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Fractal-Controlled Multiscale Evolution of Gas–Water Two-Phase Flow Patterns in Rough Sheared Fractures: A Pressure-Based Predictive Framework

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Abstract

The roughness of rock fractures has complex features that affect how fluids move through them. This research looks at how gas and water flows change in rough fractures when they are moved using a model based on fractal geometry. Rough surfaces are created using a method called fractional Brownian motion. When the surfaces are moved, the space in the fractures becomes uneven. By using a level-set method together with a fluid flow model, the study explores how the speed the fluid enters, the roughness of the surface, and the movement of the surfaces affect the change between bubble, slug, and ring-like flow. The results indicate that more roughness and movement make the flow less stable, which causes a reverse change from ring-like flow to slug and bubble flow. A framework based on pressure is built, showing that the outlet pressure decreases quickly with fluid speed, rises steadily with roughness, and changes in a square relation with movement. A single prediction formula is made with $R^2 = 0.98$, allowing precise identification of the flow types using pressure change limits. This research gives insights into flow changes in fractured reservoirs and offers a way to predict flow in real-time.

Keywords: fractal rough fractures; two-phase flow; slug flow; flow structure classification



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1. Introduction

Reducing global carbon emissions has become a major international consensus, and the increasing reliance on clean, efficient, and low-carbon energy systems has elevated the strategic importance of natural gas in global energy transitions [1–5]. Compared with conventional fossil fuels, natural gas offers lower carbon intensity, stable supply performance, and compatibility with renewable energy systems, making it an indispensable component of current and future energy portfolios. In subsurface formations such as shale, tight sandstone, and coal measures, fractures represent primary pathways for fluid transport because their permeability is orders of magnitude greater than that of intact rock [6,7]. Consequently, understanding gas–water two-phase flow behavior within fractures is fundamental for

predicting production efficiency, ensuring operational stability, and optimizing long-term reservoir management. The coexistence of gas and water in subsurface fractures creates inherently complex flow behavior governed by the competing influences of inertial, viscous, and interfacial-tension forces. Depending on their relative magnitudes, representative flow regimes—bubble flow, slug flow, plug flow, and annular flow—may form [8–10]. Each regime exhibits distinct flow morphology, interfacial interactions, and pressure signatures. Among them, slug flow is of particular engineering concern because it induces strong pressure oscillations, intermittent transport, and severe operational instability in natural gas production [11,12]. Therefore, accurately characterizing the evolution, transition, and instability of gas–water flow regimes is essential for ensuring extraction reliability and mitigating flow-induced risks.

Considerable progress has been made in two-phase flow research in microchannels and capillary tubes [13]. Key observations indicate that flow-regime transitions in microscale conduits are strongly influenced by surface tension, viscosity, and inertial effects—parameters far more dominant than in conventional-scale pipelines [14,15]. Flow-pattern maps constructed from gas–liquid superficial velocities have become widely used tools for predicting flow transitions [16]. However, these maps only capture major transitions (e.g., bubble to plug flow) and cannot resolve subtle variations within similar regimes [17]. For plug flow, variations in plug length and number significantly influence flow stability and pressure drop [18]. Recent studies highlight that flow-pattern maps alone cannot fully characterize the multiscale evolution of plug structures in natural fractures [19]. This indicates a need for more detailed investigations into flow-regime evolution under varying velocity ratios in rough geological fractures.

Pressure drop plays an equally critical role in fractured reservoirs such as shale gas and tight gas systems. It directly influences gas–water interface positions, flow morphology, and displacement efficiency [20,21]. Classical theory predicts that bubbles form when resistance and interfacial forces reach equilibrium [22], implying that bubble length should correlate with frictional pressure drop [23]. Building on this, empirical models have been developed that significantly improved bubble-length prediction accuracy [24]. However, most of these models were developed for smooth microchannels, leaving the coupling between pressure drop and flow structure inside rough fractures poorly resolved.

Fracture surface roughness introduces additional complexity. Geological fractures exhibit multiscale self-affine roughness, shaped by mineral dissolution, geomechanical loading, and long-term structural evolution [25,26]. This roughness modulates flow pathways by creating spatially variable apertures, distorted cross sections, and tortuous trajectories. Such geometric perturbations intensify interfacial disturbances, promote nonlinear hydrodynamic fluctuations, and significantly alter flow-regime transitions [27,28]. Experimental and numerical evidence further shows that high roughness suppresses annular flow formation and enhances bubble-dominated structures [29]. However, despite these insights, quantitative descriptions of how roughness regulates gas–water flow structure remain incomplete.

Shear displacement adds another dimension of geometric complexity. During natural deformation or production processes, geological fractures frequently undergo shear slip, generating heterogeneous aperture distributions with localized dilation, compaction, and contact zones [30,31]. These deformation-induced aperture variations strongly influence the stability of gas cores, the formation of recirculation zones, and interfacial morphology evolution in two-phase flow [32,33]. Existing models, however, often treat fractures as static or idealized rough-walled channels, failing to capture shear-induced structural reorganization [34], which leads to substantial deviations when predicting actual two-phase

flow behavior [35]. Thus, the mechanisms by which shear displacement modifies multiscale interfaces, shifts regime boundaries, and triggers flow instability remain underexplored.

In practice, roughness and shear displacement coexist and evolve dynamically in fractured reservoirs. Under long-term production, pressure drawdown, cyclic injection, and geomechanically perturbations continually reshape the multiscale asperity structure and aperture network. Consequently, flow behavior at any moment results from both the instantaneous hydraulic state and the geological history encoded in fracture geometry. This dynamic coupling underscores the need for mechanistic models that incorporate both roughness-induced heterogeneity and deformation-driven aperture restructuring. Subsurface fractures are inherently inaccessible, making direct visualization of internal two-phase morphology extremely challenging. Unlike laboratory microchannels, real formations do not permit optical imaging. Therefore, developing robust indirect diagnostic methods is of significant engineering value. Pressure signals at fracture outlets or wellheads provide one of the most practical measurement options [21]. However, existing correlations between pressure fluctuation and flow morphology rely primarily on smooth-channel assumptions [23], failing to account for nonlinear effects arising from multiscale roughness and shear deformation.

To address these gaps, this study integrates fractal geometry, two-phase flow dynamics, and pressure-signal analysis to systematically investigate flow-regime evolution in rough, sheared fractures. Fracture surfaces are generated using fractional Brownian motion (FBM) to preserve the self-affine multiscale characteristics observed in nature. A level-set-based Navier–Stokes framework is employed to simulate gas–water flow under varying injection velocities, joint roughness coefficients (*JRC*), and shear displacements. Furthermore, to overcome observational limitations, a pressure-based prediction method is developed by analyzing the standard deviation (*SD*) of transient outlet pressure. Statistical evaluations show that *SD* decreases exponentially with injection velocity, increases linearly with fractal roughness, and rises quadratically with shear displacement. These relationships enable the construction of a unified predictive model that classifies flow regimes using *SD* thresholds. This provides a practical, theory-supported diagnostic tool for real-time monitoring of instability and flow-regime transitions in fractured reservoirs. Overall, this study advances the understanding of gas–water two-phase flow in natural fractures by elucidating how fractal-controlled multiscale roughness and shear deformation jointly shape flow morphology. By linking measurable pressure signals to internal interface dynamics, the findings provide both mechanistic insight and engineering strategies for enhancing production stability, mitigating flow-induced risks, and improving extraction performance in subsurface energy systems.

2. Model Construction and Numerical Solution

2.1. Governing Equations of Two-Phase Fluid Flow

Although gas is intrinsically compressible, in the present study the gas phase is treated as incompressible due to the relatively low injection velocities ($V_{in} \leq 0.6$ m/s), near-atmospheric outlet pressure, and limited pressure variations observed during the simulations. Under such low-Mach-number and weak pressure-gradient conditions, gas density variations are negligible, and compressibility effects have been widely ignored in previous numerical investigations of gas–liquid two-phase flow in microchannels and rough fractures. Therefore, the incompressible flow assumption is considered appropriate for the scope of this work.

For incompressible and immiscible gas–water two-phase flow within a rough fracture, the fluid motion can be described using the transient Navier–Stokes equations coupled with the continuity equation. These governing equations provide a unified framework for

capturing the interface evolution, momentum exchange, and pressure distribution in the multiphase system [36]. The physical system considered in this study satisfies two essential characteristics. First, the diffusion effect at the gas–water interface remains constant, ensuring the stability and smoothness of the evolving interface morphology. Second, the convective velocity field strictly satisfies the zero-divergence constraint, consistent with the incompressible-fluid continuity requirement [37]. These assumptions are widely accepted and supported by previous experimental verification and theoretical analyses [38]. Accordingly, the governing equations of the two-phase system are expressed as follows [39]:

$$\rho \frac{\partial u}{\partial t} + \rho(u \cdot \nabla)u = \nabla \cdot [-pI + \mu(\nabla u + (\nabla u)^T)] + F_g + F_{st} + F \quad (1)$$

$$\nabla \cdot \mathbf{u} = 0 \quad (2)$$

where u is velocity vector, ρ is the fluid density, p is the pressure, I is the identity matrix, F_g is the gravitational force, F is the other external forces in the system and F_{st} is the surface tension force which can be expressed as:

$$F_{st} = \nabla \cdot [(\tau(I - nn^T))\delta] \quad (3)$$

where n is the unit normal to the interface, τ is the surface tension and δ is the Dirac delta function.

