MODELING OF UNCONVENTIONAL SHALE GAS RESERVOIRS FOR A DECARBONIZED ECONOMY

Abstract

Meticulous research in unconventional resources like shale gas has started to burgeon with the augmentation in the demands of people for energy sources. Gas-bearing unconventional shale reservoirs possess intricate multi-mechanistic gas transport processes. Different flow mechanisms are eminent in different continuums (more permeable fractures and less permeable matrix) on account of discrepancies in the petrophysical properties of the continuums. Much of the preceding research is gleaned from idealistic speculations and non-pragmatic simplifications owing to the dubiety in elucidating the peculiar attributes of shale gas reservoirs. Characterizing the reservoir geo-physically and involving fluid-solid interactions, phenomena of adsorption/desorption, and non-linear behavior of microscale reservoir properties prognosticate the future reservoir behavior in its various stages. It is obligatory to have a detailed inspection of reservoir properties arising from the tangled pore structure that sways the dynamic flow behavior of shale gas reservoirs or vice versa. This work presents an ameliorated approach for modelling fractures in dual-porosity framework shale gas model to understand Non-Darcian flow behavior of gas through fractures under the influence of various petrophysical properties for achieving better shale gas production, reservoir characterization, and production behavior prediction. This chapter is specifically written for energy modelers and researchers in the field of simulation who would find crucial information regarding characterization of unconventional reservoirs for a cleaner and decarbonized economy.

Keywords: Clean Energy, Unconventional reservoir, green house gases, flow mechanisms, fractures

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I. INTRODUCTION

Shale Gas Reservoirs have grabbed a lot of attention due to its plentiful reserves. Shale gas, if exploited efficiently is going to be one of the prominent opportunities contributing to the change in the energy mix of the world. Though the hydro, solar, wind, nuclear, and geothermal powers are the centre of interest today, the reliance on fossil fuels for instance, shale gas remains inexorable in the frame of reference of facing the growing energy demand. The existing environmental concerns permits Shale gas reservoirs to become a possible replacement to 'mould the world a cleaner, safer place'. Shale gas is considered as the cleanest fossil fuel as it burns hardly half amount of carbon dioxide and very less nitrogen when compared to coal. In addition to that, there is no release of carbon monoxide, mercury, sulfur dioxide and black carbon. Furthermore, it accomplishes the major three "Energy Triangle" objectives and concerns: environmental protection, affordability, and security of supply. After the breakthrough in the exploration and development of U.S. Barnett, Haynesville, and Marcellus shale, gas-bearing shale gas reservoirs have been persistently promoted across other parts of the world. According to Energy Information Administration (EIA), shale gas has abundant reserves around the world, which are sufficient to meet the demand of clean energy for many years to come. Since conventional supplies are already on the decline, this energy can become a game changer in global energy market. Albeit there are notable environmental impacts that involve in the contamination of groundwater aquifers resulting from the hydraulic fracturing of a gas bearing shale gas reservoirs. Nonetheless, since, there are no noteworthy discoveries of new conventional oil and gas resources, more emphasis is being given on the unconventional oil and gas resources which are abundant in the world. Cashing in unconventional reservoirs also helps growing economies like India and China to have abridged import reliance on fossil fuels. Production from these gas-bearing reservoirs will lessen the coal consumption in such developing economies and thereby alleviating the massive effusions of greenhouse gases. As per data obtained from 2015 EIA reports, India has got technically retrievable shale gas of 96 Trillion Cubic Feet (Tcf).

