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Formation damage and improved recovery in kaolinitic high enthalpy gas fields with fabric geological settings

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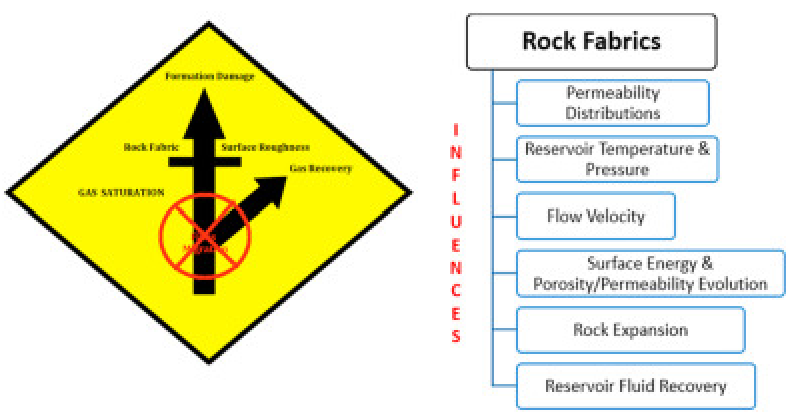
Highlights

- High enthalpy fluid flow enhances the mass transfer of kaolinite and rock expansion.
- Rock expansion creates new surface energy in the sandstone rock.
- Rock fabric contributes in the elevation of reservoir temperature and velocity of gas flow.
- Under high reservoir temperature kaolinite has undergone a compaction.
- Huge amount of kaolinite is trapped between rock teeth and thereby enhancing the gas recovery.

Abstract

This paper investigates the fines migration and transport in natural gas reservoirs as a function of porous rocks with fabric geological settings. So, an analytical and surface thermodynamic model was developed for high temperature permeable media. Two sets of core flood experiments were conducted under normal (50°C) and high temperature (150°C) fluid flow, where the major results revealed that there is an increase in the rock core thermal expansion of 57 $\left(10^{-6}\,{}^{\circ}C^{-1}\right)$ and 192 $\left(10^{-6}\,{}^{\circ}C^{-1}\right)$ at 50°C and 150°C. The rock core underwent a thermal strain to 0.36% and 0.86% under normal and higher temperature conditions. At 50°C the pressure stabilized to 20 psi and 50 psi was recorded as the peak pressure under 150°C rock temperature. The fines concentration under higher temperature is significantly higher than the normal rock temperature and yielded maximum up to 77.28 ppm. The rock permeability exhibited a linear and stabilized decline, but at higher temperature new surface energies was created in the rock core and as a result, the reservoir permeability begun to rebound. Microstructural images revealed that the kaolinite clay fine particle under 50°C has a platelet structure and has multiple straining mechanism. Whereas, under higher temperature the clay fines have transcended to compaction over the rock surface fabrics. Exponential gas recovery of 15% and 25% was observed for both 50°C and 150°C cases. In the former case, a linear growth rate to 25% was noted and then gradually it fell to 12.9%. While, in the latter case the gas recovery rate climbed to 33.7% and stabilized, which indicates that the gas recovery rate was monotonous. The experimental and analytical models have been verified using multiple linear regression method and the model's outcome revealed an excellent agreement whose R^2 values were found to be 0.9997 and 0.9995.

Graphical abstract



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Introduction

The world is still relying on the fossil fuels for fulfilling their energy needs even after global pandemic Covid-19 (Erias and Iglesias, 2022). Specifically, the natural gas demand is in the exponential growth and this stimulate the natural gas producing companies to explore and produce gas in enormous quantity unlike before from existing and new fields across the globe (Safiyari et al., 2022), and as a result, there is an expansion and optimization of global natural gas supply chain network (Sharma et al., 2021). Moreover, Karakurt and Aydin (2023), analysed the fossil fuels demand and supply in BRICS and MINT nations, and their CO_2 emissions forecasting using Regression Models. Their modelling outcomes indicated that BRICS and MINT countries will dominate the world economy in fossil fuels, especially the natural gas business and they will be the largest emitter of CO_2. Hence, there is a strong outlook for worldwide natural gas demand and it is essential to explore, extract, store, and utilize the existing and new gas reserves for meeting the global energy demand. Enhancing the gas production should be the primary criteria for energy companies and governments. But gas fields containing clay minerals deposits, particularly kaolinite often induce reservoir formation damage that is permeability decline and plummet the well production (Prempeh et al., 2020; Kanimozhi et al., 2018; Russell et al., 2017; Zeinijahromi et al., 2012).