Following are definitions for fluid density and dynamic viscosity:

$$\rho = \rho_w + (\rho_g - \rho_w)\varphi \quad (4)$$

$$\mu = \mu_w + (\mu_g - \mu_w)\varphi \quad (5)$$

where φ is a smooth continuous level set function, ρ_g is the gas density, ρ_w is the water density, μ_g is the dynamic viscosity of the gas and μ_w is the dynamic viscosity of water.

Computational Fluid Dynamics (CFD) is employed to solve the two-phase flow system under typical atmospheric temperature conditions (20 °C), consistent with standard laboratory setups [40]. Because the pressure drop in the simulated range is relatively small and gas dissolution into the aqueous phase is negligible, gas compressibility effects are ignored. The physical properties of the fluids used in the simulations are summarized in Table 1.

Table 1. Physical properties of two-phase fluids.

Phase	Temperature (K)	Density (kg/m ³)	Dynamic Viscosity (Pa·s)
gas (air)	293.15	1.184	1.81×10^{-5}
water	293.15	1000	1×10^{-3}

To accurately track the gas–water interface, the level-set method is adopted. The transport of the interface is governed by the advection Equation [41]:

$$\frac{\partial \varphi}{\partial t} + v \cdot \nabla \varphi = 0 \quad (6)$$

To simulate the fluid interface with a constant thickness and allow for smooth parameter variation, the two-phase flow equation is augmented by a phase reinjection scheme. This augmentation significantly enhances the stability of the solution process. The governing transport equation for the interface is given as [42]:

$$\frac{\partial \varphi}{\partial t} + v \cdot \nabla \varphi = \gamma \nabla \cdot (\varepsilon \nabla \varphi - \varphi(1 - \varphi) \frac{\nabla \varphi}{|\nabla \varphi|}) \quad (7)$$

where ε and γ are model parameters. ε is related to the mesh size and controls the thickness of the interface and γ is related to the velocity field and controls re-initialization and stabilization amount. In this study, γ is 1 m/s. This enhanced formulation ensures numerical stability, smooth interface evolution, and accurate representation of multiphase flow behavior within the highly heterogeneous rough-fracture geometry.

2.2. Construction of Fractal Rough Fracture Surfaces and Mesh Generation

The geometric morphology of natural fracture surfaces exhibits prominent self-affine fractal characteristics, making fractal theory an effective tool for describing the spatial variability and multiscale roughness of rock joints. In this study, the rough fracture surfaces are generated using fractional Brownian motion (FBM), a generalized form of classical Brownian motion capable of reproducing the random, self-affine, and scale-dependent features commonly observed in natural rock fractures [38]. Among various FBM simulation techniques, the Sequential Random Addition (SRA) algorithm is adopted due to its high computational efficiency and capability to generate statistically stable fractal surfaces. In the SRA framework, the fractal surface is represented by a continuous single-valued function $Z(x, y)$. The incremental height variation over a spatial separation l follows a Gaussian distribution with zero mean and variance governed by the Hurst exponent H . The FBM increments maintain self-affine invariance, expressed as [43]:

$$Z(x + rl_x, y + rl_y) - Z(x, y) = 0 \quad (8)$$

$$(Z(x + rl_x, y + rl_y) - Z(x, y))^2 = r^{2H} (Z(x + rl_x, y + rl_y) - Z(x, y))^2 \quad (9)$$

One-dimensional fractional Brownian motion $Z(x)$ is a continuous and single-valued random function whose statistical properties are uniquely characterized by the Hurst exponent H . This process is distinguished by the Gaussian nature of its stationary increments: for any lag h , the increment $Z(x + h) - Z(x)$ follows a normal distribution with mean zero and variance σ^2 . According to the variance and mean of increments, the statistical self-affine properties of FBM can be expressed as follows [44]:

$$\langle Z(x) - Z(x + rh) \rangle = 0 \quad (10)$$

$$\langle (Z(x) - Z(x + rh))^2 \rangle = r^{2H} \langle (Z(x) - Z(x + rh))^2 \rangle \quad (11)$$

where $\langle \rangle$ denotes the mathematical expectation, r is a scaling factor, and H (ranging from 0 to 1) controls the roughness degree and correlation of the surface profile. The corresponding variances satisfy [45]:

$$\sigma_{rh}^2 = (Z(x) - Z(x + rh))^2 \quad (12)$$

$$\sigma_h^2 = \langle (Z(x) - Z(x + rh))^2 \rangle \quad (13)$$

$$\sigma_{rh}^2 = r^{2H} \sigma_h^2 \quad (14)$$

where σ_{rh}^2 represents the variances of increments for FBM with lag rh and σ_h^2 represents the variances of increments for FBM with lag h .

The empirical correlation expressed in Equations (15) and (16) was originally established through statistical analysis of a large number of natural rock joint profiles, where the root mean square of the first derivative (Z_2) was found to correlate strongly with vi-

sually assessed *JRC* values. This relationship has been widely validated and adopted in subsequent rock mechanics literature for quantitatively estimating surface roughness [46]:

$$Z_2 = \sqrt{\frac{1}{L} \sum_{i=1}^{N-1} \frac{(z_{i+1} - z_i)^2}{x_{i+1} - x_i}} \quad (15)$$

$$JRC = 32.2 + 32.47 \log Z_2 \quad (16)$$

The effect of stress and deformation on the behavior of fractured rock masses constitutes one of the primary concerns in research on fluid flow through fractures [47]. To incorporate shear effects, the fracture model is constructed as a two-surface system consisting of matching rough profiles. Prior to shearing, full mechanical engagement is assumed, meaning that the upper surface is an exact replica of the lower surface. Shear displacement is introduced by shifting the upper block horizontally while allowing vertical displacement (normal dilation) to occur. Due to asperity interactions, shear induces changes in mechanical aperture and normal opening, jointly determining the evolving void-space distribution. If the lower surface is represented by $(x, Z(x))$, then after applying shear displacement u_s , the upper surface geometry becomes $(x, Z(x) + u_v)$, where u_v is the shear-induced normal displacement u_s . To investigate gas–water flow evolution under shear, four shear displacements $l = 0.0, 0.2, 0.4$, and 0.6 mm are applied. In this study, all fracture apertures are uniformly set to 0.3 mm, and fracture matching is imposed to isolate the individual effects of roughness and shear deformation. Mesh generation is performed in COMSOL Multiphysics® version 6.2. Figure 1 shows fractal-generated rough fracture surfaces with different joint roughness coefficients and their corresponding mesh discretization. To minimize the influence of mesh size on numerical results, a uniformly refined mesh with element sizes ranging from $0.5 \mu\text{m}$ to $0.8 \mu\text{m}$ is applied throughout the computational domain. This resolution ensures accurate representation of sharp asperity gradients, interface curvature, and the complex recirculation zones that emerge in rough sheared fractures.

2.3. Boundary Conditions and Numerical Solver Configuration

In this study, the influence of fracture aperture distribution on the two-phase flow field is intentionally excluded in order to isolate the independent effects of fractal roughness and shear deformation. Accordingly, all fracture surfaces are assumed to be perfectly matching, such that the upper and lower roughness profiles are fully aligned. Under this assumption, a uniform mechanical aperture of 0.3 mm is prescribed throughout the fracture domain. This treatment ensures that variations in flow structure arise solely from multiscale geometric perturbations induced by surface roughness and shear displacement, rather than from aperture mismatch. The length of each fracture is set to 10 cm.

Figure 2 illustrates the computational domain and the boundary conditions adopted for the rough fracture model. Impermeable boundaries are imposed above and below the fracture surfaces, indicating that no fluid exchange with the surrounding rock matrix is permitted. This configuration isolates flow within the fracture void space, enabling a systematic investigation of the effects of fractal roughness and shear deformation on gas–water two-phase flow patterns while neglecting matrix–fracture interactions that may occur under field conditions. Initially, the fracture domain is fully saturated with water to represent a realistic subsurface state in which formation brine occupies the fracture voids prior to gas invasion. Subsequently, a gas–water two-phase mixture is injected from the left inlet boundary under a velocity-controlled condition, with both phases entering the fracture at identical superficial velocities and volumetric flow rates. Six inlet velocities, $0.10, 0.15, 0.20, 0.40$, and 0.60 m/s, are applied to investigate multiscale transitions among bubble, slug, and annular flow regimes under varying hydraulic forcing conditions.

