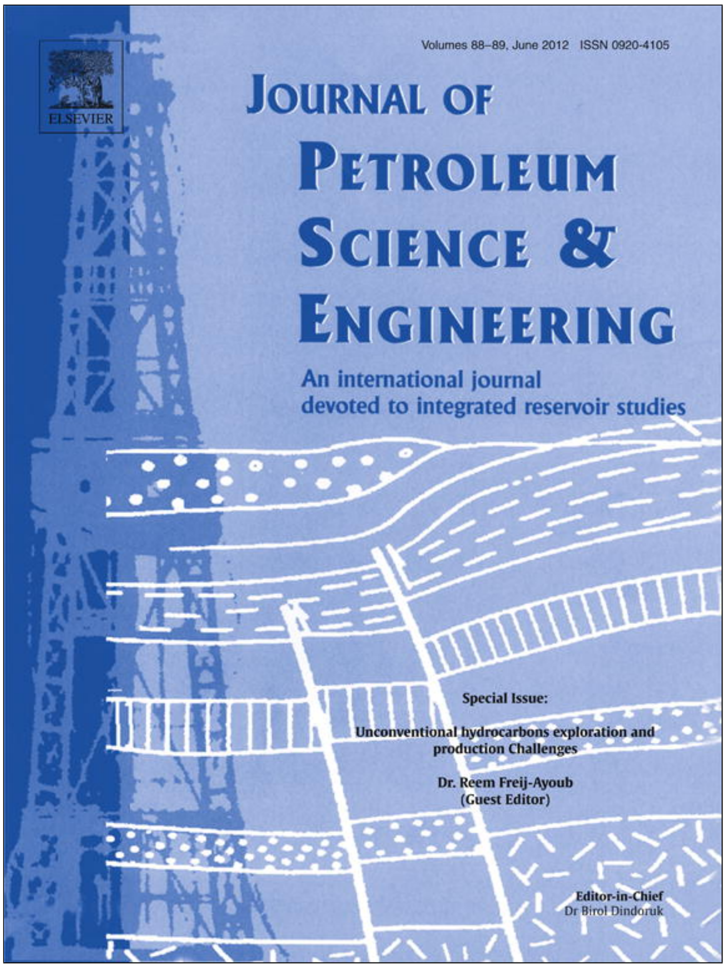
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Well impairment by fines migration in gas fields

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ABSTRACT

Well productivity decline has been widely observed for gas wells producing reservoir fines. The phenomenon has been explained by lifting, migration and subsequent plugging of the pores by the fine particles, finally resulting in permeability decrease. It has been observed in numerous core flood tests and field cases. The new basic equations for the detachment of fine particles, their migration and size exclusion, causing the rock permeability decline during gas production, have been derived. The analytical model developed for the regime of steady state gas production with a gradual accumulation of strained particles, exhibits linear skin factor growth versus the amount of produced reservoir fines. The modelling results are in a good agreement with the well production history.

1. Introduction

Extremely low-permeable gas reservoirs form a majority in the current exploitation market for unconventional gas production including shale gas reservoirs, tight gas sands and gas producing coal beds. Low well productivity and high skin factor are the major problem during exploitation of low-permeable unconventional gas fields.

Well productivity decline under fines production is a well known phenomenon in the low consolidated and high clay content reservoirs, as well as in the heavy oil and high rate gas fields (Civan, 2007; Lever and Dawe, 1984; Mungan, 1965; Tiab et al., 2004; Watson et al., 2008). This decline is due to detachment of the in-situ particles and clay fines by drag and lifting forces from the moving fluid when the mobilised fines plug thin pores causing the decrease in permeability.

The previous publications report transportation of the fine particles by a wetting fluid–water in the case of gas–water flow (Bennion and Thomas, 2005; Bennion et al., 2000; Miranda and Underdown, 1993). Although it is considered that gas phase does not transport the fines, their migration has been observed in many gas reservoirs prior to water movement (Paveley, 2002; Watson, 2001). High pressure draw downs with the exploitation of low-permeability unconventional gas reservoirs or with high rate wells in conventional gas fields may cause mobilisation of fines with consequent decline in well productivity. In low-permeable reservoirs, fines may be formed by booklets of kaolinite clays, hairy illite clays, silt particles, uncrystalline silica, quartz, feldspar, etc. (Byrne and Waggoner, 2009; Byrne et al., 2010). Significant decline in gas well productivity due to fines migration and straining has been reported in the literature (Byrne, 2010). Decision making on well stimulation in unconventional gas reservoirs is based on reliable productivity prediction by the field-data-based mathematical models.

Kinetics of particle capture by a rock from the flowing suspension is described by the filtration equation (Herzig et al., 1970; Vafai, 2000)

$$\frac{\partial\sigma}{\partial t}=\lambda cU \tag{1}$$

where c and σ are the concentrations of suspended and retained particles, U is the flow velocity and λ is the filtration coefficient.

Various mathematical models of fines detachment produce different expressions for particle detachment rate that is assumed to be proportional to the retained concentration and to the detaching factors such as drag force, difference between equilibrium and current velocities, difference between the equilibrium and current suspension concentrations, etc. (Civan, 2010; Ju et al., 2007; Massoudieh and Ginn, 2010; Tufenkji, 2007). The shortcoming of the models describing kinetics of particle detachment is the asymptotical stabilisation of the retained concentration and permeability as time tends to infinity, whereas fines release due to an abrupt increase in pressure gradient or decrease in salinity happens almost instantly (Khilar and Fogler, 1998; Miranda and Underdown, 1993). The corefloods with sharp rate increase show an immediate permeability response (Ochi and Vernoux, 1998).

It was long recognised that particle detachment occurs if a particle retained on the internal filter cake is not in the mechanical equilibrium (Bergendahl and Grasso, 2000; Bradford and Torkzaban, 2008;

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Bradford et al., 2009, 2011; Civan, 2007; Schechter, 1992). A particle located on the internal cake surface is under the action of electrostatic, drag, lifting and gravitational forces. Some authors consider a force balance between the drag force, acting on the particle from the bypassing fluid, and the friction force by introduction of an empirical Coulomb coefficient (Civan, 2007), while the others describe mechanical equilibrium of a retained particle as the balance of all forces moments/torques (Bradford et al., 2011; Freitas and Sharma, 2001; Jiao and Sharma, 1994). Mathematically, these two approaches are equivalent. The current mathematical models describing the detachment kinetics of a particle do not consider the mechanical equilibrium of a retained particle. Therefore, the expression for the detachment rate is not affected by the mechanical equilibrium of a single particle.

A recently developed deep bed filtration model with a migrating layer of the fine particles attached in the secondary energy minimum (Yuan and Shapiro, 2010b) also does not consider the forces acting on the retained particles.

Since these forces depend on micro parameters like particle and pore sizes, stochastically distributed in natural rocks, the detailed modelling studies on micro (pore) scale have been carried out (Payatakes et al., 1973, 1974). These include: population balance models (Bedrikovetsky, 2008; Sharma and Yortsos, 1987a,b,c), random walk equations (Cortis et al., 2006; Shapiro and Bedrikovetsky, 2008; Yuan and Shapiro, 2010a), stochastic models (Lin et al., 2009) and direct pore scale simulation (Bradford et al., 2009, 2011; Roussel et al., 2007). The population balance and random walk models, as well as large scale phenomenological models, use the kinetics detachment rate term with an empirical coefficient and also do not consider the forces, acting on a single particle.

