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GEOMECHANICAL ASPECTS OF HYDRAULIC FRACTURE PROPAGATION IN THE LUBLIN SHALE GAS FIELD IN POLAND***

1. INTRODUCTION

The propagation of hydraulic fracture in a shale gas rock is of utmost importance for the petroleum industry to stimulate reservoirs and the recovery of gas. This paper gives an insight into the comparison of different geo-mechanical parameters of shale plays in U.S. and Poland. Rheological properties coupled with the geo mechanical properties of the rock are very important parameters in estimating a reservoir characteristic for hydraulic fracturing. The successful recovery of shale gas from the U.S. basins has been due to experiment on the various basins across U.S. and finally they have achieved the horizontal hydraulic stimulation of reservoirs. This cache of success has been an intriguing factor for other countries like Poland to explore its own natural gas in the inferred shale gas basin across Poland. This country has three major basins like Baltic in the north, Lublin and Podlasie in the east. Across these basins there has been a good indication for shale gas exploration but the geological settings across these basins seems to pose a greater challenge for engineers and geo-physicist to design and recover the shale gas with greater economic viability.

2. DESCRIPTION OF SHALE ROCK

Shale rock shows a varying degree of orientation in the planes and it has the ability to break along the weak plane called as bedding plane often into lamina or splint types. Shales show mechanical anisotropy due to their organized distribution of platy clay minerals. Due to these complex characteristics of shale rock, it is difficult to recover the core of shale rock and test it in the laboratory to give the in-situ like parameters.

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The potential shale gas plays in the U.S. are the Marcellus of the Devonian age, the Barnett of the Mississippian age, the Haynesville of the Jurassic age and the Eagle Ford Shale of the Cretaceous age. These reservoir basins occurred in different geological ages and have different reservoir characteristics.

Marcellus shale occurred at a depth of 1,520–2,440 m below ground having a thickness of 15–107 m, with a porosity of 3–9% and a kerogen content (TOC) of 3–10%. The rocks in this basin are highly fractured with optimum level of maturation for reservoir stimulation. The Barnett shale of the Mississippian age was found at a depth of 1,825–2,740 m with a thickness of 90–150 m and a porosity of 3–9% and organic content of 3–8%. Eagle Ford shale is of the Cretaceous age occurring at a depth of 1,830–3,658 m with a thickness of 30–90 m, a porosity of 6–14% and 2–6% of total organic content. Similarly Haynesville shale is of Jurassic age occurring at a depth of 3,500–4,270 m below ground. It has a thickness of 45–105 m with a porosity content of 8–15% and a total organic content of 1–5%.

The Polish Shale plays are mainly located in three major basins across Poland, like Baltic in the north, Lublin and Podlasie in the east. As per the study conducted by the Oil and Gas Institute, Krakow, potential shale gas plays are in the zone passing across Poland connecting three basins namely Pomerian to the Lublin area and in the Sudeten Foreland. The Upper Ordovician and the Lower Silurian Shale gas deposits have shown a prospective area for shale gas exploration. The Lower Paleozoic rocks also gave a good indication of organic rich shale for the unconventional gas fields. For example, in the Southwest of Poland, the well logging data in the Carboniferous part of the sections in the well showed a average TOC of more than two percent. The major regions concerning the shale gas exploratory zones in Poland can be categorized into following:

– The Baltic basin – the Ordovician and Silurian formations,
– Lublin – Podlasie basin – the Ordovician and Silurian formations,
– Carpathian Foredeep – the Ordovician and Silurian formations,
– Carpathian Foredeep – the Miocene formations,
– Wielkopolska region of Poland – the Carboniferous formations.

As per the study conducted on the U.S. and Polish shale formations, the mechanical properties of the shale rock are similar in both the U.S. and Poland. Other characteristics like depth, temperature, porosity and clay content vary across the basins and formations. The potential unconventional shale deposits are located at a depth of up to 5,000 m in some sedimentary basins. Moreover, some of the Polish shale formations are located at a depth 1.5 times deeper than U.S. shale formations, and higher geothermal gradients cause a challenge in exploring the shale gas. Basic properties comparison of Lublin shale and some U.S. shales are shown in Table 1.

3. FRACTURE PROPAGATION MODELS

Khristianovic and Zheltov (1955) developed the first model to simulate fracture propagation in rocks. The two dimensional formulation is based on the assumption of plane strains in two different planes namely in the horizontal and vertical planes. These two basic conditions gave a breakthrough in various fracture propagation models.

