

Characteristics of Coal-Powder Migration and Accumulation in Coalbed-Methane Wellbores Based on Physical Simulation

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Abstract: The accumulation of coal fines in the wellbores of coalbed methane (CBM) wells is the result of gas-liquid-solid transport; it reduces the effective flow area, blocks drainage, damages equipment, and causes scaling and corrosion. The components of the physical simulation in this paper are particle entry, entrainment, migration, settling, wall interaction, deposition, resuspension and localised accumulation. The foundation of the above framework is the laws of conservation, particle force balance and evidence from peer-reviewed studies published between 2024 and 2026; no unverified experimental results have been used as facts. Primary influencing factors include agitation speed, gas-liquid ratio, particle size distribution, solids concentration, fluid properties, well inclination, wall conditions and local geometry. According to the above framework, changes in these factors will cause changes in the pressure gradient, transported-solids fraction, deposit mass, bed height and deposition location. Continuous deposition occurs in areas with a low local carrying capacity; thus, particles accumulate, the flow reverses, liquid holdup happens, and wall interaction strengthens. A similarity-aware transparent-loop experiment for synchronous pressure imaging and solids recovery can distinguish between transient holdup and steady accumulation. Therefore, the framework offers a way to explain the problem of blockage and separates facts from hypotheses and tests.

Keywords: Coalbed methane, coal powder, multiphase flow, particle migration, wellbore deposition, physical simulation.

1. Introduction

Pressure depletion reduces the effective stress of the coal reservoir; gas and water in the fractures can cause detachment and movement of weak particles. Flow-channel opening, closing and diversion are also ways to discharge coal powder. Morphological, mineralogical and flow-channel analyses of deep wells in the Qinshui Basin have shown that the production of fine particles is related to coal composition and transport paths [1-2]. The structure of the coal body affects both the amount and the time distribution of solid release, and migration experiments on structurally different coals have shown that mobile fines can change the reservoir conditions. While solids are generated within the reservoir, their actual transport to the surface remains uncertain.

Long-term monitoring of the Liulin Block has shown that coal-fines production should be considered in light of drainage conditions and production history. Gas and water are not distributed evenly in the wellbore; the velocity changes along the completion; and particles may contact the walls, joints, pumps, bends and area changes. Retained solids reduce the effective flow area, increase the pressure drop, obstruct drainage and damage the equipment. Deposited fines can also cause scaling and corrosion, accumulate in the structure, and obstruct the flow of water.

Therefore, the main problem is to determine which combinations of hydraulic, particulate, geometric and operating conditions can keep coal powder in suspension, settled, adhered, resuspended or as a persistent bed. The average production rate is too low, and due to phase redistribution, intermittent flow, liquid holdup, inclination and recirculation, there will be areas of low shear. Specific

studies of the gas-water flow and gas-production stages have shown that there is a need for wellbore migration and deposition, but a general framework that links particle forces to observable accumulation has not yet been established [6-7].

This paper is a physical-simulation Design and does not show the results of an experiment. It is a force-based description of particle motion, and it is a set of boundary conditions that relate operating parameters to deposition risk, issue a warning signal for wellbore problems, etc. The three tables are the data, Design Variables and the direction of parameter coefficients. The four original schemes are the transport sequence, the proposed apparatus, force balance and interpretation path.