Kaolinite clay is ubiquitous and bountiful in oil and gas reservoir rocks (Jiang, 2012). Actually, the layered silicate mineral kaolinite clay ($\mathrm{Al_2Si_2O_5(OH)_4}$) is a family of phyllosilicates in which its solid-state chemistry comprises of oxygen atoms bonded with a silica tetrahedral sheet to an alumina octahedral sheet (Kanimozhi et al., 2021) and this clay occurs due to weathering and dissolution of feldspar, which is native to siliciclastic sedimentary rocks (Kanimozhi et al., 2019a). Kaolinite clay is prevalent in sandstone rocks, which is frequently prone to permeability deterioration (Kanimozhi et al., 2020). Although, carbonate rocks are poor in clay minerals, but in some oil and gas carbonate fields kaolinite influencing reservoir triggers permeability decline due to higher grain density, geochemical reactions during permeating fluid flow, temperature, etc (Aoyagi and Chilingarian, 1972). Long back there were field reports of kaolinite presence in carbonate reservoirs, for example Bombay High oil field in India during 1981 (Rao, 1981), and most recently in Malaysian offshore carbonate gas field (Sazali et al., 2020). In general fines are bounded to rock surface and are under the influences of four forces namely, lift (F_l), drag (F_d), electrostatic (F_e) and gravity (F_g). Actually, the F_e *and* F_g hold the clay fine particle over the rock surface, while, F_l *and* F_g detach it from the rock surface (Mahalingam et al., 2019; Zeinijahromi et al., 2016). Generally, fines have a size of order 1 μm (Wang et al., 2012; Raha et al., 2007;

Khilar and Fogler, 1998). Commonly, a fine particle over a pore surface is held by a torque balance criterion, as mentioned by the below equation (Yang et al., 2016; You et al., 2016):

$$\frac{\partial(\varphi c+\sigma_s+\sigma_a)}{\partial t}+U\frac{\partial c}{\partial x}=0 \text{where}$$

$\sigma_s+\sigma_a = Concentrations\ of\ attached\ and\ strained\ fines, U = Darcy\ velocity, c = Volumteric\ concentration\ of\ suspended\ particles, t = time, \varphi = Porosity\ and, x = Distance$.

Fig. 1 shows the schematic diagram of fines behaviour in a gas reservoir and Table 1 presents the mathematical conditions for fines attachment and detachment in the permeable media. Due to permeating fluid, temperature, ionic strength, and surface heterogeneity the fines are detached from the rock surface and transport in the porous interspace along with the carrying fluid and in end these fines are captured in the pore-throat and thereby blocking the space for oil, gas, and water transport/recovery to the well, which overall decrease the permeability and surface well production (Zhou et al., 2022; Lin et al., 2021; Trauscht et al., 2015; Schembre and Kovscek, 2005). Furthermore, Russell et al., 2018a, Russell et al., 2018b, conducted laboratory modelling to examine the kaolinite content effects on formation damage in unconsolidated sandstone rocks due to fines migration during low-salinity water injection. The authors have taken five cores for analysis with kaolinite weight percentage ranging from 1% to 10%. The $\mathrm{Al_2Si_2O_5(OH)_4}$ along with $NaCl$ solutions were sequentially injected in the cores in order to investigate the permeability decline. The major experimental results revealed that kaolinite presence has declined the rock core permeability and also, it was predicted that the rock mineralogy and pore-geometry play a considerable role triggering formation damage. Additionally, Pranesh et al. (2019), investigated the kaolinite fines migration in CBM reservoir at Neyveli Lignite Field, Cauvery Basin, Southern India. The authors conducted a laboratory modelling and analysis for evaluating the formation damage, which includes permeability decline, coal fines production, and structural collapse. Therefore, they conducted three sets of coreflood experiments at ambient conditions. The main results indicated that even at normal room temperature the lignite core has undergone a deterioration in permeability, structural collapse, gas recovery, and increase in coal fines, due to kaolinite clay migration during gas flow. Specifically, the kaolinite clay mineral fine particle structure, in this case it is flake (geometry) has strained the rock cleats and pore-throat, and causing permeability decrease. Hence, it is emphasized that all gas fields are prone to reservoir formation damage under the existence of kaolinite clay.