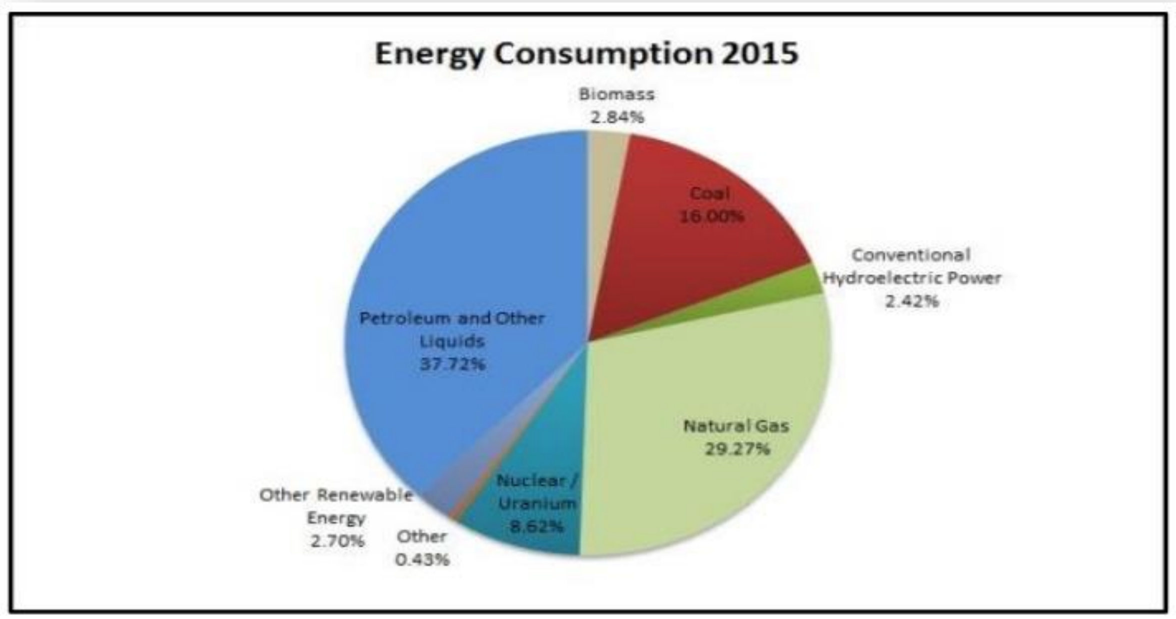

Figure 1: Shows Energy Consumption Scenario 2015 (EIA, Annual Energy Outlook, 2016)

However, the effectual and methodical expansion of these unconventional gas energy resources requires a thorough understanding of gas transport mechanisms due to their multiscale nature. As both solid and fluid constitute a unified single system in porous media, it is pivotal to include all the physical phenomena within that geomaterial system. In contrast to the conventional gas reservoirs, these unconventional reservoirs consist of wide range of pore sizes making its physics complicated and complex to understand. Flow in shale gas reservoirs is attained through a system of pores with different diameters that vary from nanometers to micrometers. Unlike the conventional natural gas reservoirs where the crucial petrophysical properties like porosity and permeability over a large scale do not vary much, these properties in unconventional shale gas reservoirs differ by orders of magnitude.

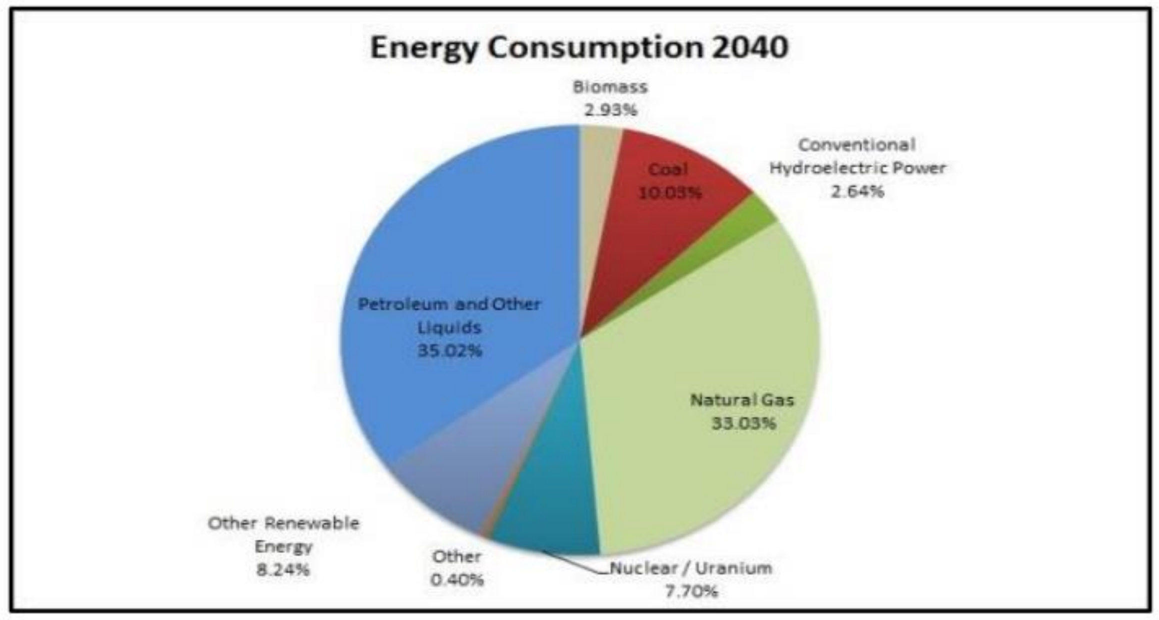

Figure 2: Energy Consumption Scenario 2040 (EIA, Annual Energy Outlook, 2016)

II. SHALE: FLOW AND RETENTION MECHANISMS

Quantification and assessment of flow in nanopores of these gas-bearing reservoirs present another notable challenge. The movement of gas in shale nanopores cannot be delineated simply by implementing the use of Darcy's equation due to the existence of a large number of nanopores. The phenomena like Knudsen diffusion and slip flow at the solid matrix contrast the gas-flow behavior from Representative Elementary Volume (REV) based Darcy-type flow. The presence of a high level of curtailment in shale matrix makes continuum modeling inadequate and leads to the integration of the composite formulation of advection, desorption, and diffusion. Modeling of a complicated system with widely differing pore sizes makes capturing the pertinent physics indispensable along with the amalgamation of petroleum, geological, geophysical, and chemical engineering concepts. According to their mode of occurrence, the gas present in solid shale is bifurcated into free gas, dissolved gas, and adsorbed gas. It is well recognized that majority of the gas in the shale rock is present as free gas (present in the fractures and matrix of shale) as well as adsorbed gas (present on the surface organic kerogen and inorganic clays in the matrix).

