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Physical and analytical modelling of permeability damage in bituminous coal caused by fines migration during water production

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ABSTRACT

This study presents a systematic experimental methodology to investigate permeability damage caused by fines migration. The workflow starts with a thorough characterization of a bituminous coal sample by the XRD, SEM-EDX, petrographic, proximate and ultimate methods. Then, a single-phase water flow test is conducted on the coal sample whose surface is covered with Araldite resin to eliminate coal creep. The water permeability is monitored continuously and produced water samples are collected at regular intervals. The produced water samples are tested for conductivity, ionic concentration and fines concentration and sizes. Finally, the produced fines are separated from water using a membrane filter and the fines are examined using the SEM-EDX analysis. The theory of maximum retention function is used to investigate the fines release mechanism.

Experimental results indicate a ~35% decline in coal permeability during 33 days of water flow. The produced fines are mostly coal and coal-clay mixtures, which is different from the observation of Guo et al. (2015) for the anthracite coal where the majority of fines were clay only. Analytical modelling suggests that the major controlling parameters for fines migration during the flow test are the flow rate, interaction energy and coal characteristics. The analytical model also reveals that most of fines are mobilized in the beginning of the flow test.

1. Introduction

Coal seam gas (CSG) production is strongly affected by coal permeability. The widely-studied major factors that affect coal permeability are the stress state and gas desorption (Seidle, 2011). Yet, there are also claims that clay swelling, mineral dissolution and precipitation, and fines migration can alter coal permeability. Swelling clay, such as montmorillonite and smectite-illite mixed layer, is capable of expansion in volume when contacted with water. The expansion can reduce the cross-sectional area of the cleats in coal. The dissolution and precipitation of minerals within coal may also alter porosity and permeability. Decrease in coal seam pressure during CSG production reduces the solubility of carbonate in water which leads to carbonate precipitation in the cleat system (Moghadasi et al., 2007; Connell et al., 2008).

Fines migration in porous rocks is a process which involves particle detachment from the grain/matrix surface, migration with flowing fluid, and retention at narrow flow paths or re-attachment onto other grain/matrix surfaces. Fines migration in sandstone reservoirs and its effect on permeability for formation damage have been studied extensively (Mohan et al., 1993; Mohan, 1996; Khilar and Fogler, 1998; Tang and Morrow, 1999; Civan, 2000; Bedrikovetsky et al., 2011; Hussain et al., 2013; Bedrikovetsky and Caruso, 2014; Yuan et al., 2015, 2016). Yuan et al. (2015, 2016) used nano-technology to control fines migration in deep water reservoirs. However, in coal, the knowledge of fines migration in CSG reservoirs and its effect on production performance has not been examined thoroughly.

Fines migration in coal has been observed in the field. Field studies show that the mineral content of fines is 10%–30% higher than that of coal (Chen et al., 2009; Massarotto et al., 2014). Clay particles are believed to be one of the major components of fines that can be mobilized and retained to cause permeability damage in different sandstones (Mohan et al., 1993; Mohan, 1996; Khilar and Fogler, 1998; Civan, 2000). Liu et al. (2011) presented a comparison of produced fines in different phases of CSG production from the South Quinshui Basin in China. They reported that the average size of the produced fines decreases from about 8 mm in the early phase of dewatering to smaller than 1 mm in the later phase of gas

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Symbols

c	Concentration of suspended fines
g	Gravitational constant or a function
h	Separation distance
p	Pressure
r	Radius
s	Concentration of attached fines or concentration of trapped fines
t	Time
x	Distance coordinate
C	Dimensionless concentration of suspended fines
F	Force
H	Cleat aperture
J	Dimensionless permeability
K	Permeability; solubility product or ionization constant
L	Length
P	Dimensionless pressure
S	Dimensionless concentration of trapped fines or attached fines
T	Temperature
U	Flow rate
V	Interaction energy
X	Dimensionless distance coordinate
Y	Conductivity
α	Coefficient of permeability damage by fines attachment
β	Coefficient of permeability damage by fines trapping
δ	A function of F_e and U
λ	Coefficient of fines attachment, straining or detachment rate
μ	Viscosity
ρ	Density
τ	Factor of drift delay
χ	Coefficient of hydrodynamic lift force
ω	Coefficient of hydrodynamic drag force
Φ	Porosity

Subscript

a	Attached
c	Filter cake
e	Effective or electrostatic
m	Maximum retention function
o	Initial
p	Pore; fines
r	Release/detachment
s	Strained/trapped
B	Breakage
D	Dimensionless
T	Total
aq	Dissolved in water
so	solid

Superscript

f	Concentration front

production. During the gas production phase gas desorption effect may also affect the fines migration. Although, two-phase gas/water flow has been addressed before (Moghanloo et al., 2015), the effect of desorption on fines migration has not been studied.

Some laboratory studies have also reported results which suggest permeability variation due to fines migration in coal (Gash, 1991; Hyman et al., 1990; Nick et al., 1995; Zhang et al., 2011; Keshavarz et al., 2014). Review of these studies about fines migration reveals a number of shortcomings as listed below:

(i) Effluent water was not investigated. Characterization of produced fines and dissolved elements in the effluent water would explain the mechanism of permeability variation in coal.
(ii) Coal characterization (coal rank and mineralogy etc.) was not conducted. Any correlation between the permeability variation and coal rank and mineralogy could help us to understand whether these parameters have any impact on the permeability variation.
(iii) The effect of coal creep was not separated from that of fines migration in the permeability variation. So, it was difficult to analyze and conclusively demonstrate the impact on coal permeability of each mechanism.

In the preceding paper of this study (Guo et al., 2015), epoxy-coated anthracite coal sample was used to minimize the stress effects in the single-phase water flow tests. The effluent water samples were collected and analyzed. The coal sample was characterized using various techniques such as XRD, proximate test, and ultimate and petrographic analyses. This approach has eliminated the limitations of previous studies. In the present paper, an improved experimental methodology is presented to study the impact of coal type and rank on permeability damage during water flow. Bituminous coal sample is used in this study. The theory of maximum retention function (Bedrikovetsky et al., 2011) is applied to simulate the permeability damage and interpret experimental results for fines migration mechanisms.

This study improves our understanding of the permeability change in bituminous coal caused by fines migration under laboratory conditions. The laboratory experiment was designed in a way to exclude/minimize any effect of other controlling parameters on coal permeability change (stress, adsorption/desorption, clay swelling, mineral dissolution/precipitation) than fines migration so that the impact of fines migration on permeability change could be assessed directly. As such, the outcomes from this study serve the purpose but may not be directly applicable in the field.

2. Experimental methodology

A cylindrical coal sample is drilled from a coal block. The length and diameter of the coal sample are 7.0 and 3.8 cm, respectively. The coal sample is carefully assembled in a stainless pipe as shown in Fig. 1. The sample is then jacketed by the stainless steel radially with inlet and outlet parts covered by epoxy. This sample preparation allows us to run the flow tests with no confining stress.

2.1. Water flow test

Filtered distilled water is used to vacuum-saturate the coal sample as described in the preceding paper (Guo et al., 2015). Then, the epoxy coated sample is connected to a pump to inject filtered distilled water. The flow test consists of four phases. In the first three phases, the injection pressures are 45, 75 and 105 psi, sequentially, while the outlet is kept atmospheric. Afterwards, the flow direction is reversed at the last injection pressure. An ISCO pump is used for water injection, which facilitates recording the