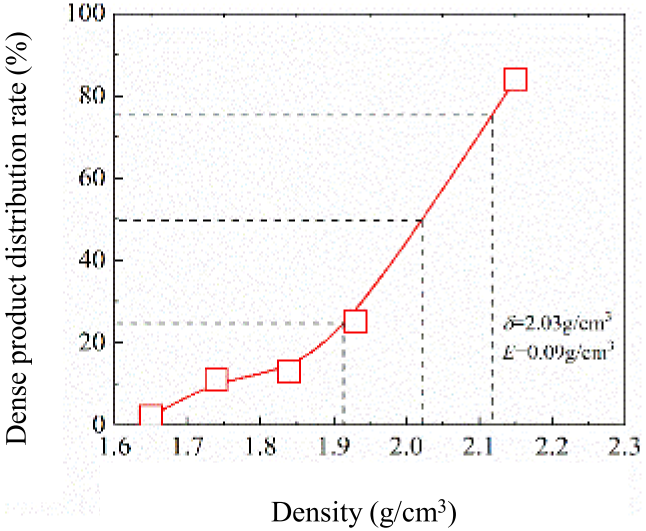
3. Theory and technology of dry separation of fine coal

3.1 Vibrated fluidized bed dry coal preparation technology

- The vibration energy of the gas flow is introduced into the dense phase separation fluidized bed.
- The transfer model of the vibration energy in the separation fluidized bed was constructed.



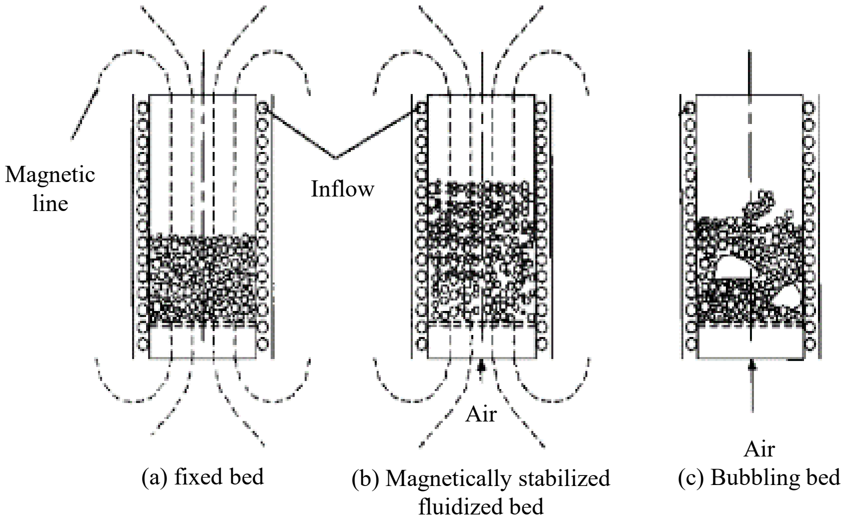
Multi-degree-of-freedom vibration system of bubble-particle interaction



