Fuel 236 (2019) 622–635

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Full Length Article

A novel approach for solving nonlinear flow equations: The next step towards an accurate assessment of shale gas resources

Yashar Bezyan[a], Mohammad Ebadi[b,*], Shahab Gerami[c], Roozbeh Rafati[d], Mohammad Sharifi[e], Dmitry Koroteev[b]

[a] Department of Petroleum Engineering, Science and Research Branch, Islamic Azad University, Tehran, Iran
[b] Skolkovo Institute of Science and Technology, Skolkovo Innovation Centre, Moscow Building 3, Moscow 143026, Russia
[c] IOR Research Institute, Tehran, Iran
[d] School of Engineering, University of Aberdeen, Aberdeen AB24 3UE, United Kingdom
[e] Department of Petroleum Engineering, Amirkabir University of Technology, Tehran, Iran

ARTICLE INFO

Keywords:
Shale gas reservoirs
Apparent permeability
Adsorbed gas
Kerogen distribution
Newton's method
Particle swarm optimization

ABSTRACT

As ultra-tight porous media that include organic contents, shale gas resources are technically known as complex systems having various mechanisms that impact storage and flow. The slippage, Knudsen diffusion, the process of desorption, an adsorbed layer that affects apparent permeability, and solute gas in kerogen are recognized to be the most important ones. However, simultaneous effects of multi-mechanism flow and storage, and influences of scattered organic contents on shale gas flow behaviour are not well-understood yet.

According to the mass conservation law, a basic mathematical model has been developed to investigate, step-by-step, the effects of different changes that are introduced, and examine whether patterns of how kerogen is distributed affect the production plateaus. The discretization of the second-order nonlinear Partial Differential Equation (PDE) that is evolved results in a certain number of nonlinear simultaneous algebraic equations, which are conventionally solved with the application of Newton's method. To overcome the inherent difficulties of the initial guess, the derivations, and the inversion of the Jacobian matrix, a new application of Particle Swarm Optimization (PSO) as a nonlinear solver was applied to extract the anticipated pressure profile for each step in time outside the bounds of the reference equations.

The results show that not only can the PSO effectively meet the required criteria, but also it performed faster than conventional techniques, especially in cases with a larger number of grids that encompass more phenomena. It was further revealed that the insertion of a multi-mechanism apparent permeability model in which the pore radius is also a pressure-dependent parameter causes the lower rate of production. A higher level of production has been recorded after including storage terms of adsorption and solute gas in kerogens. Although different patterns of kerogen distribution have finally overlapped, the different taken trend of each production profile underlines the impact of kerogen distribution as an important parameter within the procedure of history matching.

1. Introduction

Shale gas resources, which are discussed on a daily basis, have drawn many researchers' attentions towards the new wonder of "The Shale Gas Revolution". This slowly growing movement started the century by compromising just less than 2 percent of domestic outputs. Surprisingly, today it accounts for nearly one-third, and the projection is that by 2030s is a half of the gas produced in the USA and China will be from shale gas resources [1]. Recent industrial and scientific advances have caused experts to conclude that organic-rich shales have the potential to be regarded not only as sources containing typical oil and gas, but also as reservoirs to be produced [2].

Applying modern methods like high pressure mercury injection (up to 60,000 psi) and novel photo techniques have proved the existences of nano scale pores and throats in organic-rich shale gas resources [3,4]. Nano scale pores have strong effects on the storage and flow in shale gas resources. First, they provide large exposed surface areas known to hold the potential for a considerable amount of adsorbed gas. Also, Darcy's law is not applicable to shale gas resources because it has originally been developed for micro scale pores [3–10]. Moreover, the trapped

* Corresponding author.
E-mail address: Mohammad.Ebadi@Skoltech.ru (M. Ebadi).

https://doi.org/10.1016/j.fuel.2018.08.157
Received 14 May 2018; Received in revised form 4 July 2018; Accepted 30 August 2018