2. Evidence Base and Physical Problem Definition

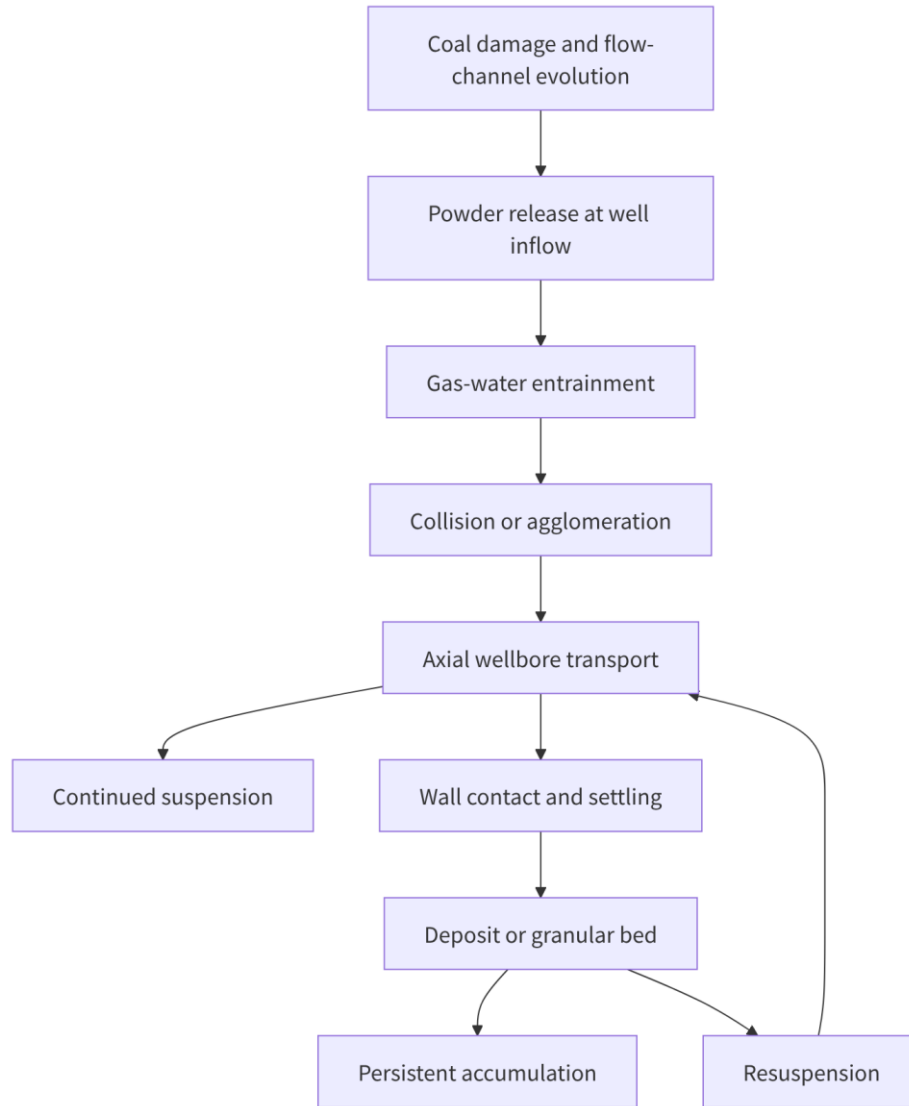
The sources of the evidence are field observation, laboratory experiments, numerical calculations, conceptual induction, etc. Based on field observations, the coal structure, drainage and solids production are related but cannot be regarded as independent. Although controlled studies have found some reasons, there are still differences in the scale, walls, fluids and phase representation of the field. Coupled modelling of fractured coal has been used to construct a reservoir-boundary framework [8], studies on coal fines in fractured-seam CO₂ storage have shown that many transport effects can be observed without direct measurement of wellbore deposition [9], analysis of CBM co-production has added more multiphase and safety information, and based on these studies, hypotheses for physical testing have been put forward. Table 1 summarizes all ten verified sources without adding unverified operating values.

Table 1. Verified 2024–2026 evidence supporting the wellbore coal-powder transport framework

Lyu et al., 2024 ¹	Deep Qinshui wells; morphology, minerals, and flow-channel analyses	Fines origin and characteristics	Particle morphology and mobility
Ren et al., 2024 ²	Southern Qinshui Basin; coal-structure/output analysis	Structure and fines output	Structural control on generation
Wei et al., 2024 ³	Diverse coal structures; migration experiments	Migration and reservoir behavior	Reservoir entry conditions
Liu et al., 2025 ⁴	Liulin Block; long-term monitoring	Drainage parameters and fines output	Operating-history context
Ma et al., 2026 ⁵	Deep CBM wellbores; deposition investigation	Scaling and corrosion interactions	Coupled integrity risk
Li et al., 2025 ⁶	Gas–water production stage; transport investigation	Initiation, migration, and deposition	Multiphase mechanism
Zhang et al., 2025 ⁷	CBM gas-production stage; transport analysis	Wellbore migration and deposition	Wellbore mechanism
Guo et al., 2025 ⁸	Fractured coal; multiphysics modeling	Coupled CBM migration	Reservoir boundary context
Wang et al., 2025 ⁹	Fractured coal; CO ₂ -storage evaluation	Effects of coal fines	Broader fines consequences
Jia et al., 2025 ¹⁰	CBM co-production; fluid-migration analysis	Multiphase migration and safety	Production-system context