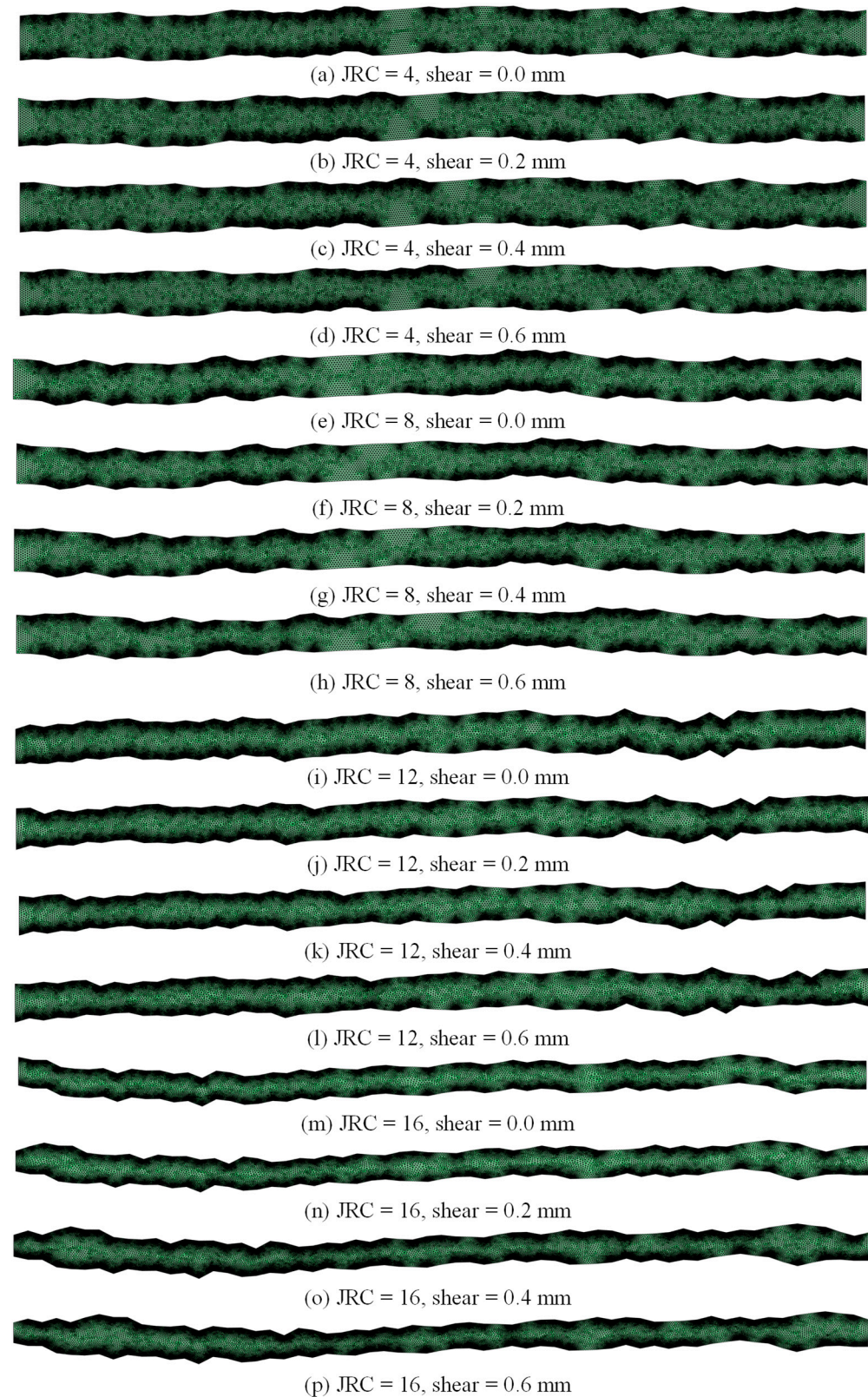


Figure 1. Fractal-generated rough fracture surfaces with different joint roughness coefficients and their corresponding mesh discretization.

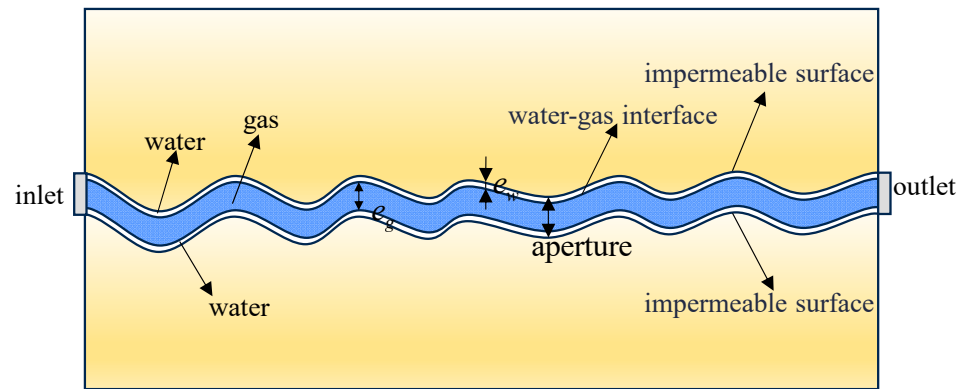


Figure 2. Boundary conditions for two-phase fluid flow in a fractal-rough single fracture.

The outlet boundary is treated as a zero-pressure condition, representing an open boundary exposed to atmospheric pressure. A stress-free (no-viscosity) condition is also imposed to prevent artificial momentum reflection at the outlet, thereby ensuring physically realistic discharge behavior of the gas–water mixture. The remaining fracture walls, including both the upper and lower rough surfaces, are treated as no-slip boundaries, where the tangential velocity component is constrained to zero. Owing to the complex morphology of the self-affine fractal surfaces, this no-slip condition induces spatially distributed shear stresses and localized recirculation zones, which play an important role in controlling flow instability and interface deformation.

The gas–water interface along the boundary Γ is subject to both kinematic and thermodynamic constraints. Let n denote the outward unit normal vector and t the unit tangent vector at the interface. For the no-slip condition, the velocity along Γ satisfies Equation (17):

No-slip boundary:

$$u|_{\Gamma} = 0 \quad (17)$$

For the wetting boundary, the contact-angle condition is enforced using the level-set formulation:

$$\varepsilon \nabla \varphi \cdot u|_{\Gamma} = \varepsilon^2 \cos \theta |\nabla \varphi| \quad (18)$$

where θ denotes the static contact angle at the rough surface and ε controls the prescribed interface thickness. This formulation ensures a physically consistent interface shape near the boundary while maintaining numerical stability. In this study, the contact angle on the fracture surfaces is uniformly set to 60° .

During the simulations, the gas–water mixture enters the fracture domain from the left inlet boundary, flows through the rough and potentially sheared fracture, undergoes complex morphological evolution, and ultimately exits through the right outlet boundary. The combination of a velocity-controlled inlet, zero-pressure outlet, no-slip fracture walls, and contact-angle-based interface constraints constitutes a well-posed boundary condition system, enabling accurate numerical resolution of multiphase flow behavior in multiscale fractal rough fractures.

The governing equations of multiphase flow are solved using COMSOL Multiphysics. To accurately resolve the strongly coupled momentum transport and interface evolution in rough and sheared fractures, a decoupled solution strategy is employed. The flow variables of each phase are solved independently using the Generalized Minimal Residual (GMRES) iterative solver, with a convergence tolerance of 10^{-3} . To enhance solver robustness and computational efficiency, the GMRES method is combined with a preconditioning scheme, in which the Parallel Sparse Direct Solver (PARDISO), as implemented in COMSOL Multiphysics® version 6.2, is used as the preconditioner. This configuration is particularly

effective for the ultra-fine mesh employed and for handling the strong nonlinearities induced by interface curvature and rough-surface shear effects.

Given the transient nature of gas–water interface evolution, time-dependent simulations are conducted over a total duration of 0–0.2 s with a time step of 0.001 s. This temporal resolution allows accurate capture of bubble breakup, gas-core deformation, slug formation, and oscillatory behavior near the fracture outlet. To maintain numerical stability and ensure consistent solution quality across all roughness and shear scenarios, the maximum mesh element growth rate is limited to 1.13, and the curvature factor is fixed at 0.3, thereby preventing excessive mesh distortion around highly curved rough-surface asperities.

3. Analysis of Single-Factor Influence on Flow Structure

3.1. Effect of Two-Phase Fluid Injection Rate

To investigate how inlet velocity governs the evolution of gas–water flow regimes in fractal rough fractures, the injection velocity V_{in} was systematically varied from 0.05 to 0.60 m/s. Table 2 summarizes the resulting flow morphologies and the corresponding classifications of bubble flow (BF), slug flow (SF), and annular flow (AF) under four roughness levels ($JRC = 4, 8, 12, 16$), with shear displacement fixed at zero. The contour maps presented in Table 2 clearly illustrate the progressive transformation of flow structure as the inlet velocity increases.

Across all roughness conditions, the fracture exhibits a consistent and monotonic transition sequence with increasing V_{in} . At low injection velocity (e.g., $V_{in} = 0.05$ m/s), interfacial tension dominates the force balance, suppressing bubble coalescence and maintaining a dispersed gas phase. Consequently, BF is the predominant regime, characterized by isolated gas bubbles transported within a continuous water phase. This behavior is universally observed in the lower rows of Table 2 for all JRC values.

As V_{in} increases to intermediate levels (typically 0.10–0.20 m/s), inertial forces become comparable to interfacial tension, enabling gas bubbles to merge into elongated gas pockets separated by liquid slugs. This transition results in the development of SF, which emerges consistently in the intermediate velocity range for all roughness levels. The appearance of SF signifies the onset of intermittent flow and enhanced interface deformation, reflecting the shift in force balance toward inertia-driven behavior.

At higher inlet velocities ($V_{in} \geq 0.30$ m/s), inertial forces dominate over both viscous resistance and surface tension. This dominance promotes phase segregation, where the gas phase forms a continuous core surrounded by a thin liquid film, yielding an AF regime. AF occupies the upper portions of each JRC column in Table 2, confirming that high-velocity conditions stabilize the continuous gas pathway and suppress intermittent breakup.