On other side, there were early reporting of positive aspects of fines migration (mostly clay minerals-kaolinite in specific) in which fines assist in the recovery of oil, gas, and water by fluid flow diversion, subsurface strata structure and wettability alterations (Borazjani et al., 2017; Hussain et al., 2013; Zeinijahromi et al., 2011). For instance, Nguyen et al. (2013), studied the fines-migration-assisted improved gas recovery during gas field depletion. Authors have applied the concept of permeability deterioration in order to reduce the production of water during gas field depletion. Their concept and aim are to decelerate the intruding the aquifer water by injection of a little volume of fresh water into an abandoned watered-up well. They have derived an equation for the immiscible compressible two-phase fluid with fines mobilization and capture. Those equations are transformed to the black-oil polymer flooding model in large scale approximation. The fresh water bank injection considerably improves the gas recovery and reduces the production of water, which was revealed in reservoir simulation modelling results. Moreover, in a recent study, Mehdizad et al. (2022) performed a visual inspection and analysis on the effects of clay-induced fluid flow diversion on oil recovery, as a mechanism of low salinity water flooding. The authors conducted an investigation on sandstone rocks in order to increase the oil recovery with help of fines migration. The results shows that the during low salinity water flooding the clay fines has undergone swelling and migration. There was a wettability alteration and fluid diversion phenomenon, which lead to incremental oil recovery. Ultimately, the authors claim that presence of clay in reservoirs is essential in order to enhance the oil production.

Gas bearing reservoir rocks are of high enthalpy, which means having huge amount of heat contents in other words it is called a thermal potential (Pranesh and Ravikumar 2019). Mostly, rock enthalpy is often spoken and associated with geothermal rocks (High and Low Enthalpy), but it is also applicable to oil and gas reservoirs. During water and CO_2 injection in oil and gas reservoirs the fluids act as a heat transfer fluid, which liberates the heat (enthalpy) from the rock to assist in the sweep, transport, and recovery. But this scenario frequently causes formation damage. However, in this paper the reservoir gas act as a heat transfer fluid (HTF) and actually HTF is a gas or liquid that participate in the process of transferring heat to the designed medium or phase reaction. Its main role is to transport and store the thermal energy (Kanimozhi et al., 2017, 2019b; Weiguo et al., 2016; van der Stelt et al., 2015). Actually, HTF is a fascinating concept, which is common and popular energy acceleration method in mechanical and thermal engineering fields, but to our best of our knowledge this technique is not applied and almost unprecedented to the reservoir engineering community. So, this paper makes an audacious attempt to analyse the fines behaviour and improved gas recovery in porous sandstone rock with fabric geology.

Rock fabric or fabric theory is fundamentally indicating the rock pattern and actually, it is an arrangement of elements such as textures, layers, fossils, and minerals that make up the rock (Gokhale, 2019; Singh, 2013; Wall, 2006; Ghosh, 1993). Geologic fabric theory describes the spatial and geometric configuration of rock texture which includes surface roughness, cleats, cracks, fissure, and fractures (Hobbs et al., 1976). In reality, all reservoir porous rocks are fabric in nature and to be specific, its pore walls have fabric design (Britannica, 2022; Hills, 1963; Davis et al., 2011; Fossen, 2010). Its major types are primary, shape, crystallographic, S-fabric, L-fabric, and penetrative fabric (Twiss and Moores, 2007). However, in this paper the rock fabric denotes the surface roughness or technically speaking the rock fabric is a function of surface roughness. Fig. 2 presents the general rock expansion coefficient with respect to increasing temperature at normal and high temperature during gas and heat flow. This research just focuses on the shape fabric and penetrative fabric. Actually, the former deals with the specific rock's inequant elements orientation and structures, and the latter describes about the grain scale that is the entire rock is composed of fabric (Passchier and Trouw, 2005).