The modelled area is the part where the reservoir fluid and coal powder enter the completion and the downstream separator. Particles can be entangled, collide, aggregate, settle, touch a rough surface, join a bed, or return to suspension. As

shown in Figure 1, deposition is reversible. Accumulation will only occur if the rate of particle arrival and retention exceeds the rate of removal.

**Figure 1.** Conceptual sequence of coal-powder generation, entry, migration, deposition, and resuspension (conceptual schematic; not to scale)

3. Physical-Simulation Framework

3.1. Apparatus and Similarity Logic

A good facility should have a regulated gas supply and a liquid circulation system, and also needs a calibrated particle

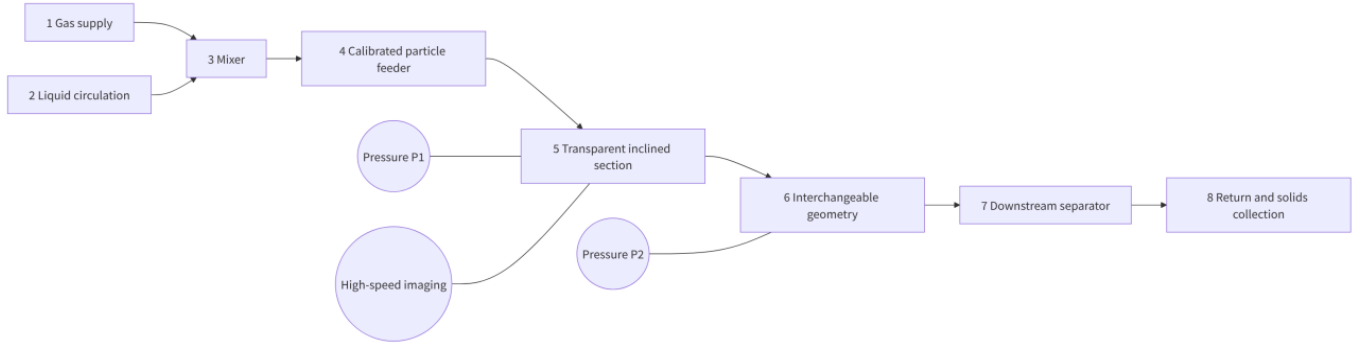


Figure 2. Proposed gas–liquid–solid physical-simulation loop and measurement locations (conceptual schematic; not to scale)

Geometric Scaling is not Field Equivalence alone. Reynolds, Froude, particle Reynolds and Stokes numbers should be used to compare inertia, viscosity, gravity and particle response. Particles and other fluids are compressible and have other characteristics, so it may not be possible to achieve an exact simultaneous match. The Defensible Goal is mechanism similarity: keep the main force balance and increase the dimensionless ratio.

3.2. Model Assumptions and Phase Representation

Gas and water can be taken as continuous carrier phases, and coal powder is added in a certain size. The first calculation can use equivalent spherical diameters, but particle angularity should be recorded as it affects drag, rotation, collision and wall contact. Temperature is not a focus of this study and will be ignored. Specify the Wall Material and Roughness, as smooth transparent tubing cannot reproduce all the adhesion and trapping effects of field tubing.

Euler-Lagrange method is employed for dilute solids; the continuum equations are for the carrier phase, and trajectories represent particles or parcels. Two-way coupling is necessary if the solid significantly changes the carrier momentum. If the load is large, the problem of extended contact and bed formation must be addressed by Eulerian granular or coupled discrete-element methods. The first kind of test is a steady-state test, and those who study drainage adjustment, interruption and resuspension of flow rate are regarded as second-tier. Neither of the above is a solution; irregular shapes, fragmentation, coal-water chemistry and adhesion are still difficult to quantify.