A lot of literature has been evolved examining different flow and retention mechanisms in shale. The notion of dynamic gas slippage was first given by Klinkenberg, who gave an empirical model skipping the phenomena of Knudsen diffusion [1]. Various experiments were carried out under low pressure and expanded the Klinkenberg Model [2], [3]. Beskok and Karniadakis (1999) proffered a model that incorporated all well-known multiple flow mechanisms in nano-shale consisting of advective flow, slippage, transition flow, and free molecular flow while failing to consider the Knudsen diffusion [4]. Javadpour et al. (2007,2009) introduced an apparent permeability framework comprising of Knudsen and viscous diffusion [5], [6]. The slip term was added to the advection term in the linear experimental model. The extension of the Beskok and Karniadakis model was done by Xiong et al. (2012) who added the concept of surface diffusion of the adsorbed gases in the gas permeability model [7]. Shabro et al. (2011) extend the apparent permeability concept given by Javadpour to the modelling of shale gas at the pore-scale level [8]. Civan et al. (2013) and Ziarani and Aguilera (2012) deduced an apparent permeability expression as a function of Knudsen number possessing its roots from the Hagen-Poiseuille unified equation [9],[10]. However, these experimental models constitute unknown weighting coefficients resulting in their restricted and bounded application. This restricted utilization can also be attributed to very few well-grounded obtainable data points due to the composite nature of shale. The complications arising from cores being much smaller than the REV is also a highly unfavourable one, which is more prominent for fractured formations that generally have a higher REV. In such cases, one is left with a narrow band of grid blocks, beyond which solutions are either unstable (too small grid blocks) or meaningless (large grid blocks). These issues are much more severe for unconventional reservoirs where data from cores are mostly non-representative and only a few logging techniques bring out relevant results. The usage of the pseudo pressure approach in almost all the fast analytical and semianalytical models leads to the inability to accurately capture the non-linear relationship in gas compressibility, viscosity, as well as the compressibility factor in contrast to the incorporation of real gas equation [11].

The critical temperature and pressure of methane are 190.55K and 4.595 MPa respectively. The natural gas which is present within the shale reservoir possesses pressures and temperatures which are much larger than these values [12]. Thus, the dual porosity simulation model cannot be modeled using an ideal gas assumption. More importantly, the interplay and collisions of gas molecules are considerably small at lower temperatures and pressures, resulting in their ideal behavior. Firozabadi et al. (1978) and Shateri et al. (2015) concluded based on their experiments that the interplay and collisions of gas molecules become consequential because of the higher temperatures and pressures in shale gas reservoirs [13], [14]. Therefore, gas compressibility is decisive when forecasting the production, considering the gas expansion and shrinkage. For proper prediction of gas flow and pressure profile in dual porosity framework shale gas model (SGM), fracture porosity and permeability have to be modelled. As, pressure profile obtained from fracture will act as the boundary condition for shale gas matrix.

1. Numerical Modeling to Forecast Reservoir Performance

Today, pragmatically all facets of problems related to reservoir engineering are worked out with the assistance of reservoir simulators, stretching from well testing to the prognostication of Enhanced Oil Recovery (EOR). In every implementation of a reservoir problem, however, there is a mannerly-formulated simulator. It is well known that the current simulators at one's disposal only confront a limited range of solutions for a distinct problem in the field of reservoir engineering. Simulation is like the know-how which amalgamates physics, reservoir engineering, and mathematics along with computer programming to generate a tool for predicting hydrocarbon reservoir performance under various operating strategies. To model the fluid motion, Darcy's law is more or less utilized in all of the accessible reservoir simulators. Every model and approach which is developed is based on certain approximations and assumptions. This may seldom lead to inaccurate results and predictions. Despite these analytical models being much faster than numerical simulators, they by and large cannot handle the very high nonlinear aspects of shale gas and tight gas reservoirs. These analytical solutions fail to incorporate non-linearity. Other limitations involve the hurdles in precisely capturing gas movement from assorted complex and composite fracture networks.

This work addresses the eccentric behavior of flow related to the fracture systems in the reservoir taking into account the Darcy and non-Darcy flow, heterogeneity, and fluid–rock properties interactions. Also, this chapter is anticipated to eventually assist in inferring better shale gas reservoir management decisions with the assessment and production of gas from an Unconventional Shale Gas Reservoir (USGR). This work presents an ameliorated approach for modelling fractures in dual-porosity framework shale gas model to understand Non-Darcian flow behavior of gas through fractures under the influence of various petrophysical properties for achieving better shale gas production, reservoir characterization, and production behavior prediction.

III. PHYSICAL SYSTEM AND GOVERNING EQUATIONS

The elemental conceptual modelling of a shale gas reservoir itself has many intricacies linked with it because of the fact that shale gas reservoir forms both as a source rock as well as a reservoir rock. One should be aware of the intricacies linked with conceptual modelling, or else one may not be able to deduce a pertinent mathematical model. However, for better production and recovery of shale gas, the building of comparatively lucid mathematical and conceptual models not only aids in making intelligent and sensible reservoir management decisions but also assists in dynamically modernizing the model outline as a function of the production period. It takes into account fracture and rock-matrix as two distinct continuums with completely non-identical properties. In this work, the dual-porosity model is assumed to be a set of parallel blocks of rock-matrix partitioned by fractures. As a consequence of the recurring symmetry of the dual-porosity system along the fracture axis, exclusively half of the rock-matrix thickness and corresponding half of the fracture crevice are taken into consideration for the solution. The fluid flow equations are worked out uniquely in each of these continuums and are linked at the matrix-fracture connection face by a coupling term. The coupling term considers the fluid mass reciprocity between the fracture and the rock matrix [15]. The fracture is taken to be parallel and smooth and it is presumed beforehand to be very long juxtaposed to the thickness of the fracture aperture. The fracture which is uniform throughout its length accounts for the fluid flow, and the flow is assumed to be fast enough so that it can be taken into account as one-dimensional. Figure 3 shows the modeled 3 D reservoir scaled down to 2 D containing fracture and matrix.