Although the precise velocity thresholds for each flow pattern vary slightly with roughness, the regime sequentially evolves from bubble flow (BF) to slug flow (SF) and finally to annular flow (AF). Higher roughness tends to broaden the velocity range in which SF occurs, indicating that interface disturbances induced by asperities modulate the sharpness of regime transitions. However, despite these modifications, inlet velocity remains the primary controlling parameter, with roughness acting as a secondary modulating factor that affects the stability and coherence of flow structures.

This systematic transition sequence reflects the multiscale competition among interfacial tension, inertial acceleration, and wall-induced roughness disturbance. At low velocities, capillary effects dominate; at intermediate velocities, inertia–capillary balance yields intermittent behavior; and at high velocities, inertia stabilizes a continuous gas core. The universal nature of this transition across all JRC values underscores the robustness of the velocity-driven regime evolution within fractal rough fractures.

Table 2. Classification of gas–water flow patterns in fractal rough fractures under different injection velocities and roughness levels (shear = 0).

				JRC = 4				JRC = 12			
Re _w	V _{in}	Contour Map		BF	SF	AF		Contour Map	BF	SF	AF
15	0.05										
30	0.10										
45	0.15										
60	0.20										
90	0.30										
120	0.40										
150	0.50										
180	0.60										

				JRC = 8				JRC = 16			
Re _w	V _{in}	Contour Map		BF	SF	AF		Contour Map	BF	SF	AF
15	0.05										
30	0.10										
45	0.15										
60	0.20										
90	0.30										
120	0.40										
150	0.50										
180	0.60										

Note: Blue, orange, and red colors correspond to bubble flow (BF), slug flow (SF), and annular flow (AF), respectively.

3.2. Effect of Fracture Surface Roughness

To elucidate the regulatory role of fractal roughness on the development of gas–water flow regimes in rough fractures, the joint roughness coefficient ($JRC = 4, 8, 12, 16$) was systematically varied under a fixed injection velocity of $V_{in} = 0.4$ m/s. Table 3 presents the flow morphologies and corresponding regime classifications across different shear displacement conditions. The results highlight that fracture roughness exerts a decisive influence on flow stability, interfacial continuity, and the transitions among bubble flow (BF), slug flow (SF), and annular flow (AF).

Across all shear conditions, a consistent trend emerges: increasing JRC leads to a progressive shift in the dominant flow regime from AF to SF and eventually to BF. This monotonic transition reflects the strengthening of geometric disturbance induced by the self-affine asperities on the fracture walls.

At low roughness ($JRC = 4$), the fracture surface is relatively smooth, enabling the gas phase to maintain a continuous core during high injection velocity flow. Under these conditions, AF is prevalent, while SF appears only intermittently and BF is almost absent. This indicates that the smooth fracture profile provides a stable preferential pathway that suppresses interfacial fragmentation and promotes inertia-dominated, stratified transport.

At moderate roughness ($JRC = 8$), the enhanced amplitude and frequency of asperities begin to disturb the gas–liquid interface. As a result, AF becomes less stable and SF becomes more common. Local constrictions formed by rough asperities intermittently compress the gas phase, enhancing the tendency for the gas core to break into elongated slugs. The system therefore exhibits a mixed flow regime where inertia-driven segregation competes with roughness-induced disturbances.

At higher roughness levels ($JRC = 12$ and 16), the fracture surface becomes markedly irregular. Table 3 shows that BF becomes the dominant flow pattern under these conditions. The heightened geometric complexity induces strong local velocity gradients, intensified shear along the walls, and frequent formation of recirculation zones. These multiscale roughness effects fragment the gas phase, preventing the formation of coherent slugs or stable annular structures. As a result, the flow behavior transitions into a fully dispersed bubble-dominated regime, marked by high interfacial instability and strong fluctuation in the pressure field.

Importantly, the observed roughness-dependent transitions remain consistent across all tested shear displacements, indicating that fractality is an intrinsic geometric control mechanism that shapes the overall flow behavior. Rough surfaces introduce long-range, nonlocal perturbations that propagate through the fracture network, amplifying interfacial disturbances and shifting the system toward more unstable, fragmented flow patterns.

Overall, the results demonstrate that increasing fractal roughness systematically reduces flow stability, suppresses annular core formation, enhances intermittent slugging, and ultimately drives the system toward bubble fragmentation. The roughness-driven evolution can therefore be summarized as a transition from AF to SF and subsequently to BF. This progression highlights the essential role of multiscale asperity structures in modulating the balance among inertial forces, interfacial tension, and wall-induced shear stresses in gas–water two-phase flow.

Table 3. Classification of gas–water flow patterns in fractal rough fractures under different roughness levels at $V_{in} = 0.4$ m/s and varying shear displacements.

Shear = 0					Shear = 0.4			
<i>JRC</i>	Contour Map	BF	SF	AF	Contour Map	BF	SF	AF
4								
8								
12								
16								

shear = 0.2					shear = 0.6			
<i>JRC</i>	Contour Map	BF	SF	AF	Contour Map	BF	SF	AF
4								
8								
12								
16								

Note: Blue, orange, and red colors correspond to bubble flow (BF), slug flow (SF), and annular flow (AF), respectively.

3.3. Effect of Shear Displacement

Shear displacement is a key geometric control parameter in rough fractures because it directly alters the aperture distribution and introduces multiscale structural heterogeneity. Based on the flow-pattern identification results presented in Table 4, the evolution of gas–water two-phase flow under shear displacements ranging from 0 to 0.6 mm was systematically examined for a representative base roughness of $JRC = 4$. The results demonstrate that shear deformation gradually destabilizes the flow field, reshaping the regime transitions associated with increasing injection velocity.

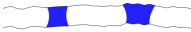
At zero shear displacement ($l = 0$ mm), the fracture maintains a uniform and relatively smooth aperture profile. Under these conditions, flow morphology is controlled primarily by the inlet velocity. At low velocities ($V_{in} \leq 0.10$ m/s), surface tension suppresses bubble coalescence, resulting in the dominance of bubble flow (BF). As velocity increases, iner-

tial effects strengthen, producing a sequential transition from BF to slug flow (SF), and eventually to annular flow (AF), consistent with the behavior observed in smooth conduits.

When shear displacement increases to $l = 0.2$ mm, clear modifications to the flow structure emerge. Although the overall velocity-driven sequence (BF→SF→AF) remains, the range of velocities in which SF occurs expands significantly. Shear deformation introduces mild aperture fluctuations and localized geometric constrictions that periodically compress the gas core, intensifying interfacial disturbance. Consequently, SF becomes more prevalent at intermediate velocities ($V_{in} = 0.15$ – 0.30 m/s), where AF was previously dominant under the no-shear condition.

At $l = 0.4$ mm, the fracture geometry becomes noticeably more irregular. The mismatch between upper and lower asperities generates tortuous pathways and recirculation zones that disrupt the continuity of the gas phase. Under these conditions, SF becomes the dominant flow regime across a wide range of velocities. Even at higher velocities where AF would normally develop ($V_{in} > 0.30$ m/s), the gas core becomes unstable and repeatedly collapses into intermittent slugs. The pronounced expansion of the SF regime observed in Table 4 highlights the increasing influence of shear-induced geometric perturbations on interface stability.

Table 4. Classification of gas–water flow patterns in fractal rough fractures under different shear displacements at $JRC = 4$.

Shear	$V_{in} = 0.05$			$V_{in} = 0.30$				
	Contour Map	BF	SF	AF	Contour Map	BF	SF	AF
0.0								
0.2								
0.4								
0.6								
$V_{in} = 0.10$								
0.0								
0.2								
0.4								
0.6								
$V_{in} = 0.15$								
0.0								
0.2								
0.4								
0.6								
$V_{in} = 0.20$								
0.0								
0.2								
0.4								
0.6								

Note: Blue, orange, and red colors correspond to bubble flow (BF), slug flow (SF), and annular flow (AF), respectively.

When shear displacement reaches the highest tested level ($l = 0.6$ mm), the aperture field exhibits substantial nonuniformity, with strong asperity interference. This structural

distortion generates intense localized velocity gradients and complex internal circulation. As a result, AF becomes nearly impossible to sustain at any injection velocity. Instead, SF dominates most conditions, while BF re-emerges at the lowest velocities due to extreme interface fragmentation. This behavior indicates a complete collapse of annular flow stability under strong shear deformation.

Overall, the results demonstrate that increasing shear displacement systematically suppresses annular flow, broadens the velocity range of slug flow, and ultimately induces gas-phase re-fragmentation into bubble flow under severe deformation. The governing mechanism lies in the multiscale aperture perturbations introduced by shear, which enhance flow tortuosity, strengthen wall-induced shear stresses, and intensify interfacial instability. These effects shift the balance among inertial, viscous, and capillary forces, thereby reshaping the flow-regime transitions within fractal rough fractures.

4. Pressure-Based Multiscale Analysis and Flow-Regime Prediction in Fractal Rough Fractures

4.1. Principle of Pressure-Based Prediction

In subsurface engineering systems, the internal distribution of gas–water two-phase flow within rough fractures cannot be directly observed due to the geometric confinement and limited accessibility of underground environments. This limitation is particularly pronounced in natural and hydraulically induced fractures, where the walls exhibit self-affine fractal roughness. Such surfaces possess multiscale asperities whose heights and spatial correlations follow fractal scaling laws, resulting in a hierarchy of geometric disturbances that affect the fluid interface across multiple spatial and temporal scales. Consequently, developing a pressure-based diagnostic method capable of capturing these multiscale flow behaviors is of substantial scientific and engineering importance.