3.3. Governing Equations

Carrier-phase mass conservation is

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,$$

Where ρ and $\mathbf{u}$ denote density and velocity for the chosen phase or mixture representation. Momentum conservation is

feeder, an interchangeable transparent test section, pressure and flow instruments, an imaging area, and a downstream separator. The Test Area should be able to freely vary the inclination, diameter, wall condition and local geometry. Figure 2 is a proposed Design, not the result of an already built apparatus.

written generically as

$$\frac{\partial(\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{g} + \mathbf{S},$$

Where p is pressure, $\boldsymbol{\tau}$ is the stress tensor, and $\mathbf{S}$ contains interphase momentum exchange. These equations impose conservation requirements; they are not numerical results.

Particle motion may be represented by

$$m_p \frac{d\mathbf{v}_p}{dt} = \mathbf{F}_D + \mathbf{F}_G + \mathbf{F}_B + \mathbf{F}_L + \mathbf{F}_{VM} + \mathbf{F}_C,$$

Where the terms denote drag, gravity, buoyancy, lift, virtual-mass, and collision/contact forces. Drag promotes adjustment to carrier velocity; gravity and buoyancy provide net body forcing; lift redirects particles in shear; virtual mass may matter during rapid liquid acceleration; and contact forces govern rebound, friction, and bed support.

Particle responsiveness can be summarized by

$$St = \frac{\tau_p}{\tau_f},$$

Where τ_p is the particle relaxation time and τ_f is the flow timescale. A small St indicates that the carrier has been changed frequently, and a large St indicates a long path. The chosen relaxation-time correlation must be appropriate for the corresponding shape and particle Reynolds number.

A prospective deposition ratio is

$$\eta_d = \frac{m_{\text{deposited}}}{m_{\text{injected}}}.$$

Only after adding the added, recovered, sampled and retained masses should this ratio be normalised. No value of η_d is given here.

3.4. Variables and Boundary Conditions

Table 2 shows the test matrix without invented levels. Test values should be obtained in a traceable field or through independent measurement, and the calibration uncertainty must be stated.

Table 2. Proposed simulation variables, boundary conditions, measurements, and evidence roles

Variable or response	Unit	Control or measurement	Test status	Evidence role
Gas flow rate	$\text{m}^3 \cdot \text{s}^{-1}$	Calibrated controller	Select from cited or measured conditions	Boundary condition
Liquid flow rate	$\text{m}^3 \cdot \text{s}^{-1}$	Pump and flowmeter	Select from cited or measured conditions	Boundary condition
Mixture velocity	$\text{m} \cdot \text{s}^{-1}$	Derived from phase rates and area	Select from cited or measured conditions	Entrainment control
Gas–liquid ratio	Stated basis	Derived from phase rates	Select from cited or measured conditions	Phase-regime control
Particle-size distribution	μm	Sieving or imaging	Source-specific or measured	Particle response
Solids concentration	$\text{kg} \cdot \text{m}^{-3}$	Feeder calibration and sampling	Source-specific or measured	Collision/loading control
Liquid density and viscosity	$\text{kg} \cdot \text{m}^{-3}$; $\text{Pa} \cdot \text{s}$	Densitometer and viscometer	Independently measured	Drag and settling
Inclination	degrees	Adjustable mount	Geometrically defined	Gravity projection
Inner diameter	m	Interchangeable tube	Geometrically defined	Velocity and scale
Wall roughness	m	Profilometry	Independently measured	Retention control
Pressure gradient	$\text{Pa} \cdot \text{m}^{-1}$	Differential transducers	Measured response	Hydraulic indicator
Deposit mass and bed height	kg; m	Recovery, imaging, and weighing	Measured response	Accumulation indicator
Transported-solids fraction	Dimensionless	Inlet–outlet mass balance	Measured response	Carrying performance

4. Mechanisms of Migration, Deposition, and Accumulation

4.1. Entrainment and Sustained Transport

Entrainment is the hydrodynamic force and turbulent fluctuation that exceed the submerged weight, friction and cohesive or interlocking forces. A small particle has a short response time and can quickly react to changes in carrier flow. A large, dense or clustered particle will have a relatively low speed, and it may be carried away from the flow sideways or reach a wall in areas of flow change.