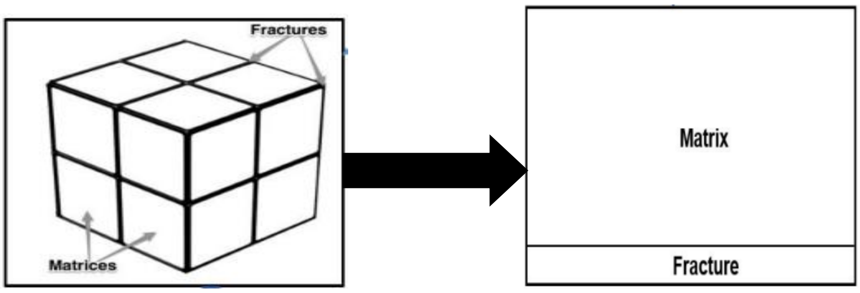

Figure 3: Shows the modeled 3 D reservoir scaled down to 2 D containing fracture and matrix

1. **Assumptions:** "Single Phase Flow (where water phase is immobile), isothermal conditions, negligible heterogeneity and gravitational effects, uniform and rectangular formation".

2. **Governing Equations:** Employing solely Darcy's law to illustrate the fluid flow of hydrocarbons in shale reservoirs when encountered highly fractured areas or when the excessive gas flow rate is anticipated is misleading. The rudimentary question to be answered while modeling fracture flow is the applicability and the validity of the governing equations employed. It is expected that unconventional gas reservoirs will be desirable prospects for using the Forchheimer extension of the momentum balance equation, preferably over the traditional Darcy's law [16]. Taking into account one-dimensional flow in the fractures, the mass conservation equation can be written as in Equation (1).

$$\frac{\partial(u\rho_g)}{\partial(x)} = -\phi_f \frac{\partial(\rho_g)}{\partial t} \tag{1}$$

Equation (2) represents the Forchheimer's equation in x direction.

$$\frac{\partial P_f}{\partial x} = -(u\frac{\mu_g}{k_f} + \beta\rho_g u^2) \tag{2}$$

Equation (3) and (4) represents the differentiation of momentum balance Equation (2) for fracture with respect to x.

$$-\frac{\partial^2 P_f}{\partial x^2} = \frac{\mu_g}{k_f}\frac{\partial u}{\partial x} + 2\beta\rho_g u\frac{\partial u}{\partial x} \tag{3}$$

$$-\frac{\partial^2 P_f}{\partial x^2} = \rho_g\left(\frac{\mu_g}{k_f\rho} + 2\beta u\right)\frac{\partial u}{\partial x} \tag{4}$$

Substitution of the value of $\rho_g \frac{\partial u}{\partial x}$ from mass balance equation of fracture (1) in Equation (4),will result in Equation (5).

$$-\frac{\partial^2 P_f}{\partial x^2} = \left(\frac{\mu_g}{k_f \rho} + 2\beta u\right)\left(-\phi_f \frac{\partial \rho_g}{\partial t} - u \frac{\partial \rho_g}{\partial x}\right) \quad (5)$$

The use of chain rule for $\frac{\partial \rho}{\partial t} = \frac{\partial \rho_g}{\partial P_f}\frac{\partial P_f}{\partial t}$ and $\frac{\partial \rho}{\partial x} = \frac{\partial \rho_g}{\partial P_f}\frac{\partial P_f}{\partial x}$, results in Equation (6)

$$\frac{\partial^2 P_f}{\partial x^2} = \left(\frac{\mu_g}{k_f \rho_g} + 2\beta u\right)\left(\phi_f \frac{\partial \rho_g}{\partial P_f}\frac{\partial P_f}{\partial t} + u \frac{\partial \rho_g}{\partial P_f}\frac{\partial P_f}{\partial x}\right) \quad (6)$$

Substituting $\frac{\partial \rho_g}{\partial P_f} = c_g \rho_g$ in the above Equation, the Equation (6) yields,

$$\frac{\partial^2 P_f}{\partial x^2} = c_g \phi_f \left(\frac{\mu_g}{k_g} + 2\rho_g \beta u\right)\frac{\partial P_f}{\partial t} + c_g u \left(\frac{\mu_g}{k_g} + 2\rho_g \beta u\right)\frac{\partial P_f}{\partial x} \quad (7)$$

Simplified form of Equation (7) is given below as Equation (8)

$$\frac{\partial^2 P_f}{\partial x^2} = \left(\frac{\mu_g}{k_f \rho_g} + 2\beta u\right)\left(\phi_f \frac{\partial P_f}{\partial t} + u \frac{\partial P_f}{\partial x}\right) c_g \rho_g \quad (8)$$