To construct such a method, two pressure-monitoring points were positioned 0.5 mm upstream of the fracture outlet to record the transient evolution of pressure fluctuations generated by the multiphase flow. As the gas–water mixture progresses through the fractal rough fracture, the interface repeatedly interacts with asperities that span a wide range of scales. These interactions impose multiscale perturbations on the flow field, which are directly reflected in the temporal variation in the outlet pressure. By systematically analyzing the pressure time series under various injection velocities, roughness levels, and shear displacements, a consistent and quantifiable relationship was observed between the standard deviation (SD) of pressure and the dominant flow regime.

Figures 3–5 illustrate representative pressure signals recorded under different hydraulic and geometric conditions. Similar pressure fluctuations were also observed in the experimental studies by Wang Q and Su X [48], though they did not attempt to analyze this phenomenon from a statistical perspective. Despite variations in roughness and shear deformation, the mapping between SD and flow pattern remains robust. This universality arises because SD inherently captures the multiscale disturbances generated by the self-affine fracture surface. Specifically:

- (1) Small SD values correspond to annular flow, where inertial forces dominate and the gas phase forms a stable continuous core. In this regime, the multiscale asperities generate only weak perturbations, and the pressure field exhibits minimal fluctuations.
- (2) Intermediate SD values correspond to slug flow, where the interface periodically interacts with roughness features of multiple scales. These interactions cause the gas core to elongate, contract, and occasionally break, generating oscillatory pressure dynamics with distinct temporal periodicity.
- (3) Large SD values correspond to bubble flow, where the gas phase is repeatedly fragmented by asperities across all fractal scales. The multiscale geometry produces a

cascade of disturbances, resulting in irregular, high-frequency pressure fluctuations that signify strongly unstable and dispersed interface behavior.

From a physical standpoint, the pressure signal in a fractal fracture is shaped by a hierarchical interplay between inertia, viscosity, surface tension, and the multiscale asperity-induced forces inherent to self-affine surfaces. Fractal roughness introduces geometric perturbations at all scales, which collectively impose a multilevel disturbance structure on the two-phase interface. The SD acts as a statistical measure of the cumulative effect of these disturbances, thereby encoding the underlying multiscale flow organization. Slugging corresponds to intermediate-scale modulation, while bubble flow reflects a fully developed multiscale cascade in which disturbances from both small and large asperities contribute to the pressure field.

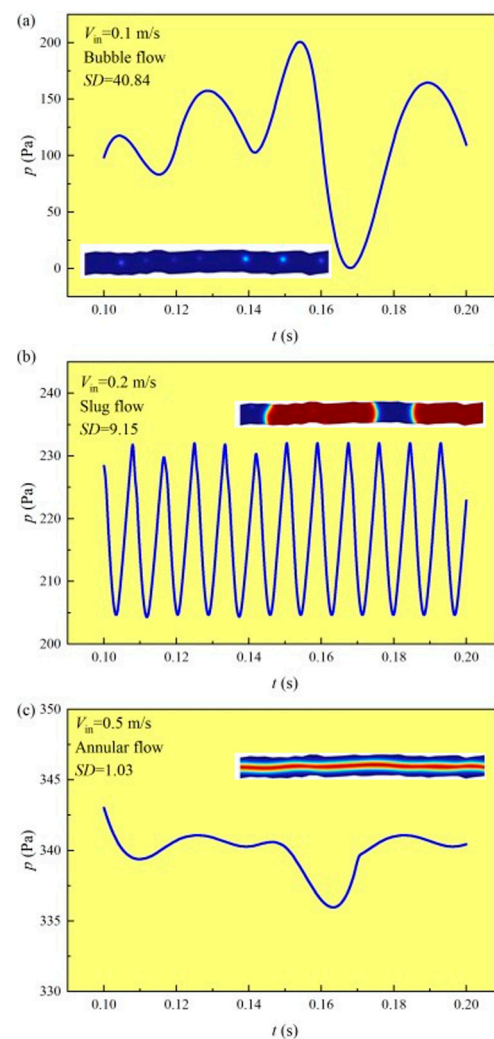


Figure 3. Pressure responses under different injection velocities at $JRC = 6$ and shear displacement $l = 0.2$ mm: (a) Bubble flow at an injection velocity of 0.1 m/s, showing irregular pressure fluctuations with relatively large amplitude; (b) Slug flow at an injection velocity of 0.2 m/s, characterized by periodic and high-frequency pressure oscillations; (c) Annular flow at an injection velocity of 0.5 m/s, exhibiting comparatively smooth pressure variations with reduced fluctuation intensity. Blue and red colors represent the water phase and gas phase, respectively.

Importantly, the relationship between SD and flow regime is insensitive to the specific combination of injection velocity, roughness level, or shear displacement. This indicates that the SD is not merely a geometric or hydraulic descriptor but rather a multiscale statistical invariant that consistently reflects the flow behavior across fractal configurations. Hence,

the SD serves as a robust, geometry-independent diagnostic parameter for identifying flow regimes in rough fractures characterized by self-affine and scale-dependent surface features. Overall, the pressure-based prediction principle establishes a direct link between the multiscale fractal geometry of rough fractures and the measurable statistical characteristics of pressure fluctuations.

To verify whether a measurement point may introduce randomness into experimental results, we set up four new pressure monitoring points along the central axis of the fracture, all located in the near-outlet region (at 0.5 mm, 1.0 mm, 1.5 mm, and 2.0 mm upstream of the outlet), to record transient pressure fluctuations under representative flow conditions (covering bubble, slug, and annular regimes). Statistical analysis of the SD values from these positions revealed only minor differences (with a maximum variation in less than 10% in SD across all points), indicating that the SD -based flow regime classification is highly robust and not significantly influenced by the specific sensor location within this zone. This minimal variation confirms that the pressure fluctuations captured near the outlet are representative of the global flow instability, rather than being artifacts of local geometry.

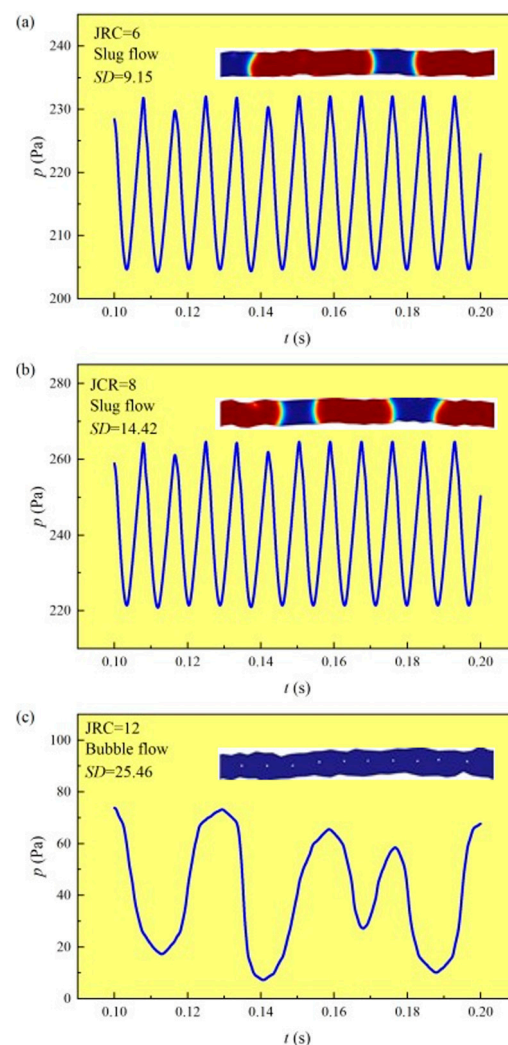


Figure 4. Pressure responses under different roughness levels at an injection velocity of $V_{in} = 0.2$ m/s and shear displacement $l = 0.2$ mm: (a) Bubble flow at an injection velocity of 0.1 m/s, showing irregular pressure fluctuations with relatively large amplitude; (b) Slug flow at an injection velocity of 0.2 m/s, characterized by periodic and high-frequency pressure oscillations; (c) Annular flow at an injection velocity of 0.5 m/s, exhibiting comparatively smooth pressure variations with reduced fluctuation intensity. Blue and red colors represent the water phase and gas phase, respectively.