In certain research, surface roughness parameter is seen as a potential influencer in fluid flow pattern, particle retention, wettability alteration, and fracture creation (Zhang et al., 2021; You and Lee, 2021; Li et al., 2021; Geistlinger et al., 2016; Argent et al., 2015). Literally, Huang et al. (2022) analysed the surface roughness influences on methane flow in shale kerogen nano-slits. Actually, the authors conducted numerical simulations to evaluate the velocity and mass flow rate of CH_4 flow in nano-pores of real kerogen. Also, a new mathematical model was developed to quantify this phenomenon and their results showed that the transport phenomena is largely affected and the authors emphasize that it is critical and vital to understand the methane flow mechanism in kerogen nano pores for accurate evaluations of gas recovery in shale formations. Obviously in cases like this there would be a heat dissipation and thermal diffusivity. For instance, Askari et al. (2018) studied the thermal conductivity in deforming isotropic and anisotropic granular porous media with rough grain surface. The authors examines that the porous materials (grain) with rough surface would undergo a deformation to a compressing pressure. Single fluid saturated porous media affects the grain conductivity, size (geometry) and shall deform. Moreover, the thermal conduction is largely influenced by surface roughness and porosity. Also, larger anisotropy appears when the granular porous media is at the function of surface roughness.

Therefore, the main objective of this paper is to evaluate and quantify the sequential formation damage and subsequent, gas recovery in sandstone rock with rough pore surface during single-phase fluid flow. Furthermore, to investigate the kaolinite fine particle geometry and propose a formation damage mechanism, and also, to support and claim the necessity of kaolinite presence in gas reservoirs for enhanced gas recovery.

Section snippets

Thermodynamics of wettability

Naik et al. (2015), studied the influence of wettability alteration on rate enhancement in unconventional gas reservoirs. Firstly, the authors analysed the water blockage problem due to the capillary end effect near the fracture face and vicinity of wellbore is a potential threat to gas production. They have proposed a solution to this problem by alteration in wettability which can also be applied to dewater acceleration and prevention in the drilling fluid leak off. Since rock surface…

Materials and methods

This section presents the materials and methods that were employed in this investigation. Actually, two sets of coreflood flow test experiments were performed at the temperatures 50°C (Normal Temperature, NT) and 150°C (High Temperature, HT).…

Results and discussions

This section explores the results that were acquired in the experimentation. A critical analysis and serious discussions were made. Fig. 6 shows the total enthalpy release with respect to increasing time. The total enthalpy is the summation of enthalpy of permeable reservoir rocks and transporting fluid (Kanimozhi et al., 2020). Already it was mentioned that enthalpy indicates the quantity of heat release or heat content (thermal potential). It can be seen from Fig. 4 that for both normal…

Conclusions

Reservoir temperature escalation, fines migration, and productivity decline are a syndrome of formation damage and well impairment. Tackling and mitigating fines migration during soaring rock temperate is a great challenge to engineers and researchers. Several studies reported the causes and solutions for reducing the intensity of this problem and also, few work demonstrated the positive aspects of fines migration in which clay particle migration leverage the fluid production to surface. Hence, …

Credit author statement

B. Kanimozhi: Experimental Setup and Work, Model Prediction, Calculation; P. Rajkumar: Rock Core Examination and Clay Minerals Characterization; S. Mahalingam: Experimental Setup and Work, and Supervision; S. Senthil: Experimental Setup and Work, SEM Interpretation; D.S. Jayalakshmi: SEM Interpretation and Sample Physical Properties Examination; H. Girija Bai: Data Evaluation, Calculation and Analysis; Vivek Thamizhmani: Data Evaluation, Calculation and Analysis; Ramadoss Kesavakumar:…

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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