Table 1: Input parameters for the simulation [17]

Parameters	Value	Unit	Definition
β	3.09*10^6.	m^{-1}	Non-Darcy Flow Coefficient
P_w	3.45	MPa	Bottom Hole Pressure
k_f	10	md	Fracture Initial Permeability
ϕ_f	0.001	Dimensionless	Fracture Porosity
P_i	10.4	MPa	Initial Reservoir Pressure
u	0. 0000001	m/s	Convective Speed (Assumed)
c_g	0.1763	1/MPa	Gas Compressibility
ρ_g	0.657	kg/m^3	Shale Gas Density
μ_g	1.84* 10−5	Pa. s	Gas Dynamic Viscosity

1. **Initial and Boundary Conditions:** To solve the governing equations for the fracture, two boundary conditions and 1 initial condition are required for each equation. The boundary conditions along with the initial condition for the fracture governing equation represented below as,

$$P_f(x,t)|_{t=0} = P_i \tag{9}$$

$$P_f(x,y,t)|_{x=0} = P_w; \tag{10}$$

$$P_f(x,y,t)|_{x=L} = P_i \tag{11}$$

where, P_f denotes Fracture Pressure.

2. **Numerical Model:** The controlling fluid flow equation in the fracture is worked out numerically using the Finite Volume Method (FVM). The finite volume method has an upper hand when it comes to solving the hyperbolic term in the Partial Differential Equation (PDE). In this work, the cell width is kept almost the same throughout as pressure variations occur only at the interface of the fracture and matrix.

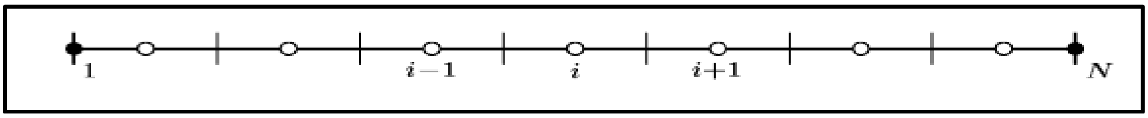

Figure 4: Representation of fracture domain in 1D

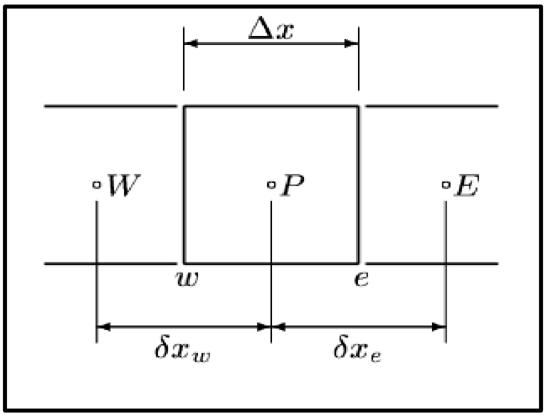

Figure 5: Geometry for single volume in one dimensional mesh

Table 2: Notation for representing cell centred values

Grid Location	Compass Notation
i, j, k	P
i-1, j, k	W
i+1, j, k	E

The upwind scheme in the governing equation for fracture is employed to discretize the hyperbolic term. The temporal part of the governing equation is discretized using first order backward differencing. Altogether for the fracture, the discretized form of governing equation can be represented below in the form of equation 12.

$$\left(\frac{1}{r\phi}\frac{\partial P_f}{\partial x}\right)|_e A_{ei} - \left(\frac{1}{r\phi}\frac{\partial P_f}{\partial x}\right)|_w A_{wi} = \frac{\partial P_f}{\partial t} + u * (\frac{1}{2}\left(P_{fP} + P_{fE}\right) - \frac{1}{2}\left(P_{fP} + P_{fW}\right) \qquad (12)$$

where $r = \left(\frac{\mu_g}{k_g} + 2\rho_g \beta u\right) c_g$ and ei denotes east face interface and wi denotes west face interface.

$$\left(\frac{1}{r\phi}\frac{P_E - P_P}{(\Delta x)_e}\right) * b - \left(\frac{1}{r\phi}\frac{P_P - P_W}{(\Delta x)_w}\right) * b = \frac{\partial P_f}{\partial t} + u * (\frac{1}{2}\left(P_{fP} + P_{fE}\right) - \frac{1}{2}\left(P_{fP} + P_{fW}\right) \qquad (13)$$

The simplest method to discretize the convective term is the First Order Upwind (FOU) Scheme.