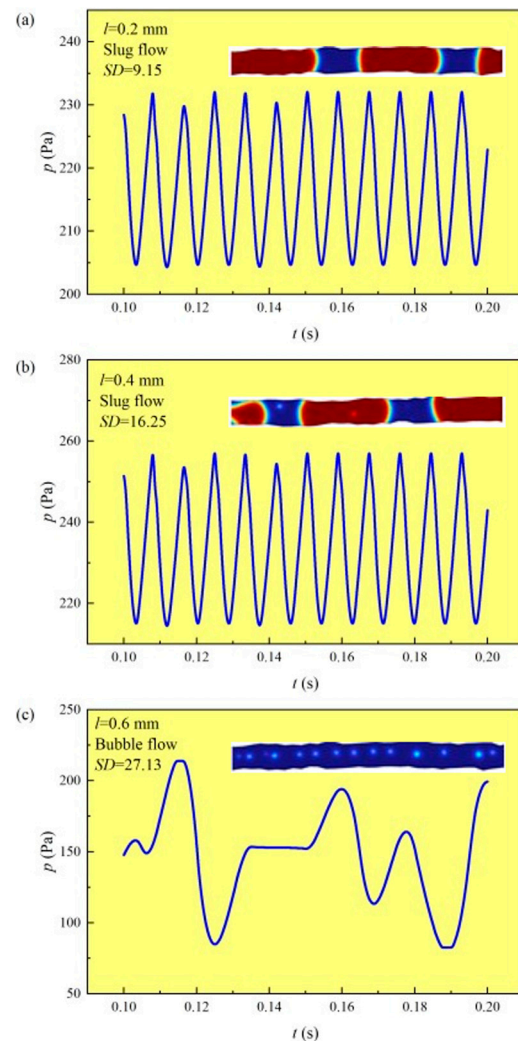


Figure 5. Pressure responses under different shear displacements at $JRC = 6$ and an injection velocity of $V_{in} = 0.2$ m/s: (a) Bubble flow at an injection velocity of 0.1 m/s, showing irregular pressure fluctuations with relatively large amplitude; (b) Slug flow at an injection velocity of 0.2 m/s, characterized by periodic and high-frequency pressure oscillations; (c) Annular flow at an injection velocity of 0.5 m/s, exhibiting comparatively smooth pressure variations with reduced fluctuation intensity. Blue and red colors represent the water phase and gas phase, respectively.

4.2. Statistical Identification

To quantitatively evaluate the relationship between pressure-fluctuation characteristics and the internal flow structures formed within fractal rough fractures, statistical analyses were performed on the standard deviation (SD) of pressure signals under different hydraulic and geometric conditions. The results reveal clear functional dependencies between SD and the key control parameters, namely injection velocity (V_{in}), roughness level (JRC), and shear displacement (l). These relationships exhibit high correlation coefficients, all above 0.90, demonstrating the robustness of SD as a diagnostic indicator of flow-regime transitions.

Because the fracture surfaces exhibit self-affine fractal roughness, the flow field experiences geometric perturbations that span multiple scales. These multiscale disturbances are reflected in the SD of the pressure signal, which therefore serves as a statistical measure of the cumulative effect of roughness-induced fluctuations. The SD can thus be interpreted as a macroscopic manifestation of microscopic, multiscale interface deformation driven by fractal asperity interactions.

Figure 6 illustrates the variation in SD with injection velocity. In all examined cases, SD decreases exponentially as V_{in} increases from 0.05 to 0.60 m/s. This trend indicates a progressive stabilization of the flow field as inertial forces begin to dominate over roughness- and capillarity-induced disturbances. The general form of the relationship can be expressed as:

$$SD = ab^{V_{in}} \quad (19)$$

where a and b are fitting coefficients that depend on the specific roughness level (JRC) and shear displacement (l). It should be noted that a and b are not universal constants, but intermediate fitting parameters obtained under given geometric conditions. Their dependence on JRC and l is subsequently quantified and explicitly incorporated into the unified predictive model presented in Equation (23). Therefore, Equation (19) is primarily used to describe the velocity-controlled trend of SD , while the combined effects of roughness and shear are captured in the final coupled formulation. Physically, the exponential decay reflects the diminishing influence of fractal-scale geometric perturbations as the flow approaches a stable annular configuration.

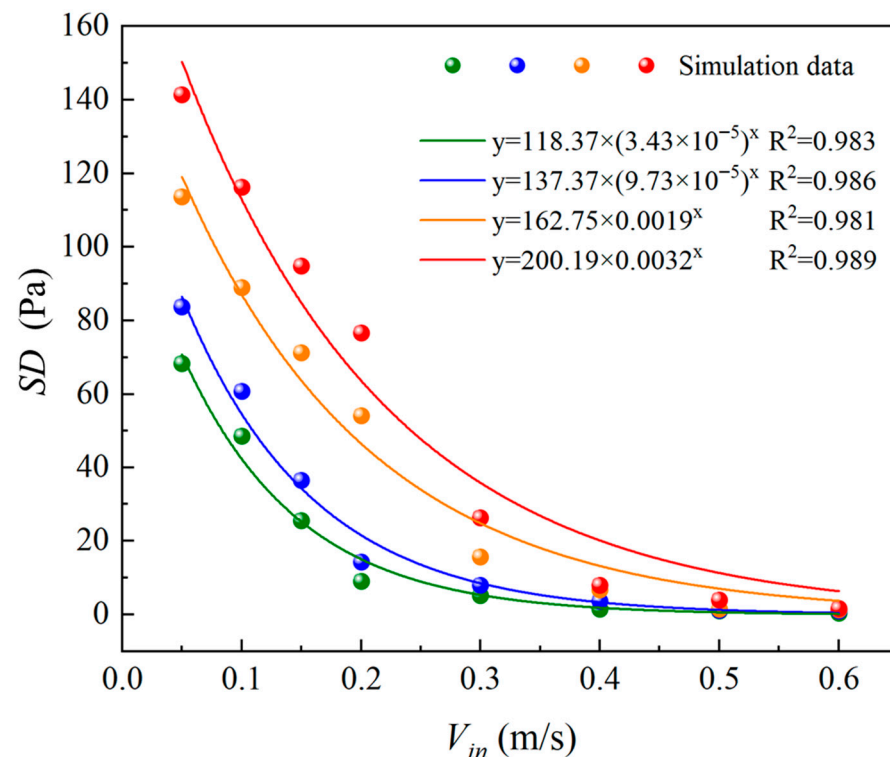


Figure 6. Relationship between pressure fluctuation (SD) and injection velocity under different fractal roughness levels ($JRC = 4, 8, 12, 16$; $l = 0.2$ mm).

Figure 7 demonstrates that SD increases linearly with increasing JRC . The relationship can be written as:

$$SD = cJRC + d \quad (20)$$

where c and d are fitting constants. This linearity highlights a direct proportionality between the fractal roughness amplitude and the strength of the resulting pressure fluctuations. As JRC increases, the asperity height and spatial frequency increase according to the scaling properties of the fractal surface, producing more intense multiscale disturbances that are directly encoded in the pressure signal. The correlation coefficients, between 0.95 and 0.98, support the robustness of this linear dependence. The coefficients are not simple constants

but are functions of the injection velocity (V_{in}) and shear displacement (l), reflecting the integrated influence of hydraulic and geometric conditions.

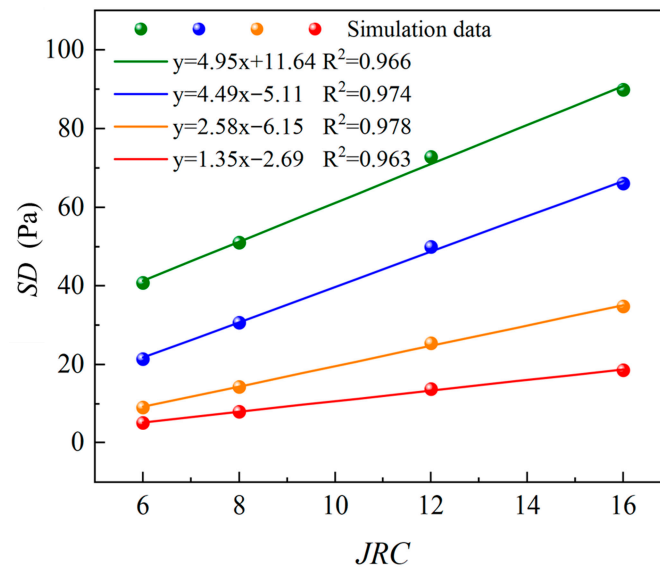


Figure 7. Relationship between pressure fluctuation (SD) and fractal roughness (JRC) under varying injection velocities ($V_{in} = 0.10, 0.15, 0.20, 0.30$ m/s; $l = 0.2$ mm).

Figure 8 demonstrates that SD increases monotonically and nonlinearly with shear displacement l . The relationship can be written as:

$$SD = el + fl^2 + g \quad (21)$$

where e, f , and g are fitting coefficients. The high correlation coefficients (0.97–0.99) confirm the effectiveness of the quadratic model. These coefficients are not constants but functions of the joint roughness coefficient (JRC) and the injection velocity (V_{in}), and were determined through multivariate regression analysis based on the complete dataset spanning all tested conditions of JRC (4, 8, 12, 16) and V_{in} (0.10, 0.15, 0.20, 0.30 m/s). The quadratic dependence reflects the nonlinear amplification of multiscale aperture heterogeneity induced by shear displacement, whereby asperity misalignment generates cascades of geometric constrictions and expansions across multiple scales, intensifying interface deformation and resulting in increasingly complex pressure-fluctuation dynamics that are quantitatively captured by the increase in SD .

From a physical perspective, the distinct functional forms derived for V_{in} , JRC , and l reflect different mechanisms through which energy and interface disturbances manifest in fractal fracture geometries. Injection velocity primarily regulates the balance between inertia and capillarity; roughness controls the intensity of fractal asperity interactions; and shear displacement induces additional multiscale geometric asymmetry. The SD consolidates these effects into a single measurable parameter, providing an efficient and physically grounded means of identifying the underlying flow regime.