The modified particle detachment model (Bedrikovetsky et al., 2011, 2012) is free of the above shortcomings of the detachment-rate-kinetics based models. It uses the maximum (critical) retention function instead of kinetics expressions describing the detachment rate: if the retention concentration does not exceed its maximum value, the particle capture occurs according to the classical deep bed filtration model; otherwise, the maximum retention concentration value, which depends on the flow velocity and brine ionic strength, holds. The maximum retention function is determined by the condition of mechanical equilibrium of a particle on the matrix or deposit surface, which is described by the torque balance of electrostatic, drag, lifting, adhesion and gravitational forces. Yet, this model describes just one particle capture mechanism (attachment) whereas the permeability decrease with fines migration is explained by both attachment and size exclusion.

In the present work, the new basic equations for one phase gas flow towards a well, accounting for two simultaneous fines capture mechanisms such as detachment and straining, are derived. The filtration Eq. (1) describes the particle retention rate by size exclusion, whereas the maximum retention function is used to model the attached fine particles mobilisation. Non-Darcy gas flow at high pressure gradients and varying connate water saturation are accounted for. The developed analytical model for quasi steady state gas production with fines captures the production period with stabilised suspended fines concentration near to a well along with deposit accumulation and skin growth proportionally to the amount of produced fines. The results derived from the developed analytical model are in a good agreement with the field data for gas well impairment.

The structure of the paper is as follows. Initially, we briefly describe non-Darcy inertial gas flow towards a well. A mathematical model for fines mobilisation and straining resulting in the permeability decline is presented in the third section. Then, the system of governing equations for one-phase flow towards a well with fines lifting, migration and size exclusion by the rock is derived. This is followed by the analytical model corresponding to the steady state flow towards a well (Section 5) and by the exact formulae for the productivity index vs time, which are derived in Section 6. Finally, the analytical model is tuned to the field data on well productivity decline (Section 7).

2. High speed gas flow under the presence of connate water

The particularities of high velocity gas flow in low-permeable formations near a wellbore follow the non-Darcy law of flow accounting for the flow turbulence, gas compressibility, high connate water saturation and also the variability of the connate water saturation due to high pressure gradient variation from the wellbore to the extent of the drainage area. Let us derive the basic flow equations accounting for the above factors.

The mass balance equation for axi symmetric gas flow around a vertical well is

$$r\frac{\partial(\phi(1-s_{wi})\rho(p))}{\partial t}+\frac{\partial}{\partial r}(r\rho(p)U)=0. \tag{2}$$

Initial water saturation monotonically decreases with the capillary number Nc in the well vicinity due to the increase of gas flow velocity (Mihailov et al., 1993)

$$s_{wi}(N_C)=s_w(N_c), N_c=\frac{U\mu}{\sigma_{gw}}. \tag{3}$$

The Darcy's law for a gas flow at low velocities corresponds to a non-inertial flow as follows

$$-\frac{dp}{dr}=\frac{\mu}{k_0k_{rg}(s_w)}U. \tag{4}$$

At high velocities, the flow depends on the inertial effects characterised by the Reynolds number $Ud\rho/\mu$, where the grain size $(k)^{1/2}$ is considered to be a reference length d (see Barenblatt et al., 1990). Therefore, the dimensionless parameter

$$-\frac{k_0k_{rg}(s_w)}{\mu U}\frac{dp}{dr}$$

is a function of the Reynolds number. From Eq. (4) it follows that

$$-\frac{dp}{dr}=\frac{\mu}{k_0k_{rg}(s_w)}Uf\left(\frac{U\sqrt{k_0k_{rg}(s_w)}\rho}{\mu}\right). \tag{5}$$

Let us keep the first two terms of the Tailor's expansion of function f(Re) at small Reynolds numbers. Since the expression (5) tends to the linear Darcy's law (4) with velocity approaching zero, we conclude that $f(0)=1$. Therefore, the Darcy's law (5) for small Reynolds numbers is as follows:

$$-\frac{dp}{dr}=\frac{\mu}{k_0k_{rg}(s_w)}U+\frac{B\rho}{\sqrt{k_0k_{rg}(s_w)}}U^2, B=f'(0). \tag{6}$$

Eq. (6) is called the Forchheimer's equation for flow in porous media (Forchheimer, 1901). The so-called inertial coefficient B depends on rock tortuosity, porosity and the porous space type (Civan and Evans, 1991; Geertsma, 1974).

Gas mass flow rate per unit of thickness

$$q=2\pi r\rho U, \tag{7}$$

allows expression of flow linear velocity, U, in Eq. (6) via this flow rate:

$$-\rho(p)\frac{dp}{dr}=\frac{\mu}{k_0k_{rg}(s_w)}\frac{q}{2\pi r}+\frac{B}{\sqrt{k_0k_{rg}(s_w)}}\frac{q^2}{4\pi^2r^2}. \tag{8}$$

Accounting for the equation of state for a real gas in the form

$$\rho(p) = \frac{\rho_a p}{p_a z} \tag{9}$$

and assuming constant compressibility factor, z, and constant initial water saturation, Eq. (8) becomes

$$-\frac{\rho_a p}{p_a z}\frac{dp}{dr} = \frac{\mu}{k_0 k_{rgwi}}\frac{q}{2\pi r} + \frac{B}{\sqrt{k_0 k_{rgwi}}}\frac{q^2}{4\pi^2 r^2}. \tag{10}$$

Let us consider a steady state gas flow towards the well. The flow rate q is constant. Integration of both parts of Eq. (10) with respect to r from the well radius, r_w, to the drainage zone radius, r_e, yields

$$\frac{\rho_a}{2p_a z}\left(p_e^2 - p_w^2\right) = \frac{\mu}{k_0 k_{rgwi}}\frac{q}{2\pi}\ln\frac{r_e}{r_w} + \frac{3B}{\sqrt{k_0 k_{rgwi}}}\frac{q^2}{4\pi^2 r_w}\left(1-\frac{r_w}{r_e}\right) \tag{11}$$

resulting in the following expression for the skin factor describing the formation damage due to the inertia losses at high flow rates:

$$\frac{\rho_a}{2p_a z}\left(p_e^2 - p_w^2\right) = \frac{\mu}{k_0 k_{rgwi}}\frac{q}{2\pi}\left[\ln\frac{r_e}{r_w} + \frac{3B\sqrt{k_0 k_{rgwi}}}{\mu}\frac{q}{2\pi r_w}\left(1-\frac{r_w}{r_e}\right)\right]$$
$$S = \frac{3B\sqrt{k_0 k_{rgwi}}}{\mu}\frac{q}{2\pi r_w}\left(1-\frac{r_w}{r_e}\right). \tag{12}$$

3. Fine particles detachment

Following Civan (2007, 2010), Khilar and Fogler (1998), Schembre and Kovscek (2005), Takahashi and Kovscek, 2010 and Valdya and Fogler (1992), let us describe physical mechanisms of permeability damage due to fines migration during well production period. Fine particles located on the rock grain surface are affected by electrostatic, gravitational, drag, adhesion and lifting forces (Fig. 1). The electrostatic, adhesion and gravitational forces attach a fine particle to the rock surface, whereas the drag and lifting forces tend to detach it. Equilibrium of fine particles in porous media is determined by a torque balance of attaching and detaching forces. The drag and lifting forces monotonically increase with flow velocity. At high flow velocities near to production well, where the drag and lifting forces are large, the electrostatic, adhesion and gravitational forces cannot hold some fine particles on the rock surface. As the result, the fines are detached and start migrating with the carrier fluid. The released particles migrate in porous media by passing through larger pores. Yet, the migrating fines can be captured by small pores (straining or size exclusion of fine particles) as shown in Fig. 2. The particle detachment results in some porosity increase. Nevertheless, this does not lead to any significant permeability increase, whereas the mobilised particles captured in small pores result in significant permeability decline due to pore plugging. Finally, the fine particle detachment, migration and straining cause decline in the permeability and the well productivity index. Figs. 1 and 2 show particle detachment during one phase flow, which is typical for water production with suspension filtering in aquifers.