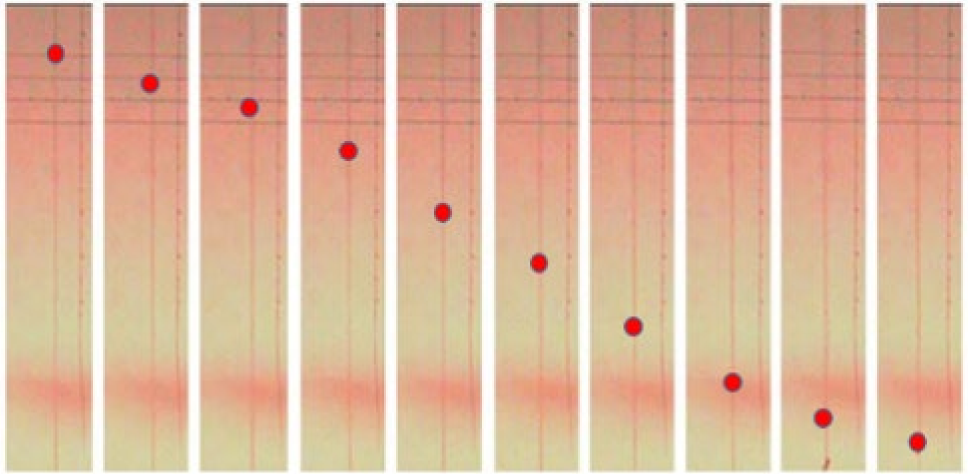
6-1mm coal distribution curve

3.2 Magnetic fluidized bed dry separation technology

- Fluidized particles are aligned along the magnetic force line by introducing magnetic field into the air dense medium fluidized bed.
- The possible error E is between 0.063-0.095 g/cm^3.



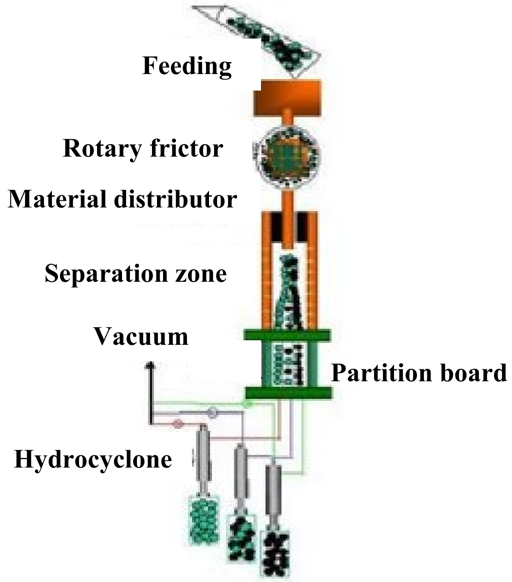
Particularization mechanism of magnetically stabilized fluidized bed



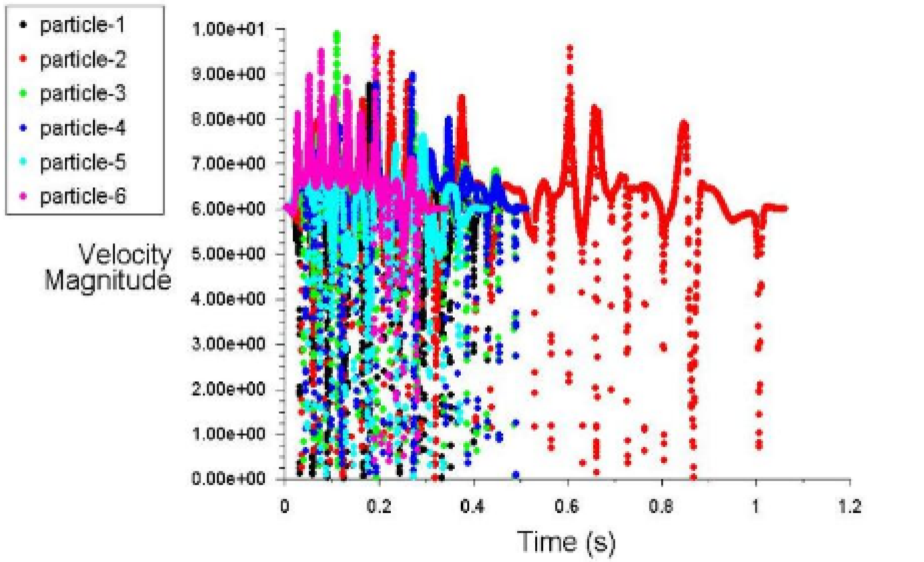
Free dropping of particles in a fluidized bed with a magnetic field

3.3 Triboelectronic separation technology

Size fraction	1-0.3mm	-0.3mm
Ash removal rates , %	96.07	81.96
Desulfurization rates , %	90.64	71.90