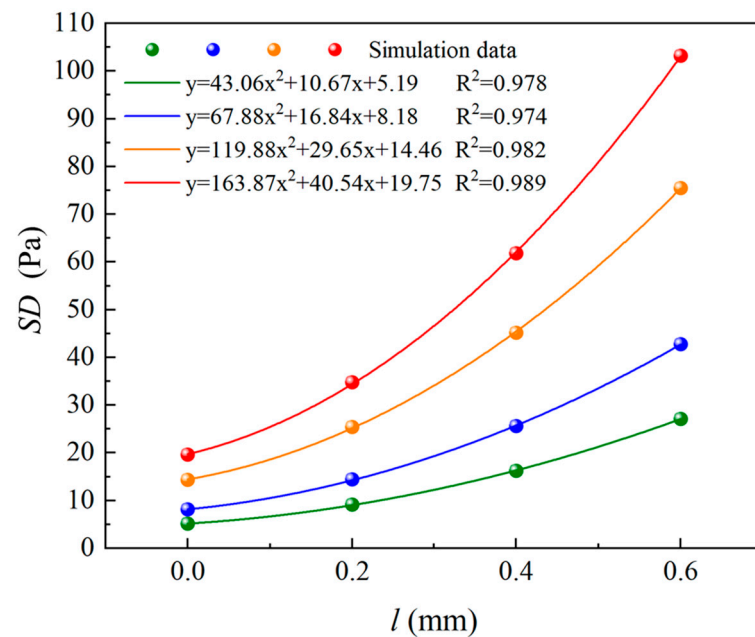


Figure 8. Relationship between pressure fluctuation (SD) and shear displacement under different fractal roughness levels ($JRC = 4, 8, 12, 16$; $V_{in} = 0.2$ m/s).

4.3. Predictive Equation Construction and Classification Criteria

Based on the statistical relationships established in Section 4.2, a unified predictive model was formulated to quantify the pressure-fluctuation intensity resulting from the combined effects of injection velocity, self-affine fractal roughness, and shear-induced multiscale aperture deformation. The purpose of this model is to encapsulate the multiscale geometric perturbations inherent to fractal rough fractures into a single analytical expression capable of predicting the standard deviation (SD) of outlet pressure. Because SD reliably reflects interface stability and flow-regime characteristics, the derived predictive equation enables flow-structure identification under a wide range of hydraulic and geometric conditions.

The fracture surfaces used in this study exhibit self-affine fractal roughness generated through a fractional Brownian motion process. This roughness introduces asperity amplitudes and spatial correlations that follow fractal scaling laws, resulting in a hierarchy of geometric features that influence the flow field at multiple scales. Shear displacement further amplifies these multiscale perturbations by altering asperity alignment and creating asymmetric aperture fields. The combined actions of roughness and shear produce scale-dependent disturbances that manifest directly in the outlet pressure fluctuations measured in the simulations.

From Equations 19–21, it is evident that injection velocity (V_{in}), fractal roughness (JRC), and shear displacement (l) influence pressure fluctuation intensity through distinct functional forms, reflecting different physical mechanisms acting on the gas–water flow system. Statistical analyses indicate that, within the investigated parameter space, these effects can be treated as independent first-order contributions. At the same time, they interact in shaping overall flow stability. Therefore, a multiplicative formulation is adopted to combine their influences, which is a common practice in empirical and semi-empirical modeling of multivariate coupled systems. This formulation preserves the individual effects of velocity, roughness, and shear while effectively capturing their coupled impact on SD . Accordingly, the general form of the predictive equation is written as:

$$SD = AB^{V_{in}}(CJRC + D)(El + Fl^2 + G) \quad (22)$$

where A, B, C, D, E, F and G are the best-fitting coefficients determined from all simulation cases. Using the complete dataset, the optimal fitted expression becomes:

$$SD = 1.72 \times \left(7.37 \times 10^{-5}\right)^{V_{in}} (2.10 \times JRC + 0.97) \left(6.92 \times l + 12.22 \times l^2 + 2.21\right) \quad (23)$$

It should be noted that the predictive model was developed and validated within the following parameter ranges: injection velocity $V_{in} = 0.05\text{--}0.60$ m/s, joint roughness coefficient $JRC = 4\text{--}16$, and shear displacement $l = 0\text{--}0.6$ mm. The reported correlation coefficient ($R^2 = 0.98$) was obtained by evaluating Equation (23) against the complete dataset spanning all combinations of these parameters, demonstrating excellent agreement between the predicted and simulated SD values. This high accuracy confirms that the proposed model effectively captures the multiscale coupling effects of self-affine roughness, shear-induced deformation, and velocity-controlled flow dynamics. Moreover, the predictive equation reveals three fundamental physical insights:

- (1) Velocity-controlled stabilization: The exponential term reflects the stabilizing effect of increasing injection velocity, which suppresses multiscale interface disturbances induced by fractal asperities.
- (2) Fractal-roughness-controlled destabilization: The linear JRC term represents the direct proportionality between fractal roughness amplitude and pressure-fluctuation intensity. Greater JRC values correspond to stronger asperity-induced perturbations at multiple scales.
- (3) Shear-induced multiscale amplification: The quadratic function of shear displacement accounts for scale-dependent geometric asymmetry created by shear misalignment. Larger shear displacements intensify aperture heterogeneity, amplifying multiscale flow disturbances.

Together, these components allow the model to express how multiscale interactions arising from self-affine fractal surfaces and shear deformation collectively shape flow-regime transitions in rough fractures.

To convert SD predictions into flow-regime identification, the following classification criteria were established based on the pressure fluctuation characteristics:

When $SD < 2$, the flow structure within the fracture is annular flow. Under this condition, the gas–liquid interface remains stable and the flow is steady, resulting in minimal pressure fluctuations.

When $2 < SD < 20$, the flow structure is slug flow. The alternating passage of gas and liquid plugs induces periodic pressure oscillations, maintaining the standard deviation at a moderate level.

When $SD > 20$, the flow structure transitions to bubble flow. The random generation, collapse, and coalescence of numerous bubbles induce violent, high-frequency fluctuations in the pressure field, resulting in the highest standard deviation.

These thresholds reflect the degree of interface stability and the underlying multiscale dynamics present within the fracture. Because the predictive model aggregates the effects of fractal roughness and shear through physically meaningful functional forms, the SD -based classification framework provides a robust and generalizable approach for identifying flow regimes in self-affine fractal rough fractures. It should be noted that this model was developed and validated within the following parameter range. The applicability of this model outside this parameter range still requires further research in the future.

Our SD -based method fundamentally differs from conventional maps by integrating measurable pressure fluctuations that inherently encode the multiscale effects of fractal roughness and shear. Unlike velocity-based maps, which require prior knowledge of flow regimes and are sensitive to channel geometry, the SD metric offers a real-time, geometry-

agnostic diagnostic tool. For example, in cases where microchannel maps predict BF to SF transitions based on superficial velocity, our approach captures the reverse transition from SF to BF under increasing roughness a phenomenon unaddressed by traditional models. By linking SD to the hierarchical interplay of forces and geometry, our framework provides a more robust and generalizable prediction for subsurface applications, where fracture morphology is dynamic and complex.

5. Mechanistic and Engineering Insights into Multiscale Flow Evolution in Fractal Rough Fractures

5.1. Multiscale Mechanistic Interpretation of Flow-Pattern Transitions in Fractal Rough Fracture

The simulation results presented in Tables 2–4 reveal a clear and systematic evolution of gas–water two-phase flow regimes within self-affine fractal rough fractures as injection velocity, roughness amplitude, and shear displacement vary. At low velocities, bubble flow (BF) dominates; with increasing velocity, the system transitions to slug flow (SF) and eventually to annular flow (AF). These transitions reflect the changing dominance among inertia, viscous resistance, and interfacial tension. However, unlike flow in smooth channels, the presence of multiscale fractal roughness introduces hierarchical geometric perturbations that significantly modify local flow dynamics.

At low injection velocities, interfacial tension overwhelmingly governs flow behavior, suppressing bubble coalescence and maintaining small dispersed bubbles. In this regime, the influence of fractal asperities is expressed primarily through small-scale perturbations that generate local recirculation but do not significantly alter the global flow structure. As the injection velocity increases, inertial forces begin to challenge surface-tension forces, enabling bubbles to merge and form elongated gas segments. The emergence of SF reflects a dynamic balance in which inertia drives elongation, while multiscale asperity-induced disturbances periodically disrupt the gas core. In self-affine rough fractures, the spatially correlated asperities interact with the gas–liquid interface at multiple scales, producing a hierarchy of breakup–reformation cycles that give SF its characteristic intermittency.

At higher velocities, inertial forces dominate, promoting phase segregation and the development of a continuous gas core. However, AF is less stable in fractal fractures than in smooth channels. Large-scale asperities introduce macroscopic undulations in the aperture field, while smaller-scale asperities impose high-frequency disturbances. This multiscale coupling makes the AF regime more sensitive to both roughness and shear deformation, often causing partial collapse of the gas core and reversion to SF in geometrically perturbed regions.

Shear displacement intensifies these multiscale effects. As asperities become misaligned, the aperture field becomes increasingly heterogeneous, altering flow resistance and producing complex shear-induced vortices. These asymmetric multiscale perturbations destabilize the gas core even under conditions favorable for AF, expanding the velocity range in which SF or BF appears. Overall, the observed regime evolution is governed by the multiscale competition among (1) inertial stabilization, (2) capillary cohesion, and (3) fractal-induced geometric disturbance. The interplay of these factors explains the diversity, intermittency, and sensitivity of flow patterns within rough fractures.