Usually the mobilised suspended fines are transported by the phase wetting these particles (Bennion and Thomas, 2005; Bennion et al., 2000; Muecke, 1979). It seems fines migration should not occur during gas production in the presence of immobile connate water. Nevertheless, the laboratory tests show that the drag and lifting forces, acting on the particles from the high rate flux, can mobilise the attached fines and further transport them along the core. In particular, Sarkar and Sharma (1990) performed coreflood by water at the presence of residual oil in oil-wet rocks and concluded that the natural reservoir fines can be mobilised by non-wetting phase. The field data analysis on gas well impairment in low consolidated rocks also supports the idea of mobilisation and transport of fines by the moving gas phase (Byrne, 2010; Byrne and Waggoner, 2009).

At small saturations, water fills in thin pores and corners of the grain junctions; the rest of the water-wet grain surface is covered by thin poly molecular water layer (Fig. 3). In the current paper it is assumed that gas phase mobilises the fine particles attached to the grain surfaces not wetted by water. The mobilised fines are transported within the high velocity gas phase near to wellbore and are either strained in thin pores or produced together with gas.

Fig. 3 shows particle detachment during gas production in water wet rocks. The immobile connate water fills pores and grain junctions, where it "holds" fine particles. The fine particles are released from the convex surfaces and wet by thin water films, where the particles are exposed to the drag and lifting forces acting from the moving fluid.

Now, let us discuss the mathematical model for particle detachment by the drag and lifting forces.

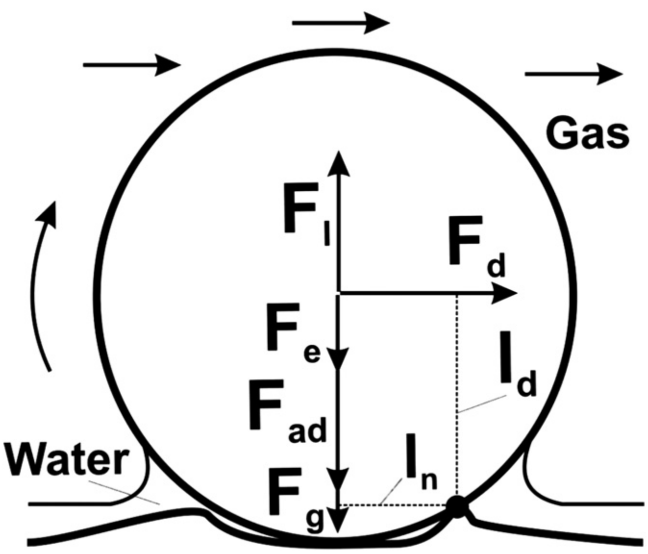

Fig. 1. Forces acting on an attached particle during gas flow in porous media under the presence of the connate water.

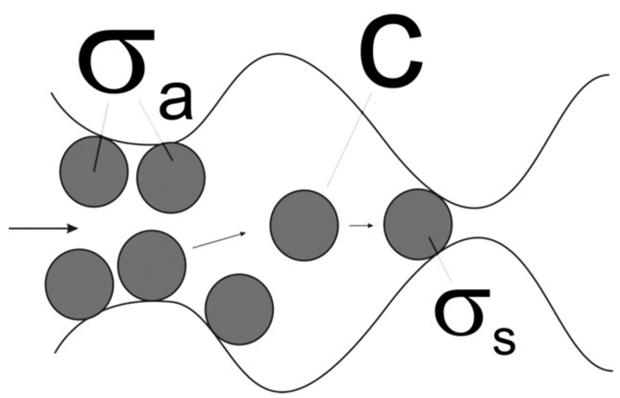

Fig. 2. Straining of detached particles in a single pore explains the permeability reduction during fines migration.

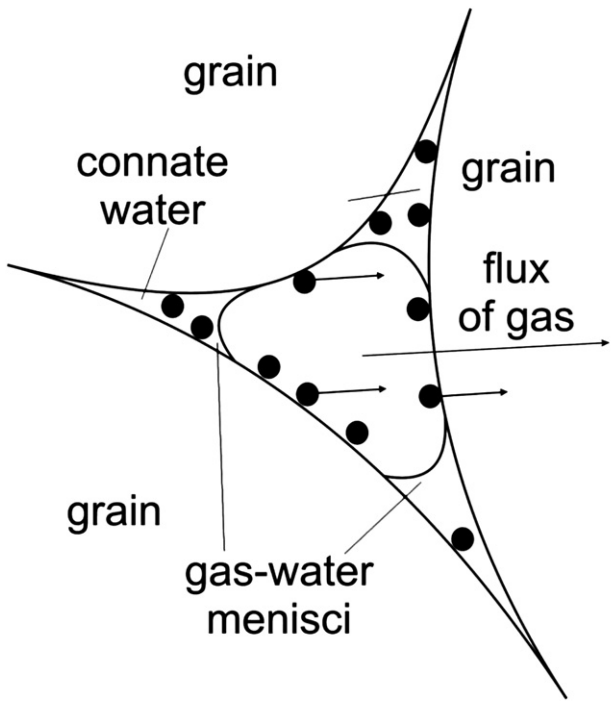

Fig. 3. Detachment of fine particles during gas production from water wet rock.

The condition of the particle mechanical equilibrium on the grain surface is the equality of the torques of the attaching and detaching forces (Civan, 2007; Freitas and Sharma, 2001; Jiao and Sharma, 1994):

$$F_e l_n + 2F_{ad} l_n + F_g l_n = F_d(U) l_d + F_l(U) l_n \tag{13}$$

where F_e, F_g, F_{ad}, F_d and F_l are electrostatic, gravitational, adhesion, drag, and lifting forces; l_n and l_d are the levers for normal and tangential forces, respectively (Fig. 1). The capillary adhesive force is included in the torque balance Eq. (13) for the cases of fines release by produced fluid from the wetting film, shown in Fig. 3.

Imagine coreflood of the rock sample containing attached fine particles with piecewise increasing rate. Terms in right hand side of Eq. (13) increase with velocity U, whereas the left hand side terms remain constant. After each velocity increase, the particles on the grain surface (for which right hand side of Eq. (13) exceeds that in the left hand side) leave the grain surface and migrate through the porous space. Therefore, the critical (maximum) retained concentration is a function of flow velocity (Bedrikovetsky et al., 2011). Since both drag and lifting forces are velocity dependent, the critical retention concentration also depends on flow velocity U.

Drag and lifting forces detach particles, which are not covered by water (Fig. 3). The particles completely immersed in immobile water in thin slots and grain intersection areas cannot be removed. Therefore, the maximum retained concentration depends also on connate water saturation as follows:

$$\sigma_a = \sigma_{cr}(U, s_{wi}). \tag{14}$$

The higher the water saturation is, the lower the grain surface area is, where the fine particles are exposed to drag and lifting forces and, consequently, the lower the maximum retained concentration is.

Dimensional velocity in Eq. (14) can be substituted by the dimensionless ratio ε between torques of the detaching and attaching forces (so-called torque or erosion ratio)

$$\sigma_a = \sigma_{cr}(\varepsilon),\ \varepsilon = \frac{{}^{l_d}\!/_{l_n} F_d(U) + F_l(U)}{F_e + 2F_{ad} + F_g}. \tag{15}$$

The critical retained concentration is a monotonically decreasing function of the fluid flow velocity.