Coal powder is not spherical or uniform. Morphology, mineral composition and transport paths will affect the equivalent size, angularity, surface condition, fragmentation or agglomeration tendency of coal. Coal structure can also affect the first production, and experiments on structurally different coals have shown various migration behaviour [3, 5]. Therefore, the physical simulation should take into account the measured size distribution and particle preparation; it should not assume a single ideal diameter.

4.2. Settling, Wall Interaction, and Bed Development

The ratio of carrier support to net gravitational force is small, so the settlement will be relatively small. A velocity deficit near the wall will place the particle in a region of low momentum, and inclination will direct the submerged weight towards the bottom wall. Particles may not be in continuous contact; they can bounce, roll, saltate or become airborne again. A stable bed will still rise slowly and is rarely eroded. Roughness prevents the shearing of particles, angular grains can interlock, the concentration increases, and thus the collision frequency and agglomeration occur.

According to the reported relationship of coal-fines

deposition, scaling and corrosion, the condition of the wall is unstable.⁵ Chemically bound deposits should be distinguished from mobile granular beds because adhesion and cementation will increase the shear force required for removal. Therefore, only the simulation of inert particles and a smooth wall will underestimate deposit persistence.

4.3. Gas–Liquid Coupling and Fluctuating Carrying Capacity

Gas–water coupling does not determine the bulk velocity. Research on the two-phase production stage has found that phase behaviour affects the start of fines generation, the transport and accumulation of fines, and analysis of the gas–production stage has shown that migration and deposition are closely related to wellbore conditions [6–7]. Although the average gas rate in the first area is relatively high, the second area will be rich in liquids and have low-speed traffic. Therefore, the pressure recovery after the change in operation is not due to solids; they may have only moved downstream.

The deposited layer is stable at the time of low flow, and then it is partially dislodged by a transient to produce a short solids pulse at the outlet. Transient liquid holdup will increase the pressure drop, but it will not stabilise particle retention. Therefore, the pressure, image and recovered-solids measurements should be carried out at the same time.

4.4. Localized Deposition-Prone Regions

Figure 3 shows testable hotspots. The bottom wall of the inclined section bears the particles due to transverse gravity. Bends and Changes in Area can result in secondary flow, separation or recirculation. Joints, the area around the pumps, restrictions and liquid-holdup zones have accumulated solids. Although these places are mechanically plausible, without matching CBM evidence, they are still only hypotheses and not general facts about the field.

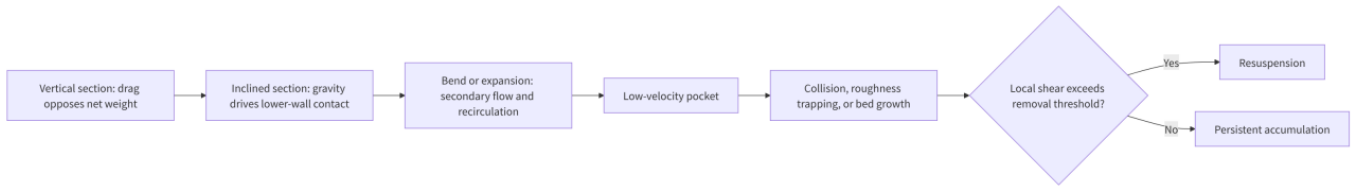


Figure 3. Force balance and deposition-prone regions in vertical, inclined, and geometrically disturbed wellbore sections (conceptual schematic; not to scale)

5. Effects of Operating and Boundary Conditions

5.1. Flow Velocity and Gas–Liquid Ratio

A small local velocity will reduce drag and turbulent support, so it is likely to settle, but it will not always do so. A strong current can move the bottom of the river and raise the water level suddenly, thus shaking loose some fine particles from the reservoir. Field monitoring links the drainage parameters to the fines output, but no general causal threshold has been set [4]. Gas-liquid ratio is also conditional on orientation, total throughput, flow regime, liquid holdup, etc., and should be interpreted together with measured phase rates.