5.2. Pressure-Fluctuation Signatures as Multiscale Indicators of Flow Morphology

The dynamic pressure signals recorded near the fracture outlet exhibit clear signatures of the internal flow morphology. The standard deviation (SD) of pressure, in particular, provides a robust and quantitative measure of interface stability, making it an effective diagnostic parameter. The multiscale roughness of the fracture surfaces induces disturbances across a spectrum of spatial scales, and these disturbances manifest as hierarchical fluctua-

tions in the pressure time series. As shown in Figures 3–5, the SD increases systematically as flow transitions from AF to SF and finally to BF.

When AF develops, the gas core remains continuous, and interfacial perturbations induced by fractal asperities are largely damped by inertial dominance. Consequently, pressure fluctuations remain small, and SD falls below 2. In contrast, SF generates periodic constriction and expansion cycles as the gas core interacts with asperities. These interactions produce intermediate SD values (between 2 and 20), corresponding to quasi-periodic oscillations reflecting the interplay between medium-scale and coarse-scale asperity features.

In BF, the interface becomes highly unstable. Small-scale asperities repeatedly drive bubble breakup, while large-scale asperities introduce macroscopic flow diversions. This multiscale fragmentation produces large, irregular, and high-frequency pressure fluctuations, resulting in SD values exceeding 20. Hence, SD encodes both the spatial hierarchy of roughness and the temporal instability of the interface.

The mathematical relationships derived in Section 4.2 further support this interpretation. The exponential decay of SD with velocity reflects inertia-driven suppression of multiscale perturbations. The linear growth of SD with JRC arises because increased roughness amplitude enhances asperity-induced forces at all scales. The quadratic dependence on shear displacement demonstrates that geometric asymmetry amplifies multiscale disturbances in a nonlinear manner. Altogether, SD serves as a multiscale statistical descriptor linking flow morphology to fractal geometry, further validating its use as the basis for predictive flow-regime classification.

5.3. Engineering Implications for Regulating Multiscale Two-Phase Flow in Fractal-Deformed Fractures

The results summarized in Figures 3–8 demonstrate that flow stability in rough fractures is governed by the coupled influences of injection velocity, self-affine fractal roughness, and shear-induced multiscale deformation. These findings have significant implications for subsurface gas extraction, shale reservoirs, geothermal systems, and any engineering process involving two-phase flow in fractured media.

From the perspective of operational stability, slug flow is particularly detrimental due to its characteristic pressure surges, periodic loading, and reduced flow continuity. In industrial settings, SF can cause severe fluid-delivery oscillations, destabilize production operations, and impose cyclic loading on wellbore structures, potentially leading to mechanical fatigue or failure. Understanding the multiscale causes of slugging is therefore essential for optimizing production strategies.

The multiscale analysis in this study leads to three main regulation strategies:

- (1) Reduction or control of fractal roughness effects: Although natural fractal roughness cannot be eliminated, its effective hydraulic impact can be moderated. In hydraulic fracturing and reservoir stimulation, appropriate proppant size distributions or surface-smoothing agents can reduce asperity-induced disturbances, thereby lower SD and suppressing BF and SF.
- (2) Optimization of injection velocity: Since SD decays exponentially with velocity, maintaining injection velocity above a threshold can stabilize the flow and promote AF. However, excessively high velocities may lead to increased pressure loss or operational risks. The predictive equation derived in Section 4.3 enables quantitative determination of the minimum stable-flow velocity for a given roughness and shear condition.
- (3) Management of shear-induced deformation: Shear displacement increases SD quadratically, meaning even small increases in shear deformation can significantly destabilize flow. In field operations, minimizing shear slip through pressure-controlled injection

tion protocols or targeted stress-management strategies can help maintain hydraulic connectivity and enhance flow stability.

For monitoring, *SD*-based flow-regime prediction offers a practical real-time diagnostic tool. Pressure sensors placed at strategic locations can instantly detect shifts in *SD*, signaling transitions between AF, SF, and BF. This enables adaptive control of injection velocity, pressure, or operational mode, ensuring both safety and efficiency. Overall, the integration of fractal roughness, multiscale shear deformation, and pressure-based prediction provides a scientifically grounded framework for understanding and regulating two-phase flow in fractured reservoirs.

5.4. Applicability to Fractured Reservoirs and Limitations

While the present study provides a systematic investigation of gas–water two-phase flow evolution in a single rough fracture, several factors relevant to reservoir-scale applications merit further discussion.

Natural reservoirs are typically composed of interacting fracture networks rather than isolated fractures. In such systems, flow partitioning at fracture intersections, pressure interference among connected fractures, and preferential transport through fractures with heterogeneous apertures may introduce additional complexity to flow-pattern evolution, potentially shifting regime boundaries or generating mixed flow structures at the network scale. Nevertheless, these effects are ultimately reflected in the statistical characteristics of pressure fluctuations. Accordingly, the pressure-based standard deviation (*SD*) indicator proposed in this study is expected to remain applicable to fracture networks, although the quantitative *SD* thresholds distinguishing flow regimes may require recalibration when fracture connectivity and network topology are explicitly considered.

The simulations further adopt a fully water-saturated initial condition together with a velocity-controlled inlet and constant-pressure outlet, which were intentionally selected to isolate the fundamental effects of injection velocity, fractal roughness, and shear displacement. Alternative initial or boundary conditions—such as residual gas saturation, pressure-controlled injection, or transient inflow—may modify the detailed transition pathways between flow regimes. However, such variations are not expected to invalidate the monotonic relationship between pressure fluctuation intensity and internal flow morphology that underpins the proposed diagnostic framework.

In addition, matrix–fracture interactions are neglected in the current model. In real reservoirs, capillary imbibition, phase exchange between the matrix and fractures, and delayed saturation equilibration may act as buffering or damping mechanisms for pressure fluctuations, particularly during transient flow stages. These effects can be incorporated in future extensions through dual-porosity or dual-permeability formulations, while retaining the pressure-based flow-regime identification concept.

Finally, gravitational effects are not considered in this study in order to emphasize the coupled roles of inertia, capillarity, fractal roughness, and shear-induced geometric perturbations at the fracture scale. In vertically extensive fractures or low-velocity flow conditions, buoyancy-driven segregation may influence phase distribution and flow stability. As gravity also modifies the pressure field, its influence can be naturally integrated into the proposed *SD*-based framework in future work.

Overall, this study is intended to provide a fundamental fracture-scale building block for understanding multiscale two-phase flow behavior in rough fractures. Extending the pressure-based predictive framework to fracture networks, matrix-coupled systems, and gravity-influenced conditions represents a natural and promising direction for future research.

6. Conclusions

This study systematically investigated the coupled influence of injection rate, self-affine fractal roughness, and shear displacement on gas–water two-phase flow structures within rough fractures using advanced numerical simulation. By analyzing the multiscale characteristics of pressure-field fluctuations, a practical pressure-based flow-pattern identification method was established. The major conclusions are summarized as follows.

- (1) The evolution of flow structures in rough fractures is jointly governed by hydraulic forcing and multiscale geometric features. As the injection rate increases, the flow regime follows a consistent progressive transition from dispersed bubble flow, to intermittent slug flow, and eventually to continuous annular flow. This hierarchical evolution reflects the changing dominance among interfacial tension, viscous resistance, and inertial stabilization. Increasing the self-affine fractal roughness (quantified by *JRC*) intensifies asperity-induced disturbances, promotes frequent breakup of the gas core, and accelerates the transition of slug flow into bubble flow. In contrast, shear displacement generates asymmetric multiscale aperture variations that destabilize the annular interface, causing reverse transitions from annular flow to slug flow, particularly under large deformation.
- (2) A quantitative relationship between multiscale pressure fluctuations and internal flow morphology was established. Statistical analyses demonstrated that the standard deviation (*SD*) of pressure serves as a robust indicator of flow-regime stability across varying hydraulic and geometric conditions. A three-level classification criterion was proposed: $SD < 2$ corresponds to stable annular flow, $2 \leq SD \leq 20$ identifies transitional slug flow, and $SD > 20$ characterizes highly unstable bubble flow. These thresholds are consistently applicable under different injection velocities, fractal roughness levels, and shear displacements, demonstrating strong universality and robustness.
- (3) A pressure-based predictive method was developed for real-time identification of two-phase flow structures in rough fractures. The approach requires only a limited number of pressure-sensor measurements, enabling rapid and accurate diagnosis of flow-regime transitions without relying on direct visualization. Its low instrumentation requirements and operational simplicity make it highly suitable for field deployment. The methodology offers substantial practical value for on-site monitoring in natural gas extraction, providing real-time feedback for flow regulation and operational optimization.
- (4) A quantitative multiscale characterization model integrating roughness, injection velocity, and shear displacement was constructed. The model effectively captures the fractal-controlled evolution of gas–water flow structures and reveals the dominant role of roughness–shear coupling in shaping interface stability. The findings deepen the mechanistic understanding of multiphase flow behavior in self-affine fractured systems and provide an important theoretical and methodological contribution to the characterization and prediction of two-phase flow in underground reservoirs.

Overall, this work advances the fundamental understanding of multiscale two-phase flow processes in fractal rough fractures and establishes an efficient and practical framework for predicting flow-regime transitions in fractured reservoirs, offering important guidance for both academic research and engineering applications.

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H.P.; funding acquisition, H.P., K.X. and L.L. All authors have read and agreed to the published version of the manuscript.

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