The electrostatic force is determined by the Derjagin–Landau–Verbeek–Overbek (DLVO) theory (see Israelachvili, 1992; Khilar and Fogler, 1998). The expressions for drag, lifting and adhesion forces acting on a spherical particle located on the pore wall are also available from the literature (Bergendahl and Grasso, 2000; Chauveteau et al., 1998; Freitas and Sharma, 2001; Jiao and Sharma, 1994). They allow calculation of the maximum retention function for a single cylindrical capillary. For one-phase flow, where there is no adhesion, the maximum retention function is a quadratic polynomial of the fluid velocity under constant saturation (Bedrikovetsky et al., 2011)

$$\sigma_a(U) = \sigma_0 \left[1 - \left(\frac{U}{U_m}\right)^2\right]. \tag{16}$$

Here, $\sigma 0$ is the maximum concentration of fine particles attached to the grain surface when gas is motionless, and *Um* is the minimum velocity for which no particle can be held on the grain surface by the electrostatic, adhesion and gravitational forces.

High production rate results in high flow velocity, particularly in the wellbore vicinity. The initial concentration of the retained fines, σ_i, determines the critical velocity, U_i (see Miranda and Underdown, 1993): the particle release occurs for $U > U_i$, where

$$\sigma_{a0} = \sigma_{cr}(U_i). \tag{17}$$

The maximum retention function (15) can also be obtained from the coreflood tests with piecewise increasing flow rates. Good agreement between the modelled results and experimental coreflood data may validate the models (15) and (16) for modelling particle detachment. Yet, Bedrikovetsky et al. (2011) present the comparison of coreflood data with formula (5) only for suspension injection cases, while the current work considers the mobilisation of the natural reservoir fines. Besides, only two sets of experimental data have been treated in the above mentioned works, whereas the laboratory results on particle detachment are widely available in the literature. Therefore, below we analyse the laboratory coreflood data on lifting the natural core fines under the flow rate increase in order to validate the model (5) for the fines mobilisation conditions.

Ju et al., 2007, performed injections of constant salinity water with piecewise increasing flow rate into a poorly consolidated sandstone core with permeability of 850 mD, porosity 0.213 and an average pore radius of 10 μm. Despite significant fines production has been observed during this test, the effluent fines concentration has not been monitored. The permeability increase with the flow rate increase (Fig. 4a) was explained by mobilisation of fines, which are significantly smaller than the pore size resulting in no straining. Fig. 4b shows the attached fine particles concentrations $\sigma_a(U)$ as obtained from the permeability values assuming the common value for the formation damage coefficient as $\beta_a = 35$ (points). The continuous curve $\sigma_a(U)$ was calculated by tuned formulae (15) and (16) (see Bedrikovetsky et al., 2010, 2011). The adjusted parameters are: salinity 0.1 M of NaCl, the Hamaker constant for clay–water sand system was calculated as 0.62×10^{-20} J, zeta potential for particles and grains are −30 mV and −20 mV, respectively. The normal pore size distribution varied between 0.1 μm and 24.9 μm with the standard deviation of 3.87 μm. The particle radius

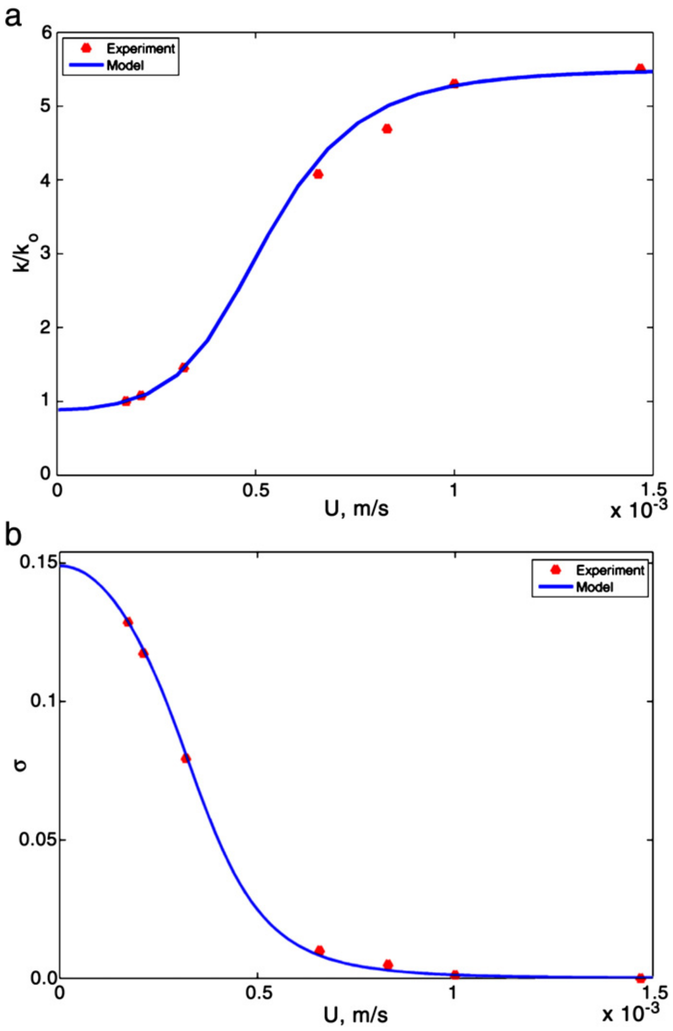

Fig. 4. Matching the theoretical model for maximum retention function with the experimental data by Ju et al. (2007): a) normalised permeability vs. velocity b) maximum retention function—σ vs velocity U.

is assumed to be 1 μm. Fig. 4b shows very good agreement between the modelling results and experimental data.

Similar agreement can also be observed for the set of data presented by Ochi and Vernoux (1998) and the modelling results.

Overall, a good agreement between the retention concentrations as obtained from coreflooding data and the model validates the assumption of the existence of the maximum (critical) retention concentration as a function of velocity (Eqs. (14) and (16)).

In the next section, the basic equations, describing steady state gas production with fines, causing pore plugging and consequent permeability damage, are derived.

4. Mathematical model of gas production with accumulation of the retained fines

Let us consider one phase gas flow towards a well in the presence of immobile connate water. The suspended particles can be captured by attachment and by straining. The attachment and straining cause porosity decline, therefore, the rock porosity is a function of attachment and straining concentrations. The mass balance equation for gas with fines production differs from Eq. (2) by the varying porosity

$$r\frac{\partial(\phi(\sigma_s,\sigma_a)(1-s_{wi})\rho)}{\partial t}+\frac{\partial}{\partial r}(r\rho U)=0. \quad (18)$$

Here, initial water saturation is velocity-dependent according to Eq. (3).

The mass balance equation for suspended, strained and attached fine particles is

$$r\frac{\partial[\phi(1-s_{wi})c\rho+\rho_s\sigma_a+\rho_s\sigma_s]}{\partial t}+\frac{\partial}{\partial r}(rc\rho U)=0. \quad (19)$$

Here, we assume a particle suspension with low concentration, c, i.e. the suspended particles do not decrease the porous space. The particles attached to grains and pore walls, and those strained in small pores form the fines deposit (Fig. 2). The pore space is saturated by connate water, by attached and strained particles and by the flowing particulate gaseous suspension. For simplicity, accessibility and flux reduction factors during particle straining are not accounted for (Bedrikovetsky, 2008; Ilina et al., 2008).

Taking derivatives of both terms of the mass balance Eq. (19) yields

$$r\phi(1-s_{wi})\rho\frac{\partial c}{\partial t}+r\rho U\frac{\partial c}{\partial r}=-r\rho_s\frac{\partial(\sigma_s+\sigma_a)}{\partial t}. \quad (20)$$

Fine particles can be attracted to grains and pore walls; the attachment rate is described by the linear kinetics filtration equation until the deposit reaches its maximum (critical) value according to

$$\frac{\partial\sigma_a\rho_s}{\partial t}=\lambda_a c\rho U, \sigma_a<\sigma_{cr}(s_{wi},U) \quad (21)$$

where λ_a is the filtration coefficient for attaching fines capture. Otherwise, Eq. (14) for critical attachment concentration holds, i.e. the retained concentration remains constant after it reaches the critical value, σ_{cr}, unless the flow velocity U changes. The proposed model assumes the significant overlap between the pore and particle size distributions, i.e., the probabilities of the particle to pass via a pore and to be captured by the pore, have the same order of magnitude. It means that straining of particles in small pores may cause a significant straining with the subsequent permeability decline.