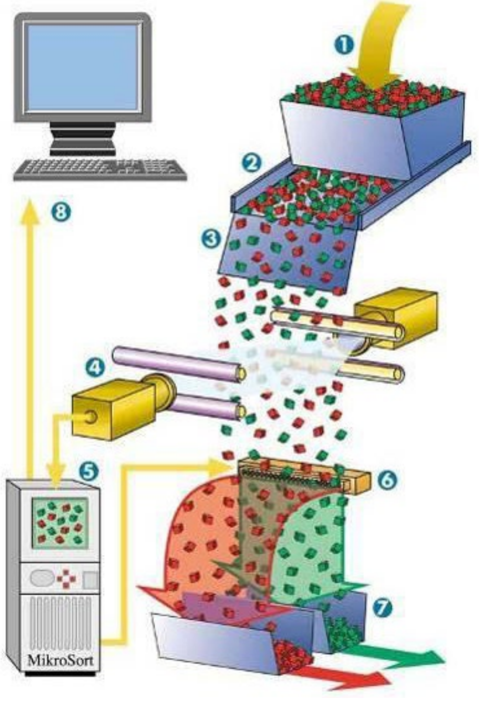
Tribological electric separation test system for micro-pulverized coal



Change rule of particle velocity in separation process

4. Photoelectric dry separation technology

- Photoelectric separation: coal separation is carried out by using different materials under different wavelength light source irradiation (γ-ray, X-ray, ultraviolet, visible, infrared), with different reflection, transmission, scattering, fluorescence and other characteristics.



Even feeding

1

Intelligent recognition

2

Precise separation

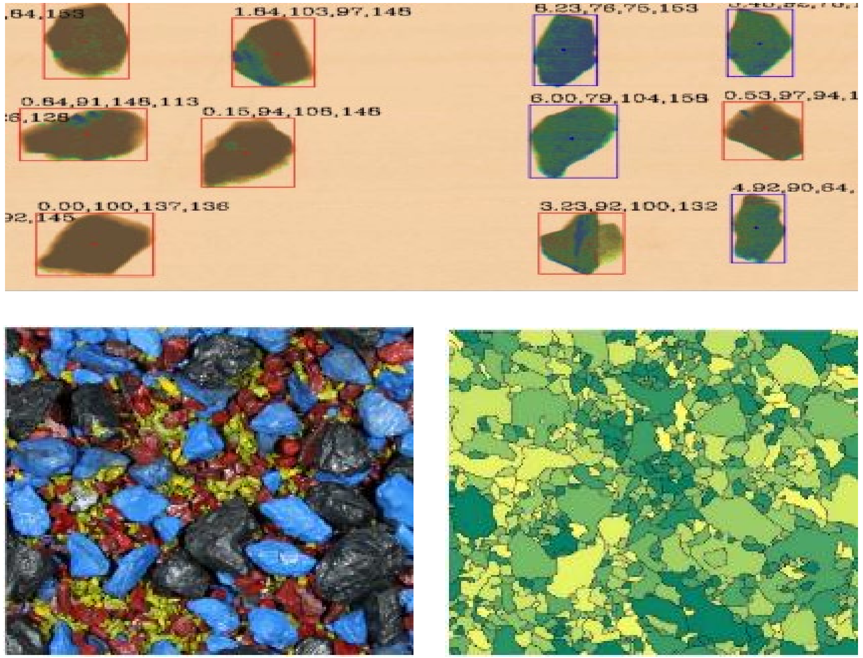
3

Photoelectric separation process

Recognition mode

X(γ) ray recognition: Difference of attenuation degree of different components of coal to ray