Nomenclature

Δx	length of each grid; *ft*
A	surface area; ft^2
A_K	kerogen surface area; ft^2
C	net heat of adsorption; *Dimensionless*
c	concentration; lb_m/ft^3
C_g	gas compressibility; psi^{-1}
d	pore diameter; *ft*
D	kerogen diffusivity coefficient; ft^2/Day
D_f	surface roughness; *Dimensionless*
d_m	normalized molecular size; *ft*
E_1	heat of adsorption for the first layer; *Dimensionless*
E_L	heat of higher layers; *Dimensionless*
k	absolute permeability; *md*
K_a	differential equilibrium partitioning coefficient; *Dimensionless*
k_{app}	apparent permeability; *md*
k_H	Henry's constant; $lb/(psi\text{-}ft^3)$
K_n	Knudsen number; *Dimensionless*
M	molecular weight; lb_m
n	number of gas moles; *lb mol*
P	pressure; *psi*
P_{cte}	constant pressure; *psi*
P_{in}	initial pressure; *psi*
P_L	Langmuir pressure; *psi*
P_o	saturation pressure of the gas; *psi*
P_{ST}	standard pressure; *psi*
q_k^*	mass flux from kerogen to matrix (kerogen mass flux); lb_m / day
R	gas constant; $(psi.ft^3)/(lb\ mol\ .^\circ R)$
r	pore radius; *ft*
r_{eff}	effective pore radius; *ft*
r_{mol}	radius of gas molecules; *ft*
T	temperature; $^\circ F$
t	time; *day*
t_{ads}	thickness of the adsorbed layer; *ft*
T_{ST}	standard temperature; $^\circ F$
V	gas volume of adsorption; ft^3/lb_m
V_b	bulk volume; ft^3
V_L	Langmuir volume; ft^3 / lb_m
V_m	maximum volume of adsorbed gas for a single molecular layer; ft^3/lb_m
Z	compressibility factor; *Dimensionless*
z	height; *ft*

Greek letters

α	adsorbed layer fitting slope; *ft/psi*
δ'	size ratio; *Dimensionless*
ζ	tangential momentum accommodation coefficient; *Dimensionless*
λ	mean free path; *ft*
μ	viscosity; *cp*
ρ_a	density of adsorbed gas; lb_m/ft^3
ρ_{avg}	averaged density; lb_m/ft^3
ρ_b	bulk density; lb_m/ft^3
ρ_f	density of free or compressed gas; lb_m/ft^3
ρ_s	density of solute gas; lb_m/ft^3
τ	tortuosity; *Dimensionless*
υ	Darcy's velocity; *(ft/day)*
ϕ	porosity; *Dimensionless*

organic content, kerogen, is also one of the other most special and unique characteristics of shale gas resources that has an impact on the storage and flow of gas [4,11,12].

Last relevant research has discovered that the organic constituents cover part of the bulk rock, and are irregularly distributed in the shale gas media. Dispersed organic materials within the shales can affect flow and storage mechanisms [5,12–15]. Specifically, gas is typically stored in pores, and adsorbed on the oil-wet surface of nano scale pores on organic contents that can also have noticeable effects on the non-Darcy's flow [16–19]. On the contrary, the water-wet nature of clays caused the provided empty sites to be filled with water. Therefore, it has been concluded that a notable fraction of the adsorbed gas is stored in the kerogen pores [12,20,21]. Besides that, more research has indicated that a portion of gas molecules remain in the solid part of the organic matter in the form of solute gas [4,22,23]. Indeed, the scattering of the kerogen is the substantial parameter that has a great impact on the modelling and simulation of storage and flow in the shale gas resources [5,12–15].

To describe the fluid flow of gas as a compressible fluid in conventional porous media, the benefits of Darcy's equation have been combined with the continuity equation. The strong functionality of gas parameters such as density, viscosity, and Z-factor on the pressure is the main reason why the supposed governing equation is presumed to be a nonlinear partial differential equation (PDE). In addition, the inclusion of other pressure-dependent phenomena with shale gas resources like apparent permeability, adsorption, and the release of gas from kerogen bodies lead the supposed second-order PDE towards a higher level of nonlinearity [24]. Undoubtedly, handling the nonlinear equations is one of the most challenging problems in numerical computations. Although there are possibilities of applying linearization techniques, the generation of results which are not satisfyingly accurate enough is the main reason to use methods which can directly solve the supposed nonlinearity. Among the different conventional techniques that have ever been proposed to solve the equations referred to, Newton's method is undoubtedly the one that is the most extensively used [25].

However, performance and convergence for Newton's algorithm are strongly dependent on the proper initial guess. Also, the heavily derivation-dependent, high computational cost of Jacobian matrix, and lack of ability to deal with ill-conditioned matrixes are known to be other disadvantages [25,26]. Therefore, researchers' attentions have been drawn towards proposing more advanced methods that meet the required level of accuracy, and with the less computational cost for solving the nonlinear problems [27–29]. Particle swarm optimization (PSO) as an evolutionary and modern optimizer, which can find the optimal solution in the space that is being searched, has recently been proposed to deal with the nonlinearity of different engineering problems [30,31]. Although there is some couple of research in which the PSO has been applied to solve nonlinear equations, the current research has taken advantages of PSO to solve a certain number of nonlinear simultaneous algebraic equations generated after the discretization of the supposed PDE.

In more details, a basic conventional Darcy's law has been modified to account for the effect of slippage, Knudsen diffusion, and impacts of the adsorbed layer on the apparent permeability. Moreover, gas desorption from the pore walls and effects of solute gas in bulks of kerogens are considered to correct the accumulation term. While the generated nonlinear simultaneous algebraic equations generated have been conventionally solved, the applicability of PSO as a free-derivation solver has also been investigated. At the final step, the positions of organic matters and their distribution effects on the fluid flow behaviour were investigated numerically.