The typical range of filtration coefficient λ_s is 0.1–100 1/m (Bedrikovetsky et al., 2001; Pang and Sharma, 1997), which corresponds to the range of the particle free path $1/\lambda_s$ of 0.01–10 m. The size of the damaged zone is usually 1–5 m (Civan, 2007; Nunes et al., 2010), i.e., the damage zone and the particle free run length have the same order of magnitude. Therefore, the straining rate of fine particles is described by the following kinetics equation (Herzig et al., 1970; Vafai, 2000)

$$\frac{\partial\sigma_s\rho_s}{\partial t}=\lambda_s c\rho U \quad (22)$$

where λ_s is the filtration coefficient for the size exclusion fines capture. So, the released fines are re-entrapped not instantaneously, but after travelling the free path distance.

The model (22) assumes that the concentration of the retained particles is negligibly smaller than the concentration of the vacant pores, where the particle straining may occur. In this case, the retention of a particle does not change further capture probability, i.e., the filtration coefficient for the size exclusion fines capture is constant. At the higher retained concentration comparable with the vacant pore concentration, the Langmuir blocking dependency $\lambda_s=\lambda_s(\sigma)$ takes place.

Thus, both particle attachment and size exclusion are considered in the fines migration model. It is also assumed that other particle capture mechanisms such as bridging, re-entrainment of deposited particles, segregation and diffusion are negligible (Civan, 2010; Nabzar et al., 1996; Rousseau et al., 2008).

Permeability monotonically decreases during particle capture. Pang and Sharma, 1997 approximated the normalised reciprocal permeability by the linear function of retained concentration

$$\frac{k_0}{k(\sigma)} = 1 + \beta\sigma \tag{23}$$

where β is the formation damage coefficient. For small retained concentrations, assumed in this model, the expression (23) can be considered as two first terms of Tailor's expansion of the normalised reciprocal to permeability. If the permeability is affected by both, the attached and retained particles, formula (23) is transformed to

$$\frac{k_0}{k(\sigma_a, \sigma_s)} = 1 + \beta_a\sigma_a + \beta_s\sigma_s \tag{24}$$

for retained concentrations of attached and size excluded particles.

The inertial coefficient B increases during particle attachment and straining. Taylor expansion series truncated after the second term for a monotonically increasing function of two variables

$$\frac{B(\sigma_a, \sigma_s)}{\sqrt{k(\sigma_a, \sigma_s)}}$$

yields

$$\frac{B(\sigma_a, \sigma_s)}{\sqrt{k(\sigma_a, \sigma_s)}} = \frac{B_0}{\sqrt{k_0}}(1 + \gamma_a\sigma_a + \gamma_s\sigma_s). \tag{25}$$

The non-linear Darcy's law for gas flux under the presence of connate water accounting for formation damage due to the attached and strained particles (Chauveteau et al., 1998; Mojarad and Settari, 2007; Nabzar et al., 1996; Rousseau et al., 2008) follows from the combination of Eqs. (8), (24) and (25):

$$-\rho\frac{dp}{dr} = (1 + \beta_a\sigma_a + \beta_s\sigma_s)\frac{\mu}{k_0 k_{rgwi}}\rho U + (1 + \gamma_a\sigma_a + \gamma_s\sigma_s)\frac{B_0}{\sqrt{k_0 k_{rgwi}}}\rho^2 U^2. \tag{26}$$

Here, k_0 is the initial rock permeability, k_{rgwi} is the relative permeability of gas in the presence of initial water, and μ is the gas dynamic viscosity.

The above explanation of the permeability damage, as a result of sequential fines release and straining capture, assumes that permeability change due to pore plugging highly exceeds that due to particle release, $\beta_s \gg \beta_a$. Further in the text, the permeability change due to attachment is ignored. The pore plugging may significantly increase the particle path tortuosity and subsequent inertial pressure losses, whereas the attachment of particles decreases pore cross-sectional areas leading to a more gradual hydraulic conductivity decline. Therefore, the inertial coefficient variation due to attachment is ignored comparing to that due to straining, i.e. $\gamma_s \gg \gamma_a$.

The simplified Eq. (26) has the following form:

$$-\rho\frac{dp}{dr} = (1 + \beta_s\sigma_s)\frac{\mu}{k_0 k_{rgwi}}\rho U + (1 + \gamma_s\sigma_s)\frac{B_0}{\sqrt{k_0 k_{rgwi}}}\rho^2 U^2. \tag{27}$$

Thus, the system of four Eqs. ((18), (20), (14)/(21) and (22)) determines unknowns c, σ_a, σ_s and p.

The gas production scenario includes the following processes: gas flow towards the well after switching the well on, propagation of pressure wave into the reservoir, gradual increase of velocity in each reservoir point until its critical value, migration of lifted fines in the formation damage zone where the deposit affects the well index, and the continuous fines straining with the gradual skin growth. The “infinite reservoir” is assumed before the pressure wave reaches the reservoir boundary. The corresponding initial and boundary conditions with the given pressure on the wellbore are as follows:

$$\begin{aligned} &t = 0 : p = p_{res}, \sigma_a = \sigma_{a0}, \sigma_s = \sigma_{s0}, c = 0 \\ &r = r_w : p = p_w \\ &r \to \infty : p = p_{res}. \end{aligned} \tag{28}$$

The condition of impermeability (zero pressure gradient) is set on the reservoir boundary after it is reached by the pressure wave.

If the mass flow rate per unit of thickness is known, it can be used as another boundary condition instead of the fixed well pressure:

$$r = r_w : -\rho\frac{dp}{dr} = (1 + \beta_s\sigma_s)\frac{\mu}{k_0 k_{rgwi}}\frac{q}{2\pi r_w} + (1 + \gamma_s\sigma_s)\frac{B}{\sqrt{k_0 k_{rgwi}}}\frac{q^2}{4\pi^2 r_w^2}. \tag{29}$$

The analytical model, presented in the next section, describes the steady state period of the above process for fine particles mobilisation and size exclusion.

5. Analytical model for steady state flow with fines migration

Let us describe gas production with constant rate, steady state distribution of suspended concentration near to a well and a gradual accumulation of migrated fines due to their size exclusion capture by the rock. Particle detachment in the damaged zone due to timely increase of the pressure gradient is ignored comparing to that from the suspended flux from the outer reservoir. It is also assumed that a low retention concentration $\sigma = \sigma_a + \sigma_s$ does not affect the porosity. The effect of velocity increase on the initial water saturation (Eq. (3)) is also ignored.

The above assumptions simplify the mass balance Eq. (20) to the following form:

$$r\rho U\frac{\partial c}{\partial r} = -r\rho_s\frac{\partial \sigma_s}{\partial t}, \tag{30}$$

Substituting a straining capture rate expression (22) in Eq. (30) results in the differential equation for the concentration of suspended particles

$$\frac{\partial c}{\partial r} = -\lambda_s c. \tag{31}$$

Separation of variables in Eq. (31) leads to the explicit formula for the suspended concentration distribution around the well

$$c(r) = c_w \exp(-\lambda_s(r - r_w)) \tag{32}$$

assuming that the produced fines concentration is known:

$$c(r_w) = c_w. \tag{33}$$

The concentration of the suspended particles in gas vs radius decreases as the suspension moves towards the well with the particle straining occurring. For the steady state flow regime Eq. (32), the gradient of the suspended particle concentration, c, causes higher influx in each elementary volume dr compared to the outflux; this difference is compensated by the gradual accumulation of the strained particles.