In MATLAB, using the [] operator, where [x, y] is the maximum of x or y (this is similar or equivalent to the MATLAB MAX intrinsic function), the advection term can further be approximated as:

$$\int_w^e u \frac{\partial P_f}{\partial x} dx = [u_e, 0]P_{fP} - [-u_e, 0]P_{fE} - [u_w, 0]P_{fW} + [-u_w, 0]P_{fP} \qquad (14)$$

The discretized equation for the fracture is solved by using Thomas Algorithm (Figure 6) in MATLAB. The fracture pressures obtained are used as bottom boundary condition for the matrix.

$$\begin{bmatrix} b_0 & c_0 & 0 & 0 & 0 & \cdots & 0 & 0 \\ a_1 & b_1 & c_1 & 0 & 0 & \cdots & 0 & 0 \\ 0 & a_2 & b_2 & c_2 & 0 & \cdots & 0 & 0 \\ 0 & 0 & a_3 & b_3 & c_3 & \cdots & 0 & 0 \\ \vdots & \vdots & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & a_{n-3} & b_{n-3} & c_{n-3} & 0 \\ 0 & 0 & 0 & \cdots & 0 & a_{n-2} & b_{n-2} & c_{n-2} \\ 0 & 0 & 0 & \cdots & 0 & 0 & a_{n-1} & b_{n-1} \end{bmatrix} \cdot \begin{bmatrix} x_0 \\ x_1 \\ x_2 \\ x_3 \\ \vdots \\ x_{n-3} \\ x_{n-2} \\ x_{n-1} \end{bmatrix} = \begin{bmatrix} d_0 \\ d_1 \\ d_2 \\ d_3 \\ \vdots \\ d_{n-3} \\ d_{n-2} \\ d_{n-1} \end{bmatrix}$$

Figure 6: Schematic Representation of Tri-Diagonal Matrix

IV. SENSITIVITY ANALYSIS OF POROSITY AND PERMEABILITY FOR MODELING FRACTURES

The sensitivity of fracture parameters, namely fracture permeability and fracture porosity has been investigated under Dirchilet boundary conditions.

1. **Fracture Permeability:** Fracture permeability remains more sensitive in contrast to the other fracture parameters, namely fracture porosity, in deciding the resultant pressure distribution. From Figure 7 it can be deduced that fracture permeability plays an important role as it decides the fracture pressure profile that is to be used as a boundary condition for the matrix.

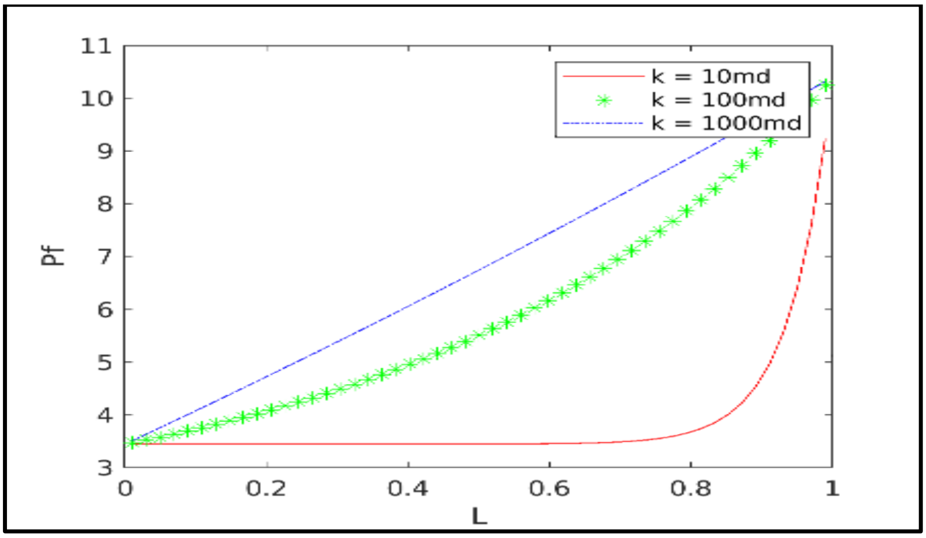

Figure 7: Pressure Profile along the fracture for different values of initial fracture permeability

Low values of fracture permeability as shown in Figure 8 will lead to misleading results in contour plots as negative values of fracture pressures are obtained that are to be used as boundary conditions for the matrix. It can also be inferred from the from Figure 8 that the low value of fracture permeability makes the pressure profile more erroneous subsequently resulting in poor analysis and prediction of flow in shale gas matrix.

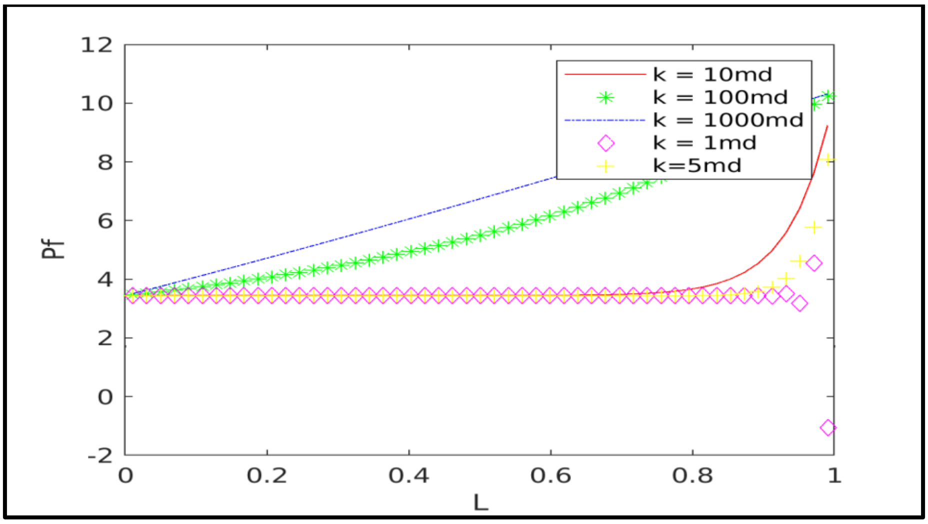

Figure 8: Pressure profile along the fracture with initial fracture permeability of 1md and 5md

2. **Fracture Porosity:** It can be deduced from the Figure 9 and Figure 10 that fracture porosity does not play a vital role in deciding the pressure profile for the rock matrix as there is no change in fracture pressures when fracture porosity is decreased or increased.