5.2. Particle Size, Morphology, and Concentration

A large equivalent particle size will respond more slowly and settle gradually. Although the very fine particles have a

long suspension time, their high surface area-to-mass ratio results in more surface interactions and aggregation; thus, they quickly form settling clusters. Irregular Grains have orientation-dependent drag and can become jammed upon contact. A high concentration increases collisions and therefore the probability of bed formation; at high loads, it can also change the effective rheology and interphase momentum transfer. Therefore, the concentrations at the inlet and outlet must be measured, not assumed from feeder settings.

5.3. Fluid Properties, Inclination, and Geometry

A relatively viscous liquid will have a small viscous drag and is less likely to settle due to gravity. A small density has little effect. Increase the lower-wall contact, and bends, expansions, restrictions or protrusions may cause separated flow and particle-rich pockets. Table 3 shows the main reasons and non-experimental results.

Table 3. Directional influence of principal variables on coal-powder entrainment, deposition, and blockage risk

Change	Transport effect	Deposition effect	Blockage implication	Evidentiary status
Higher local velocity	Generally increases	Generally decreases until redistribution dominates	Non-monotonic	Physical interpretation; drainage context from Liu et al. ⁴
Higher gas–liquid ratio	Condition-dependent	Condition-dependent	Condition-dependent	Multiphase evidence from Li et al. ⁶ and Zhang et al. ⁷
Larger effective size	Decreases flow responsiveness	Generally increases	Generally increases	Force-based interpretation
Greater irregularity or agglomeration	Condition-dependent	Increases contact retention	Generally increases	Interpretation informed by Lyu et al. ¹
Higher solids concentration	May reduce carrying efficiency	Increases bed-growth potential	Generally increases	Proposed collision effect
Higher liquid viscosity	May support particles but damp turbulence	Usually reduces isolated settling	Condition-dependent	Physical interpretation
Greater deviation from vertical	Reduces circumferential symmetry	Increases lower-wall contact	Increases localized risk	Proposed geometric hypothesis
Bend, expansion, or obstruction	Creates secondary or separated flow	Increases local retention	Increases localized risk	Proposed geometric hypothesis
Rough or reactive wall	Minor bulk-flow effect	Increases trapping or adhesion	Increases persistence	Integrity evidence from Ma et al. ⁵

5.4. Interacting Risks

Accumulated fines are not just to be cleared away. Scaling and corrosion will both change the hydraulic resistance and the material properties of the coal. Coal fines at the scale of a reservoir can change the transport and storage characteristics of fractured coal, as shown in the CO₂-storage evaluation and coupled CBM migration model. Although the broad fluid migration analysis in CBM co-production can provide some information on multiphase flow and safety [10], it cannot directly determine the wellbore deposition rate; do not confuse the reservoir scale with the wellbore scale.

6. Simulation Interpretation and Wellbore-Management Implications

6.1. Interpreting Prospective Measurements

Synchronisation pressure, images and solid-recovery data are needed to distinguish between phase holdup and accumulation. Both a continuous rise in the pressure gradient and a slow bed rise are types of accumulation. A small pressure gradient may not be caused by the accumulation of solids; there are other reasons. Increase the speed of the controlled rise; if there is bed shrinkage and renewed solids recovery, then it is considered resuspension; otherwise, it has probably adhered to or cemented. Figure 4 is the proposed