Substituting expression for suspended concentration (33) into Eq. (22) and integrating both sides in respect to t, results in the explicit formula for a strained particle concentration distribution

$$\sigma_s(r, t) = \frac{\lambda_s qt}{2\pi r\rho_s} c_w \exp(-\lambda_s(r - r_w)) \tag{34}$$

i.e., the strained particles accumulate proportional to time.

In the next section, based on solution to Eq. (34), the pressure distribution around the wellbore is calculated, and the formula for decreasing well productivity is derived.

6. Formula for well productivity

Using the analytical solution (Eqs. (32) and (34)), let us calculate the pressure square drop between the drainage radius, r_e, and the well radius, r_w.

Expressing flow velocity in (Eq. (27)) via the gas mass flow rate (Eq. (7)) and accounting for the equation of state of the real gas (Eq. (9)) yields

$$\frac{\rho_a}{p_a}\frac{p}{z}\frac{dp}{dr} = (1+\beta_s\sigma_s)\frac{\mu}{k_0 k_{rgwi}}\frac{q}{2\pi r} + (1+\gamma_s\sigma_s)\frac{B_0}{\sqrt{k_0 k_{rgwi}}}\frac{q^2}{4\pi^2 r^2}. \tag{35}$$

The pressure square drop between the drainage radius and the well radius is calculated from Eq. (35) by integration in r from the well radius r_w to the drainage radius r_e as

$$\frac{\rho_a}{2p_a}\frac{\left(p_e^2 - p_w^2\right)}{z} = \frac{\mu}{k_0 k_{rgwi}}\frac{q}{2\pi}\left(\ln\frac{r_e}{r_w} + \beta_s\int_{r_w}^{r_d}\frac{\sigma_s dr}{r} + \beta_s\int_{r_d}^{r_e}\frac{\sigma_s dr}{r}\right) + \frac{B_0}{\sqrt{k_0 k_{rgwi}}}\frac{q^2}{4\pi^2}\left(\frac{1}{r_w} - \frac{1}{r_e} + \gamma_s\int_{r_w}^{r_d}\frac{\sigma_s dr}{r^2} + \gamma_s\int_{r_d}^{r_e}\frac{\sigma_s dr}{r^2}\right) \tag{36}$$

where r_d is the so-called size of formation damage zone (see Nunes et al., 2010).

Axisymmetric variable r is located in the denominator of integrants in Eq. (36). Therefore, the larger the distance from well is, the lower is the impact of permeability on the pressure drop. The formation damage zone size is defined as follows: the particle retention outside the damage zone $r > r_d$ does not affect the well impedance, i.e., the pressure drop increase due to particle straining outside the damaged zone is negligible comparing to other terms in Eq. (36), and, therefore, is ignored (Nunes et al., 2010). For this reason, the third integral terms in both brackets in the right hand side of expression (36) are neglected.

Substituting expression for the retained concentration (34) into Eq. (36) and performing integration yields the final expression for the pressure square drop

$$\frac{\rho_a}{2p_a}\frac{\left({p_e}^2 - {p_w}^2\right)}{z} = \frac{\mu}{k_0 k_{rgwi}}\frac{q}{2\pi}\ln\frac{r_e}{r_w} + \frac{B_0}{\sqrt{k_0 k_{rgwi}}}\frac{q^2}{4\pi^2}\left(\frac{1}{r_w} - \frac{1}{r_e}\right) + \left[\frac{\mu}{k_0 k_{rgwi}}\frac{q}{2\pi}\beta_s + \frac{B_0}{\sqrt{k_0 k_{rgwi}}}\frac{q^2}{4\pi^2}\gamma_s\right]\frac{\lambda_s c_w q t \exp[\lambda_s r_w]}{2\pi}\left\{\frac{\exp[-\lambda_s r_w]}{r_w} - \frac{\exp[-\lambda_s r_d]}{r_d} - \lambda_s\left(E_1(\lambda_s r_w) - E_1(\lambda_s r_d)\right)\right\} \tag{37}$$

where

$$E_1(x) = \int_x^\infty \frac{\exp(-t)}{t}dt.$$

is an exponential integral.

The skin factor in Eq. (37) grows proportionally to time of gas production with fines.

Let us calculate the inverse to normalised well deliverability (so called impedance):

$$j(t) = \frac{\left(p_e^2 - p_w^2(t)\right)q(t=0)}{q(t)\left(p_e^2 - p_w^2(t=0)\right)}. \tag{38}$$

For the case of a constant production rate, from Eq. (37) follows

$$j(t) = 1 + \frac{\left[\frac{\mu}{k_0 k_{rgwi}}\frac{1}{2\pi}\beta_s + \frac{B_0}{\sqrt{k_0 k_{rgwi}}}\frac{q}{4\pi^2}\gamma_s\right]\left[\frac{\exp(-\lambda_s r_w)}{r_w} - \frac{\exp(-\lambda_s r_d)}{r_d} - \lambda\left(E_1(\lambda_s r_w) - E_1(\lambda_s r_d)\right)\right]}{\frac{\mu}{k_0 k_{rgwi}}\frac{1}{2\pi}\ln\frac{r_e}{r_w} + \frac{B_0}{\sqrt{k_0 k_{rgwi}}}\frac{q}{4\pi^2}\left(\frac{1}{r_w} - \frac{1}{r_e}\right)} \times \frac{\lambda_s c_w q t \exp(-\lambda_s r_w)}{2\pi\rho_s}. \tag{39}$$

For the case of slowly changing rate $q(t)$ and concentration of produced fines $c_w(t)$, the formula (38) for impedance becomes

$$j(t) = 1 + \frac{\left[\frac{\mu}{k_0 k_{rgwi}}\frac{1}{2\pi}\beta_s + \frac{B_0}{\sqrt{k_0 k_{rgwi}}}\frac{q(t)}{4\pi^2}\gamma_s\right]\left\{\frac{\exp(-\lambda_s r_w)}{r_w} - \frac{\exp(-\lambda_s r_d)}{r_d} - \lambda_s\left(E_1(\lambda_s r_w) - E_1(\lambda_s r_d)\right)\right\}}{\frac{\mu}{k_0 k_{rgwi}}\frac{1}{2\pi}\ln\frac{r_e}{r_w} + \frac{B_0}{\sqrt{k_0 k_{rgwi}}}\frac{q(t)}{4\pi^2}\left(\frac{1}{r_w} - \frac{1}{r_e}\right)} \times \frac{\lambda_s \exp(-\lambda_s r_w)\int_0^t c_w(\tau)q(\tau)d\tau}{2\pi\rho_s}. \tag{40}$$

In the case of slowly changing rate $q(t)$ and concentration of produced fines $c_w(t)$, skin factor can be calculated from Eq. (37)

$$S = \frac{B_0\sqrt{k_0 k_{rgwi}}}{\mu}\frac{q}{2\pi}\left(\frac{1}{r_w} - \frac{1}{r_e}\right) + \left[\beta_s + \frac{B_0\sqrt{k_0 k_{rgwi}}}{\mu}\frac{q}{2\pi}\gamma_s\right]\frac{\lambda_s \exp[\lambda_s r_w]\int_0^t c_w(\tau)q(\tau)d\tau}{2\pi}\left\{\frac{\exp[-\lambda_s r_w]}{r_w} - \frac{\exp[-\lambda_s r_d]}{r_d} - \lambda_s\left(E_1(\lambda_s r_w) - E_1(\lambda_s r_d)\right)\right\}. \tag{41}$$

The skin factor in Eq. (41) grows proportionally to the amount of produced fines. First term in Eq. (41) corresponds to inertia losses; first term in square brackets expresses the decrease of hydraulic conductivity due to permeability reduction; the second term in square brackets relates to increase of inertia losses due to increased tortuosity under the fine particle straining.

