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Massive fines detachment induced by moving gas-water interfaces during early stage two-phase flow in coalbed methane reservoirs

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ABSTRACT

Field observations have shown that the concentration of fines produced during the early two-phase flow stage in coalbed methane (CBM) reservoirs is much higher than single-phase water flow, leading to more frequent workover activities. The typical flow pattern in early two-phase flow is bubble-water flow, in which the liquid phase is mostly contained in the form of liquid “plugs”, separated by a series of moving bubbles/gas-water interfaces (GWIs). Here, we quantify the impact of moving bubbles/GWIs on fines detachment, aiming at better understanding of fines mobilization mechanisms in bubble-water flow towards their effective control. First, fines migration tests in the absence and presence of moving bubbles in water flow, including effluent and permeability measurements, were conducted on fractured coal plugs. The experimental flow velocity was less than the critical flow velocity (CFV) for massive fines release. Experimental results showed that both peak effluent concentration and permeability impairment in the presence of moving bubbles were much greater than when absent, indicating that the quantity of fines detached by moving bubbles/GIWs was much larger than simply by water flow. Second, forces and torques acting on coal fines were analyzed to determine the combined effects of extended Derjaguin-Landau-Verwey-Overlook (DLVO), hydrodynamic, surface tension, and frictional forces on fines mobilization. Theoretical results showed that all *in-situ* fines could be mobilized by moving GWIs, whereas no fines could be released by water flow when the flow velocity is smaller than the CFV, as the surface tension force arising from passing GWIs greatly dominates hydrodynamic forces by 2–4 orders of magnitude. Theoretical results support experimental data, in spite of some errors due to model assumptions, i.e., spherical fines and homogenous surface.

1. Introduction

Coalbed methane (CBM), as an important and well-considered natural gas resource, has received increasing attention in the past decades, particularly in China, Australia, USA, and Canada [1,2]. In the near future, CBM production is also expected to increase due to more reservoirs discovered and new technological innovations. Typically, the drainage process of CBM reservoirs can be divided into four stages: stage I – single-phase water production (initial dewatering), stage II – gas-water two-phase production, stage III – stable gas production, and stage IV – declined gas production (Fig. 1) [3]. Field measurements show that *in-situ* coal fines, originating from tectonic deformation, drilling, completion as well as hydraulic fracturing can be produced throughout the entire production process, and the coal fines yield varies greatly during different production stages [4–7]. Taking CBM wells in the eastern Ordos basin for an example [7], the distributions of fines size during stages I, II and III were 0.2–2000 μm, 0.2–1000 μm, and 0.2–105 μm, respectively; and the ranges of fines concentration were 0.3–1.0 mg/L, 0.3–2.3 mg/L, and 0.3–0.5 mg/L, respectively. The coal fines can block flow paths (i.e., cleat/fracture and proppant-filled fracture) during the migration process, which consequently impairs the permeability and reduces production rates of gas and water. Furthermore, some can also transport into the wellbore, leading to a series of downhole accidents (e.g., formation burial, pump stuck, and even production breakdown), after which workover activities are required [8]. For these reasons, fines migration trigged by gas and water flow has been recognized as one of the key issues that restrict the high-efficiency development of CBM reservoirs.

With the increasing awareness of fines-induced problems, *in-situ* migration of coal fines has been widely researched for the past several years, but mainly focusing on the dewatering phase. Bai et al. [8] and Guo et al. [9] conducted water core flooding experiments to examine the yield of coal fines and the evolution of permeability under different pressure drops across the core, and concluded that the production of

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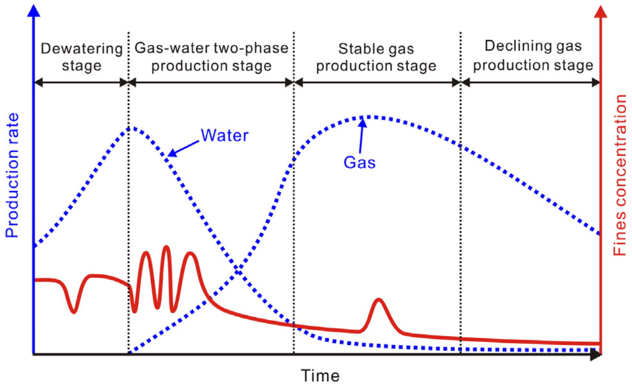

Fig. 1. Schematic of typical gas and water production stages and corresponding fines production concentrations in CBM reservoirs. The profile of fines concentration is adapted from field experimental data in Li et al. [6].

coal fines was accompanied by a gradual decline in permeability with fluctuations. In our previous research [10], the impact of the pressure gradient/pressure drop on fines released in coal fractures was also investigated under water-saturated conditions. A critical pressure gradient (CPG) exists for massive fines mobilization. Below the CPG, only a small quantity of fines can be produced and the permeability slowly decreases. Beyond the CPG, large amounts of fines can be mobilized, and the permeability significantly deteriorates. The CPG exhibits a strong negative relationship with fracture aperture. Tao et al. [5] investigated the influence of flow velocity on coal fines migration, and concluded that there is a critical flow velocity (CFV) for fines migration. Below the CFV, fine particles can be discharged from the coal sample, and the permeability consequently increases. Above the CFV, flow paths can be blocked by coarse particles, decreasing permeability. This was referred to as the “flow velocity sensitivity”. Additionally, the grain-scale mechanisms of fines mobilization were also theoretically explained. Mitchell and Leonardi [11] developed an explicit numerical model to simulate mono-sized fines detachment and transport in coal fractures during the dewatering stage, based on the coupled lattice Boltzmann-discrete element method. In our previous research [10], a mathematical model was proposed to describe the detachment of size-distributed fines in coal fractures, accounting for the torque balance between hydrodynamic and Derjaguin-Landau-Verwey-Overlook (DLVO) forces. Our modeling results revealed that the pressure gradient required for fines detachment initially decreases and then increases with increased fines size.