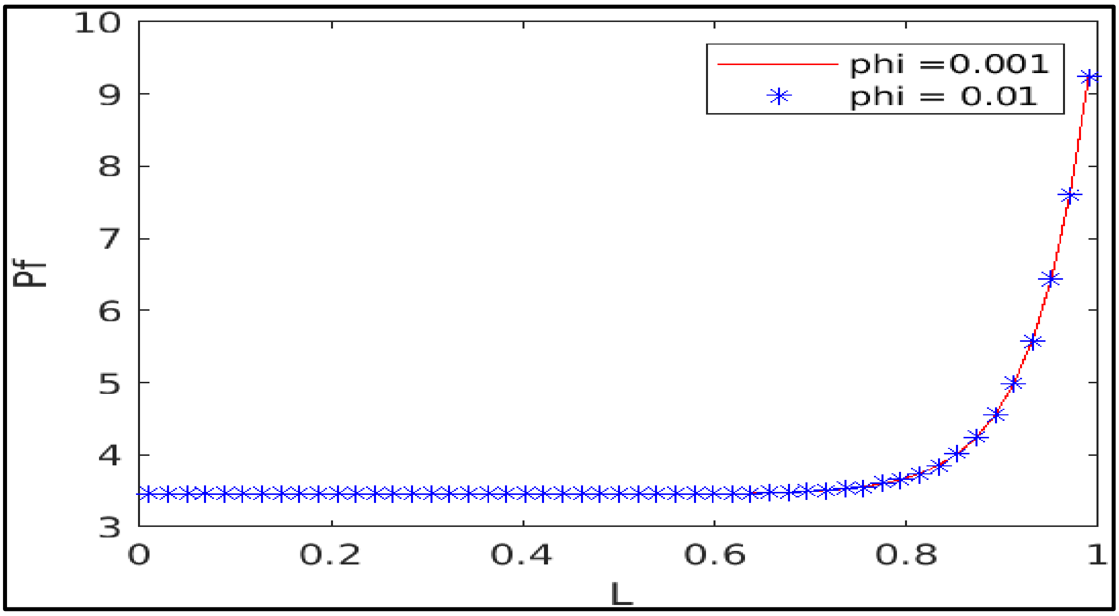

Figure 9: Pressure profile along the fracture for different values of fracture porosity (phi = 0.001 and phi=0.01)

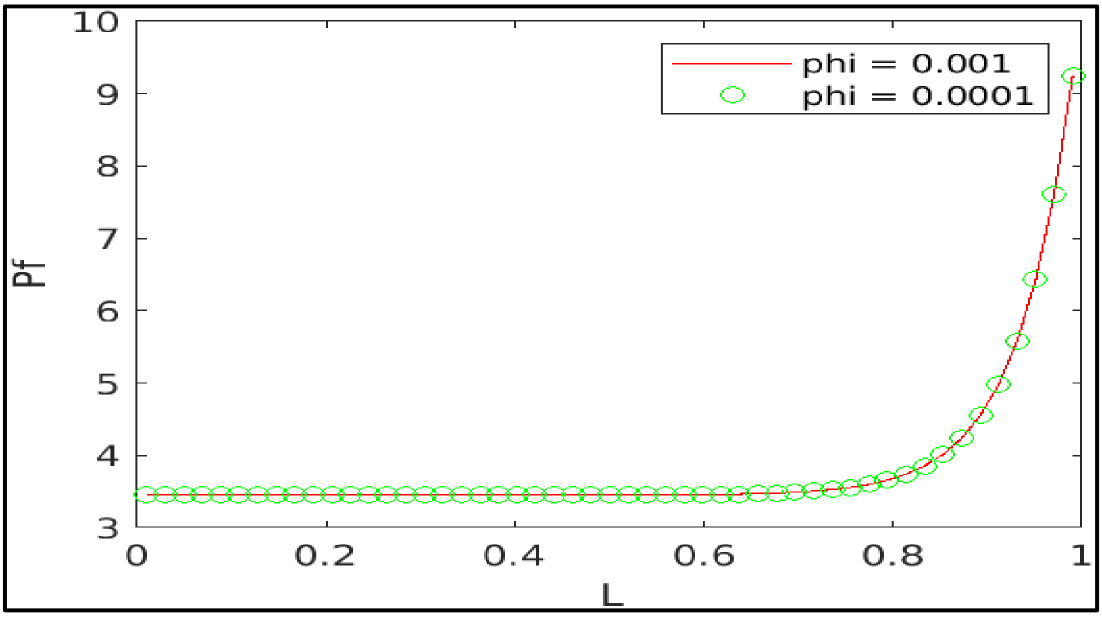

Figure 10: Pressure profile along the fracture for different values of fracture porosity (phi = 0.001 and phi = 0.0001)