7. Validation of the model

The deliverability deterioration in the North Sea gas-condensate vertical perforated well during the period 1981–1987 was explained by fines migration (Thrasher, 1995). The condensate precipitation in the reservoir has not been mentioned and considered to affect the well skin factor. The author indicates that the main reason for productivity decline is fines migration. Therefore, the presented model (40) has been applied for this field case. Thrasher (1995) presents the field data on the rate decline and decrease of the pseudo pressure drawdown versus time. Fig. 5 shows the increase of the normalised reciprocal to the well deliverability versus time. Reservoir permeability $k_0 = 3$–9 mD, porosity $\phi = 0.166$, reservoir thickness is 80–250 ft, gas viscosity $\mu = 0.015$ cP, the inertia coefficient $B_0 = 774.5$ (Norman et al., 1985), gas compressibility factor $z = 0.6$, relative permeability for gas under the presence of connate water $k_{rgwi} = 0.415$, gas density at the normal conditions $\rho_a = 0.96$ kg/m^3. The results of the fitting with the analytical model (40) are as follows: the density of the solid particles $\rho_s = 2600$ kg/m^3, the drainage radius $r_e = 500$ m, the damaged zone radius $r_d = 10$ m, the formation damage coefficient for straining $\beta_s = 90$, the inertia formation damage coefficient $\gamma = 9$, the filtration coefficient for straining $\lambda_s = 1.8$ 1/m and the produced suspension mass fraction $c_w = 8$ ppm.

Fig. 5 a,b,c,d,e shows sensitivity analysis with respect to the formation damage coefficient for straining, the filtration coefficient for straining, the inertia coefficient, the drainage radius and the formation damage zone size, respectively. All parameters have been varied by 30% with respect to the basic case obtained by the fitting of the field data. The most influential parameters are the formation damage

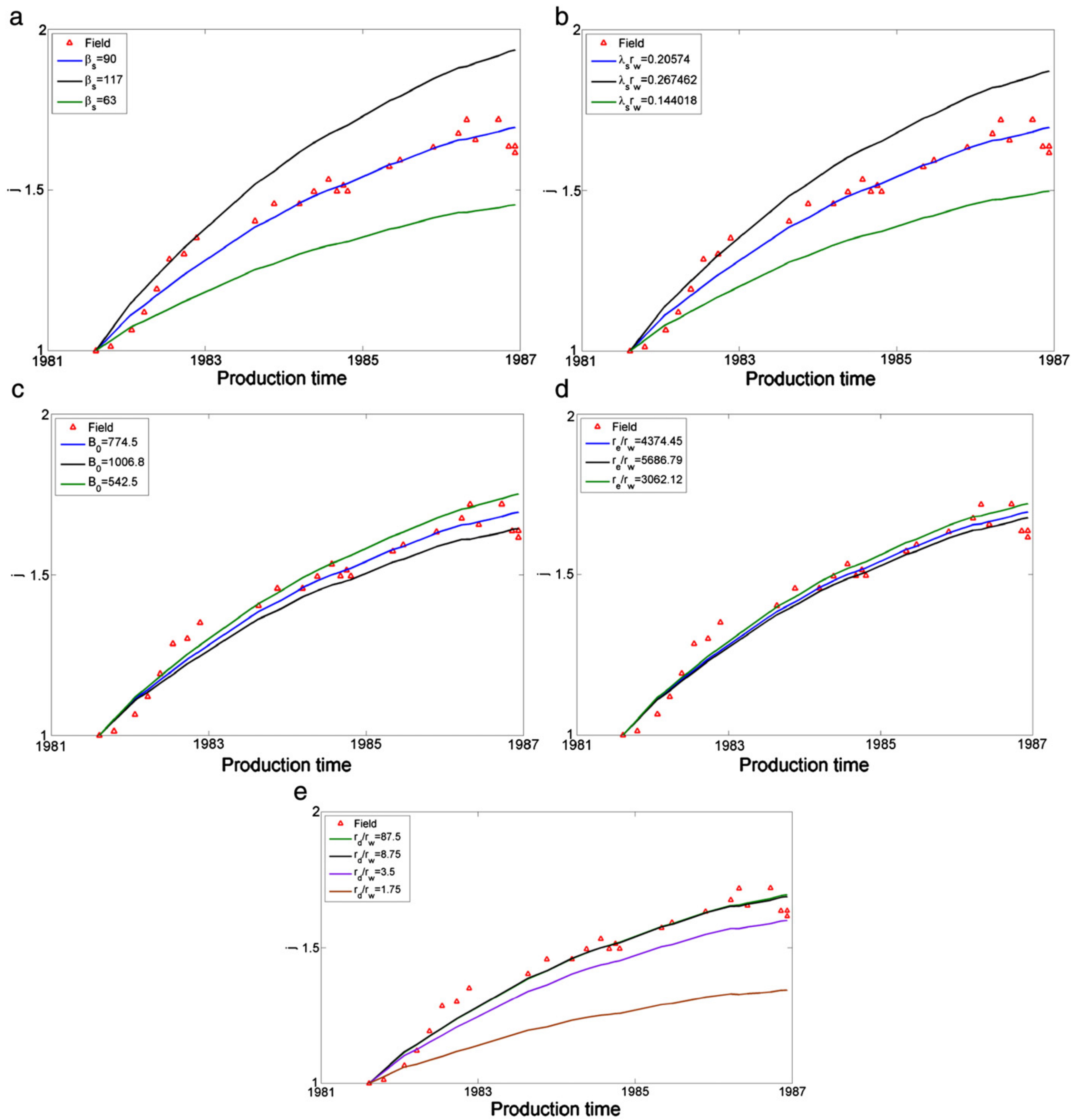

Fig. 5. Matching the field data (North Sea, UK) with the modelling-based prediction of well deliverability (impedance j) and sensitivity study: a) sensitivity with respect to formation damage coefficient β_s; b) variation of the straining filtration coefficient λ_s; c) sensitivity with respect to the inertia coefficient B_0; d) variation of drainage radius r_e; e) sensitivity analysis by the damage zone radius r_e.

and filtration coefficients. The well deliverability also changes with variation of the inertia coefficient. It is almost insensitive with regards to the drainage radius r_e.

Fig. 5e shows sensitivity study with respect to the formation damage zone radius r_d. The expression for the drop of pressure squares between the well and the reservoir (Eq. (36)) contains the overall damage, which is proportional to the integral of σ_s/r from well radius to the drainage radius. Yet, concentration of strained fines declines with radius r as an exponent, i.e. the remote deposition almost does not affect the well index. So, the damaged zone size r_d is defined as a minimum radius above which the pore straining by retained fines does not influence the well impedance (see Nunes et al., 2010). Fig. 5e shows that for all damage radii larger than $8r_w$, the impedance well history is independent of formation zone radius (black and green curves almost coincide). Yet, well index is very sensitive to the near-well permeability damage. Therefore, for values of the radii ratio r_d/r_w below 4–6, the decrease of r_d/r_w results in significant decrease of well impedance.

8. Summary and discussions

Fine particle mobilisation by drag and lifting forces exerting on particles from the flowing gas, their migration and further size exclusion by thin pores cause a significant permeability decline and increase of the inertial resistance coefficient. Therefore, the gas well index declines during the fines production. The mathematical model, predicting well productivity decline, consists of four equations for unknown concentrations of suspended, attached and strained particles and pressure. The model includes the kinetics equation for migrating particles straining and the maximum retention function for the particle detachment. The maximum retention function of flow velocity has been calculated from three sets of corefloods and from the equations of the particle mechanical equilibrium on the wall of a single capillary; the experimental and the modelling data are in a good agreement.