Field experimental results illustrate that the concentration of coal fines produced during the early two-phase flow stage is typically much larger than that during the single-phase stage (Fig. 1), which consequently results in more frequent workover treatments [7,12]. For this reason, *in-situ* fines behavior during the early two-phase flow stage should be of greater concern than the single-phase flow. Li et al. [13] and Yi and Xing [14] showed that the typical flow pattern at the early two-phase flow stage is the bubble-water flow (i.e., bubbly/slug flow in Rahim et al. [15]); the liquid phase in this flow pattern mostly exists in the liquid “plugs” form, separating successive bubbles. Previously, research about coal fines behavior in two-phase flow conditions has also been published. Bai et al. [16] investigated the micro-mechanisms of fines generation under both gas-drive-water and water-drive-gas flow conditions using a coupled hydro-mechanical model, and found that more coal fines were generated in two-phase flow than single-phase flow. In addition, Bai et al. [8] experimentally revealed that the change from single-phase gas flow to water-drive-gas flow resulted in significant permeability drop, due to fines generation and migration. But nonetheless, the studies in Bai et al. [8,16] are not without limitations: (1) the flow regimes considered in their research cannot fully reflect the actual flow pattern during the early two-phase flow stage; and (2) there is no quantitative theoretical explanation of why fines can be mobilized by the two-phase flow.

The objective of this study was to improve the understanding of the mechanisms controlling fines release in bubble-water flow. Different from a single-phase flow, in bubble-water flow there is a series of moving bubbles or gas-water interfaces (GWIs) present in the fluid phase. Thus, we hypothesized that these bubbles/GWIs play a significant role in fines mobilization. First, fines migration tests both with and without moving bubbles present in the flow were conducted on two fractured coal samples with different apertures. The measurements included permeability and breakthrough concentration, which indicated the effects of moving GWIs on fines mobilization. Second, theoretical analysis of forces/torques acting on fines was performed to elucidate grain-scale mechanisms for fines release trigged by bubble-water flow. Finally, theoretical calculations were compared with experimental results. This work provides a useful guideline as to how to alleviate fines issues during two-phase flow.

2. Theoretical considerations

2.1. Analysis of forces acting on coal fines

Coal cleats/fractures are initially saturated with water and are considered to be the main space for coal fines generation and mobilization [16]. With the reservoir pressure depleted during CBM production, methane starts to desorb from the internal surface of the coal matrix and diffuse into the cleat/fracture system as soon as reservoir pressure is smaller than the critical desorption pressure [17]. It can be imagined that the diffused gas molecules have to gather into discontinuous bubbles (i.e., bubble-water flow) before forming a continuous phase (Fig. 2a) [14]. In order to determine the mechanisms of *in-situ* fines detachment induced by bubble-water flow, analysis of the forces acting on the fine particles that are attached to a fracture surface need to be performed first, with some simplifications such as separating spherical particles, homogeneous surface, and laminar flow.

The interaction between fine particles and the bubble-water flow can be divided into three separate cases of interaction: (i) fines interacting with water flow (Fig. 2b); (ii) fines interacting with advancing fronts (Fig. 2c); and (iii) fines interacting with receding fronts (Fig. 2d). Forces acting on fines for case i include hydrodynamic forces (i.e., drag force F_d and lift force F_l), adhesive force F_a as well as frictional force F_f. For cases ii and iii, additional forces such as surface tension (capillary) force F_γ are also acting on the fines. Both adhesive force and frictional force hinder fines mobilization, whereas hydrodynamic forces and surface tension force contribute to fines release from the fracture surface. Gravity and buoyancy forces in fact also act on fines. Nevertheless, they are often neglected for fines with radii $< 500\,\mu\text{m}$ [18]. The expressions for all forces are as follows.

2.1.1. Hydrodynamic forces

Under a laminar flow regime, the drag F_d [MLT^{-2}] and lift F_l [MLT^{-2}] forces experienced by fines adhering to the fracture surface (assuming negligible inertial effects) can be calculated by [19–21]:

$$F_d = 1.7009 \times 6\pi\mu r^2(\partial u/\partial z) \tag{1}$$

$$F_l = 81.2\sqrt{\rho_l\mu}\,r^3(\partial u/\partial z)^{1.5} \tag{2}$$

where the leading coefficient (1.7009) is related to the fracture wall effects; μ [ML^{-1}T^{-1}] is the absolute viscosity of the fluid; r [L] is the fines radius; u [LT^{-1}] is the fluid velocity in the y direction; ρ_l [ML^{-3}] is the fluid density; and $\partial u/\partial z$ [T^{-1}] is the fluid shear rate at the center point of fines, which is derived from Poiseuille's law:

$$\frac{\partial u}{\partial z} = \frac{6Q}{WH^2}\left(1-\frac{2r}{H}\right) \tag{3}$$

where Q [L^{3}T^{-1}] is the flow rate of the fluid; W [L] is the fracture width; and H [L] is the equivalent hydraulic aperture (EHA) of the