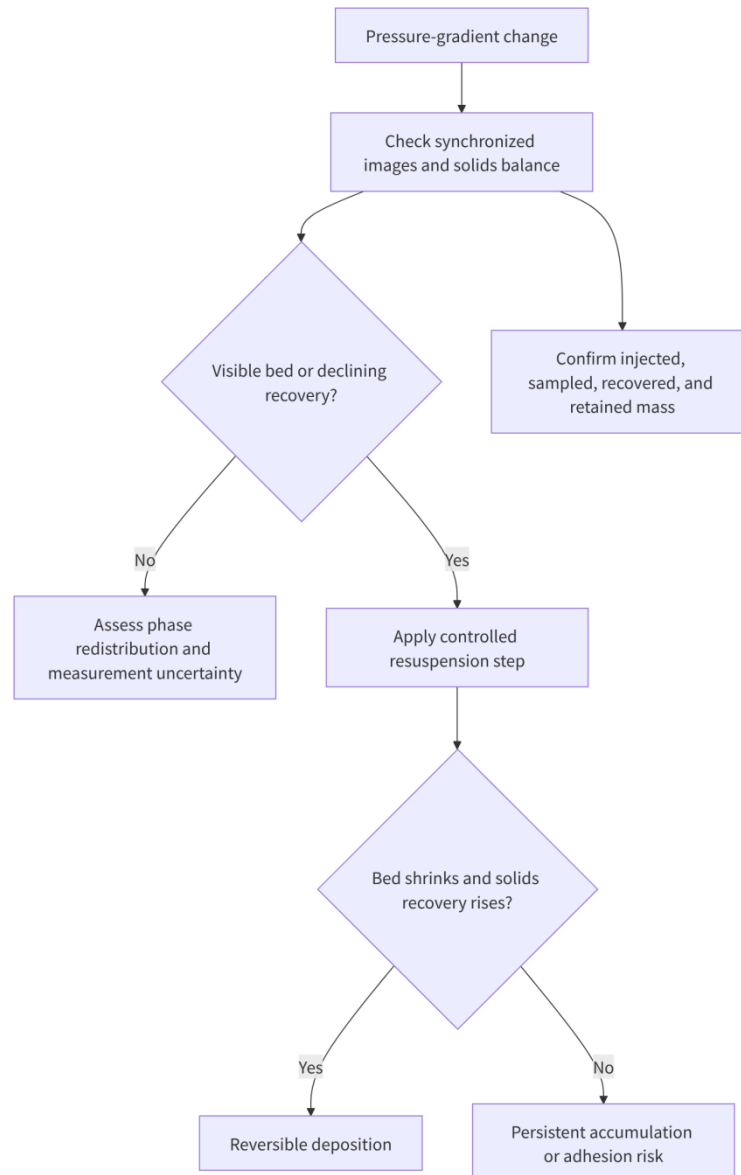


Figure 4. Decision pathway linking observable transport indicators to deposition-risk interpretation (proposed framework)

The Mass Balance Closure should include injected, recovered, sampled and retained solids. The Accuracy, Resolution, Repeatability and Uncollected Loss of the sensors are as follows: Many times, it has been confirmed that the apparent transition is reproducible and not caused by feeder fluctuations or other uncontrolled changes in phase.

6.2. Operational Implications

Coordinated Supervision is better than a fixed speed limit. Do not change the drain suddenly, or too many fine particles will be released. Pressure, phase rate and produced solids are combined to increase the weight of the inclined or disturbed-flow part. If it is technically feasible and the good support conditions are met, then do not expect the cleaning pulse to remove the deposit; rather, it will be pushed aside. These are Design and Observation Indices, not verified operating instructions.

6.3. Limitations and Validation Needs

Change the particle-to-pipe ratio, turbulence, gas expansion and residence time in the laboratory. Spherical approximations underestimate the angle of the particles and

do not consider roughness, corrosion, etc. The control-period rates cannot reproduce all of the field transients, and the coal-water chemistry is also unknown. The next validation will compare the dimensionless trend with the field data of pressure, phase rates and produced solids to determine how well they agree.

7. Conclusion

The accumulation of coal dust in CBM wellbores is the result of the combined effect of hydrodynamic support, gravity, inertia, collision and wall contact. Damage to the reservoir and changes in the flow channel will lead to the generation of solids; it is unknown whether these particles will be suspended, settled, resuspended or form a permanent deposit at the wellbore. Redistribution of gas and liquid changes the carrying capacity at different times and places; thus, only the average velocity or gas rate will exceed the limit.

Inclination and geometric disturbances are likely to be places where particles will be directed to the lower wall, and they are also areas of secondary flow, separation and low-velocity zones. All of the above will affect the deposition and desorption characteristics of particles. If the test conditions

are traceable, the force balances are explicit, and pressure, imaging and solids recovery are coordinated, then an obvious, similarity-aware loop can be formed for this control.

The former is the concept-mechanism, and the latter is the unperformed test. The equations are the conservation laws and expected results; thus, the diagrams are designs and hypotheses, not actual experimental data. Field validation and uncertainty-controlled mass balance can be used to deal with drainage control, solids monitoring, wellbore geometry, etc., to reasonably manage the risk of blockage; scaling, corrosion and reservoir transport interaction also need to be considered.

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