The analytical model describes flow towards the well with steady state suspension concentration near to well and constant production rate. Due to the steady state suspension concentration, the gradual accumulation of size excluded fines is going on proportionally to time. Well impedance grows linearly vs amount of produced fines during the commingled production of gas and fines. The proportionality coefficient of the well impedance growth is a linear function of the formation damage coefficient for straining; it increases with filtration coefficient increase and is almost independent of the drainage radius.

The model assumes small values of the retained concentration with the number of retained particles significantly smaller than the number of vacant thin pores, where the particle size exclusion can happen. It results in constant filtration coefficient for straining, in linear form of the normalised reciprocal to formation damage function and, finally, in the linear skin factor growth vs the amount of produced fines. The late stage of well clogging with the large retention concentration, where the well index may stabilise or the production may vanish is described by more complex solution of the system of governing Eqs. ((18), (20), (14), (21) and (22)).

Two field examples of well productivity decline due to fines migration (Thrasher, 1995 and Christanti et al., 2010) were successfully matched by the analytical model for steady state production of gas and fines. Yet, the values of too many relevant parameters have not been presented in the referred paper; these parameters have been obtained by matching or assumed. More well documented field cases must be analysed and tuned with the model for the solid claim on the validity of the analytical model for gas well deliverability decline due to fines migration. The preferable field case would contain both coreflood and well data.

Another field case of gas productivity decline due to fines migration has been presented by Christanti et al., 2010. Detrimental gas production from offshore Adriatic Sea reservoir, situated in dirty unconsolidated sandstone formation was explained by fines migration. The authors show that the application of fines control agents significantly decreases the skin factor growth. Fig. 6 shows the significant and fast impedance growth in frac-pack gas well. Formula (40) with equivalent wellbore radius r_w (see Barenblatt et al., 1990) has been used to describe the timely impedance increase. The following coefficient values have been obtained from matching the raw well data: dimensionless filtration coefficient $\lambda r_w = 1.89$, straining formation damage coefficient $\beta_s = 158$, the ratio between radii of formation damage zone and well is $r_d/r_w = 16.67$. The obtained values are in common ranges. The impedance curve as calculated by Eq. (40) is shown in blue; it exhibits good agreement between the raw well data and the modelling-based prediction. Fig. 6 presents sensitivity study with respect to filtration and formation damage coefficients and the ratio between radii of formation damage zone and well. Each curve corresponds to change of only one parameter if compared with the matched case. The values of the changed parameters are shown in the legend. 30% variation of formation damage coefficient causes a significant impedance change (green curves) while 30% variation of filtration coefficient results in less impedance change (black curves). Ten times decrease of damaged zone size r_d causes visible impedance decrease (violet curve). Yet, any increase of the radius of the damaged zone if compared with the basic matched value almost does not affect the impedance.

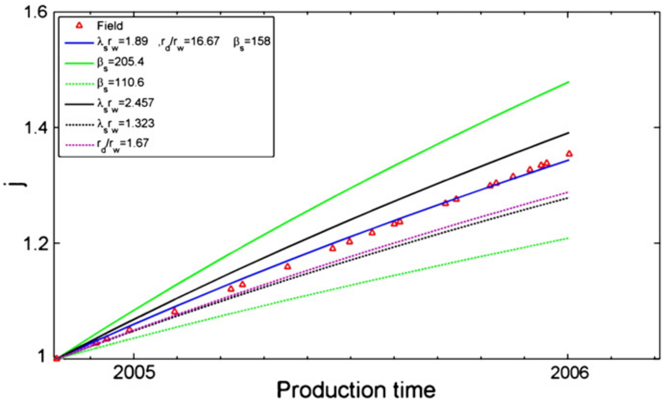

Fig. 6. Comparison between well production history (Adriatic Sea, Italy) and the analytical model.

9. Conclusions

Derivation of the governing equations for gas flow with fines migration and capture, development of the analytical model for quasi steady state gas and fines production and its matching with the field data allow concluding the following:

(1.) The mathematical model for permeability decline by the fine particles mobilization and straining contains:
- maximum retention function that describes the particle detachment,
- the particle straining kinetics equation, describing the size exclusion particle capture by the rock.

(2.) The analytical model for quasi steady state production of gas and fines exhibits a linear skin factor dependency of the amount of produced fines. This is a consequence of the model assumption of small retention concentration, so the model is not valid for the final stage of the well clogging process with skin factor stabilisation where the filtration and formation damage coefficients become functions of strained fines concentration.

(3.) The major parameter controlling well impairment due to fines production is the formation damage coefficient for straining. The straining filtration coefficient also affects the well index decline. The productivity impairment is almost insensitive to variation of the drainage radius. It is also insensitive to the damaged zone size for the large ratios r_d/r_w.

(4.) Despite achieving a good match of the well production data and the modelling-based prediction for two field cases, further field validation of the analytical model of well clogging during fines production must be performed based on well documented gas and fines production histories.

Nomenclature

B	*inertial coefficient*
c	*mass concentration of suspended particles*
c_w	*mass concentration of produced fines*
F_{ad}	*adhesion force, MLT^{-2}, N*
F_d	*drag force, MLT^{-2}, N*
F_e	*electrostatic force, MLT^{-2}, N*
F_g	*gravitational force, MLT^{-2}, N*
F_l	*lifting force, MLT^{-2}, N*
j	*impedance*
k	*absolute permeability, L^2, mD*
k_0	*initial permeability, L^2, mD*
k_{rgwi}	*gas relative permeability at initial water saturation*
l_d	*lever for drag force, L, m*

l_n	*lever for normal force, L, m*
p	*pressure, $ML^{-1}T^{-2}$, Pa*
p_{res}	*initial reservoir pressure, $ML^{-1}T^{-2}$, Pa*
q	*mass flow rate per unit of thickness, $ML^{-1}T^{-1}$, kg/ms*
r	*radial co-ordinate, L, m*
r_d	*radius of formation damage zone, L, m*
r_e	*drainage radius, L, m*
r_w	*well radius, L, m*
S	*skin factor*
s_{wi}	*connate water saturation*
t	*time, T, s*
U	*linear flow velocity, LT^{-1}, m/s*
U_m	*minimum linear velocity for which no particles can be held on the grain surface, LT^{-1}, m/s*
U_i	*critical linear velocity, LT^{-1}, m/s*

Greek letters

ρ	*gas density, L^{-3}, 1/m^3*
ϕ	*porosity*
γ_a	*inertial coefficient for of strained fines*
ρ_a	*gas density under normal conditions, M/L^3, kg/m^3*
ρ_s	*specific density of particles, L^{-3}, 1/m^3*
γ_s	*inertial coefficient for attachment particles capture*
β	*formation damage coefficient*
β_a	*formation damage coefficient for attachment*
β_s	*formation damage coefficient for straining*
ε	*torque (erosion) ratio*
λ	*filtration coefficient, L^{-1}, 1/m*
λ_a	*filtration coefficient for attachment particle capture, L^{-1}, 1/m*
λ_s	*filtration coefficient for size exclusion fines capture, L^{-1}, 1/m*
σ	*volumetric concentration of captured particles, L^{-3}, 1/m^3*
σ_a	*volumetric concentration of attached fines, L^{-3}, 1/m^3*
σ_{a0}	*initial volumetric concentration of attached fines, L^{-3}, 1/m^3*
σ_{cr}	*critical concentration of captured particles, L^{-3}, 1/m^3*
σ_i	*initial concentration of attached fines, L^{-3}, 1/m^3*
σ_o	*maximum concentration of attached particles that corresponds to zero velocity, L^{-3}, 1/m^3*
σ_s	*volumetric concentration of strained fines, L^{-3}, 1/m^3*
σ_{s0}	*initial volumetric concentration of strained fines, L^{-3}, 1/m^3*

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