Color gloss recognition: Difference of surface color, gloss and texture

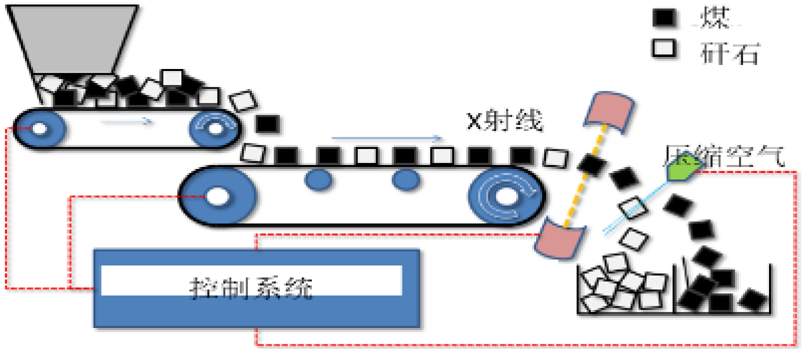


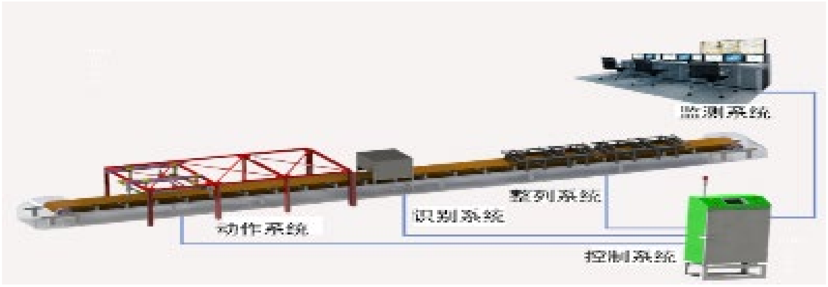
Ray and image recognition

Mode of implementation

Air Jet: Air Jet is produced by high frequency solenoid valve to blow out gangue.

Manipulator: Used to simulate manual picking to pick out the identified gangue.





Air jet and manipulator separation

- **The photoelectric separation technology can be used for discharging gangue from 300-25mm lump coal with a maximum capacity of 380 t/h.**

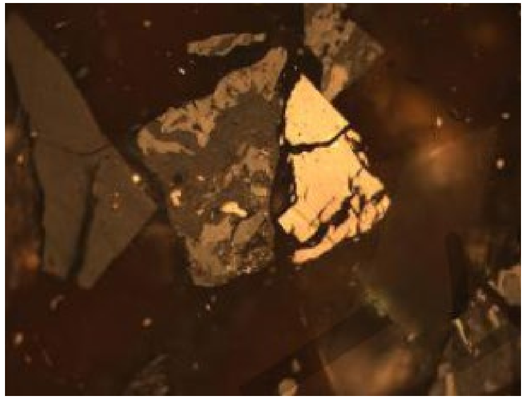
TDS separator

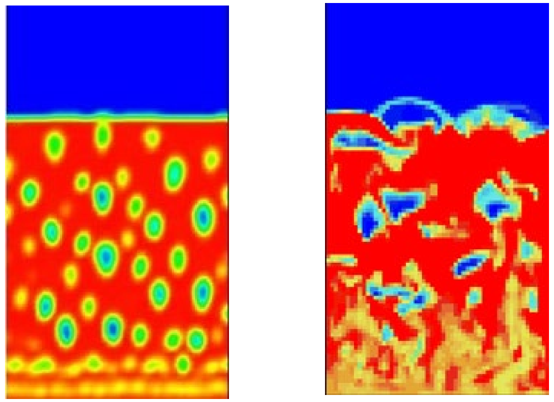
GDRT separation system

3. Development trend of dry coal preparation

1. Developing precision dry coal separation technology

- Construct the theoretical system of multi-phase, multi-component and multi-scale fluidized separation.
- Study the efficient dry separation technology of fine coal.
- Put forward the precise dry separation technology of coal.
- Improve the adaptability of coal dry separation technology.





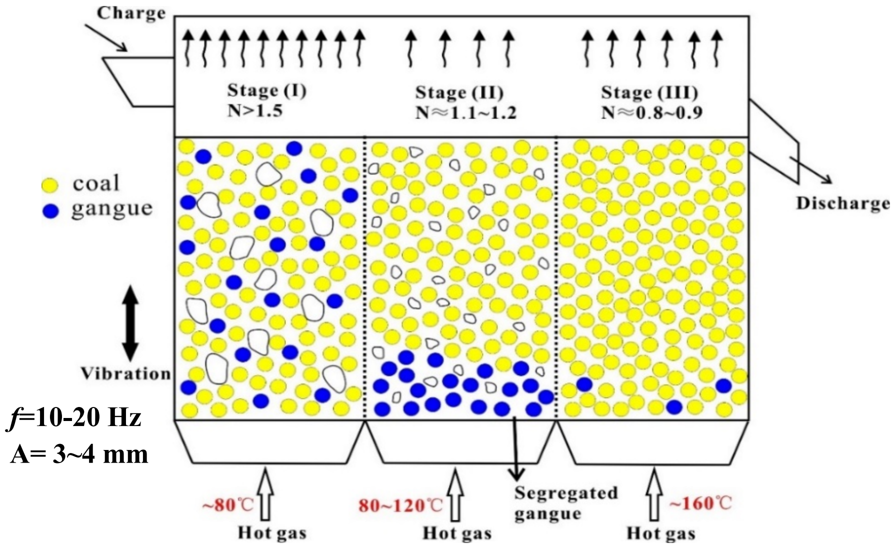
2. Constructing modern large-scale dry coal preparation plant