V. SUMMARY

The rapid transition from a fossil fuel-based economy towards a renewable economy is challenging. In order to alleviate the massive CO_2 emissions, the direct shift from coal and black gold to gas-based fossil fuel is pressing priority. Better shale gas reservoir management decisions with the assessment and production of gas from an Unconventional Shale Gas Reservoir (USGR), can basically intensifies the shale gas supply which in turn replace coal in the energy portfolio. The petrophysical properties are the great decisive factors on the productivity of shale gas. Conventional methods usually consider constant fracture and rock-matrix properties, leading to erroneous inferences related to fracture permeability, pressure distribution, and consequently in expected productivity. A sensitivity analysis was performed on fracture permeability where a rise in fracture permeability follows ameliorated and homogeneous contribution through the rock-matrix. The gas production from fractured reservoirs follows a decline in reservoir pressure and consequently a decline in the fracture permeability. Fracture porosity does not play a vital role in deciding the pressure profile for the rock matrix as there is no change in fracture pressures when fracture porosity is decreased or increased. It is also vital to take into consideration the stress-sensitive effect for an upgraded forecast of the reservoir productivity performance and its pressure distribution. The International Energy Agency (IEA) sustainable development scenario that outlines a rapid transition to 'Carbon-Negative' economy, emphasizes the importance of exploitation of USGR. As the conventional oil and gas reservoirs are already on the verge of decline, it is imperative to characterize unconventional gas reservoirs like Shale gas reservoirs for a paradigm shift towards the cleaner economy.

REFERENCES

[1] Klinkenberg L.J. (1941).The permeability of porous media To liquids and gases. Socar Proceedings. 2 (2): 200–213.
[2] Luffel, D.L., Hopkins, C.W. and Schettler, P.D., 1993, October. Matrix permeability measurement of gas productive shales. In *SPE annual technical conference and exhibition*. OnePetro.
[3] Wu, Y.S. and Pruess, K., 1998. Gas flow in porous media with Klinkenberg effects. *Transport in porous Media*, *32*(1), pp.117-137.
[4] Beskok A., Karniadakis G.E. (1999). Report: a model for flows in channels, pipes, and ducts at micro and nano scales. Microscale Thermophysical Engineering, 3(1), 43–77.
[5] Javadpour, F., Fisher, D., Unsworth, M., 2007. Nano scale gas flow in shale gas sediments. J. Can. Pet. Technol. 46 (10), 55–61. https://doi.org/10.2118/07-10-06.
[6] Javadpour F. (2009). Nanopores and apparent permeability of gas flow in mudrocks (shales and siltstone). Journal of Canadian Petroleum Technology, 48(8), 16–21.
[7] Xiong, X., Devegowda, D., Michel, G.G., Sigal, R.F. and Civan, F., 2012, October. A fully-coupled free and adsorptive phase transport model for shale gas reservoirs including non-Darcy flow effects. In *SPE annual technical conference and exhibition*. OnePetro.
[8] Shabro V., Javadpour F., Torres-Verdı ́n C. (2009). A generalized finitedifference diffusive-advective (FDDA) model for gas flow in micro-and nanoporous media. World Journal of Engineering, 6(3), 7–15.
[9] Civan F., Rai C.S., Sondergeld C.H. (2011). Shale-gas permeability and diffusivity inferred by improved formulation of relevant retention and transport mechanisms. Transport in Porous Media, 86(3), 925– 944.

[10] Ziarani, A.S. and Aguilera, R., 2012. Knudsen's permeability correction for tight porous media. *Transport in porous media*, *91*(1), pp.239-260.
[11] Houze, O., Tauzin, E., Artus, V. et al. 2010. The Analysis of Dynamic Data in Shale Gas Reservoirs - Part 1. Company report, Kappa Engineering, Houston, Texas, USA.
[12] D.G. Friend, J.F. Ely, and H. Ingham, J. Phys. Chem. Ref. Data 18, 583 (1989)
[13] Firoozabadi, A., Hekim, Y. & Katz, D. (1978). Reservoir depletion calculation for gas condensate using extended analysis in PR-EOS. Canadian Journal of Chemical Engineering.
[14] Shateri, M., Ghorbani, S., Hemmati-Sarapardeh, A. and Mohammadi, A.H., 2015. Application of Wilcoxon generalized radial basis function network for prediction of natural gas compressibility factor. *Journal of the Taiwan Institute of Chemical Engineers*, *50*, pp.131-141.
[15] Kumar, A. and Govindarajan, S.K., 2020. Numerical investigations on compressible non-linear fluid flow associated with a stress-sensitive fractured reservoir. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, pp.1-20.
[16] Islam, M.R., 2015. Overview of reservoir simulation of unconventional reservoirs. *Unconventional gas reservoirs: Evaluation, appraisal, and development: Amsterdam, Elsevier*, pp.487-547.
[17] Bustin, R.M., Bustin, A.M., Cui, A., Ross, D. and Pathi, V.M., 2008, November. Impact of shale properties on pore structure and storage characteristics. In *SPE shale gas production conference*. OnePetro.