Promote the development of large-scale, standardized and intelligent dry coal preparation plants.

- **Large-scale development:** Improve the supporting equipment of 10 million tons of large-scale dry coal preparation plant;
- **Standardization:** Promote the standardization of dry coal preparation equipment manufacturing and process design of dry coal preparation;
- **Intellectualization:** Integrate ‘ Internet plus ’ technology such as Internet of things, large data and cloud platform into the whole process of dry coal preparation plant design, construction and production management.

3. Developing dry deashing and dewatering technology for low quality coal

- The dehydration and upgrading technology of dry dehydration with low energy consumption and high efficiency was developed.
- Enhance the adaptability of dry coal preparation technology, and provide an effective way for clean and efficient utilization of low-quality coal.



Upgrading methods	For every additional 1000 kcal/kg calorific value per ton of coal, MJ
Single dewatering	15.28
Single deashing	7.21
Synergistic upgrading	9.17

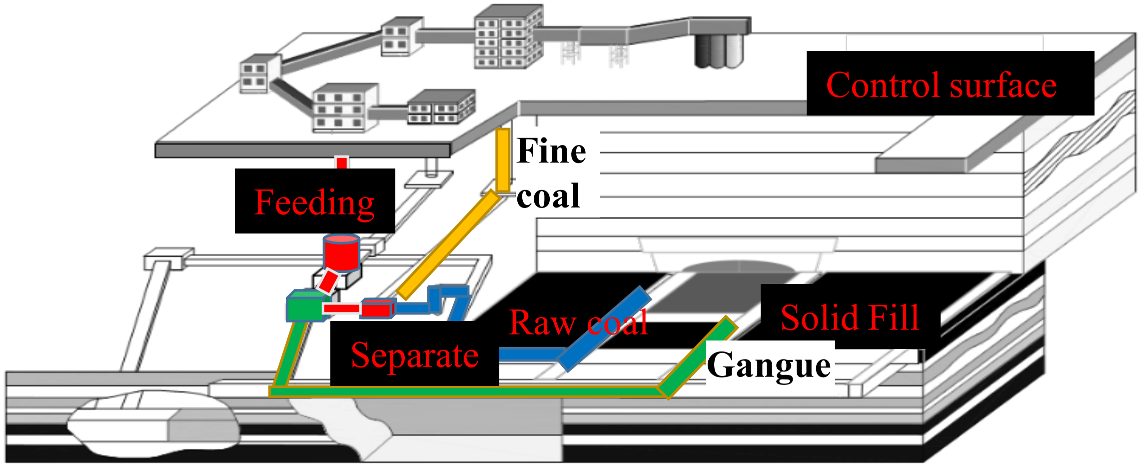
Comparison of different upgrading methods for low-quality coal

4. Developing in-situ dry coal separation technology underground

◆ Significance for coal separation underground

- Reduce the ineffective transportation of gangue, cost of transportation, storage and surface coal preparation, environmental pollution
- Fill in the gangue underground

◆ Develop the technology of underground dry coal preparation with simple technology, build underground intelligent dry coal preparation plant, and realize the integration of "Mining-Selecting-Filling" of Underground Coal.



Environment-friendly dry coal preparation provides clean raw materials for electric power, metallurgy, chemical industry, and other fields.

Thanks very much for your attention!