Table 1

Shale reservoir characteristics of U.S. shales and Lublin (Poland)

Reservoir	Barnett Shale	Eagle Ford Shale	Haynesville Shale	Marcellus Shale	Woodford Shale	Lublin Shale (Poland)
Geologic age	Mississippian	Cretaceous	Jurassic	Devonian	Upper Devonian	Ordovician
Depth	5,987–8,989 ft.	6,003–12,001 ft.	11,482–14,009 ft.	4,986–8,005 ft.	5,905–14,000 ft.	9,842 ft.
Zone Thickness	295–492 ft.	98–295 ft.	147–345 ft.	up to 885 ft. thick	98–223 ft.	up to 492 ft. thick
Composition	silica rich	high illite content and calcite (in pockets)	soft shale with organic rich silica and calcite rich in-areas; high clay mineral fraction	sandstone, siltstone, black (organic) shale and grey shale	organic-rich marine shales with minor siltstones, sandstones, black cherts	organic rich black shale; highly silicious and brittle rock
TOC	3–8%	2–6%	1–5%	3–10%	3–9%	4–20%
Porosity	3–9%	6–14%	8–15%	3–9%	1–8%	3%
Young's Modulus ($\cdot 10^6$ psi)	6–10	1–4	2–3	2–5	4–8	7–9
Poisson's ratio	0.13–0.25	0.20–0.27	0.23–0.27	0.19–0.23	0.15–0.25	0.20–0.25

The first situation is based on the consideration that the medium is discretised into number of parallel horizontal planes defined in an elastic medium. These horizontal sections act independently to each other plane without any vertical strain. The fracture zone for such type of horizontal plain strain; the parallel planes would deform independently of each other and produce a free slippage on these layers representing a horizontal penetration. This condition gives the fracture propagation of constant height and rectangular cross section.

Based on this fracture mechanics aspect of fracture tip the fracture width is proportional to the fracture length with constant fracture height, the fracture has an elliptical cross section in the horizontal plane. This condition gives rise to the (Khristianovic–Geertsma de Klerk) KGD fracture propagation model. In this model there is slippage between the layers and the fluid does not act on the entire fracture length and the cross section in the vertical plane is rectangular.

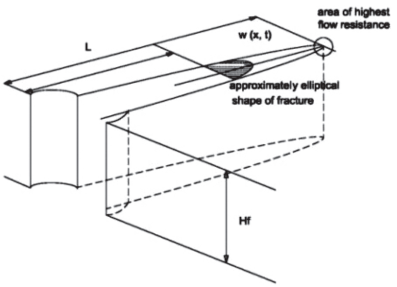

Fig. 1. KGD Model

The KGD model for fracture propagation is based on equations (1) and (2).

$$x_f(t) = 0.68\left[\frac{Gq_0^3}{(1-\nu)\mu h_f}\right]^{\frac{1}{6}} t^{\frac{2}{3}} \tag{1}$$

where:

x_f – fracture half length [ft],
G – shear modulus [psi],
μ – viscosity [cP],
h_f – fracture height [ft],
q – flow rate at fracture entrance [bbl/min],
t – time [min],
ν – Poisson's ratio.

Formula on the average width of the fracture was developed as [4]:

$$\overline{w} = 0.29\left[\frac{\mu q_i(1-\nu)x_f^2}{Gh_f}\right]^{\frac{1}{4}}\left(\frac{\pi}{4}\right) \tag{2}$$

where $\overline{w}$ – average width [ft].

The second model on fracture propagation in rock was proposed by Perkins–Kern–Nordgren, PKN based on the plain strain assumption in vertical planes and that every vertical cross section acts independently. This condition exists when there is large confinement. The pressure at a point is independent on the pressure distribution at other locations along the fracture length. In each vertical cross section the pressure is uniform and hence the shape of the fracture propagation is elliptical. The PKN model neglects the effect of fracture tip and fracture mechanics and focuses on fluid flow and their pressure gradients [2]. Perkins and Kern (1971) assumed the flow rate to be constant in this model. At any cross section the maximum width is proportional to the net pressure at that point and independent of the width at any other point [2]. The in-situ stresses are assumed to be homogeneous and the PKN model utilizes the Sneddon width equation [3].

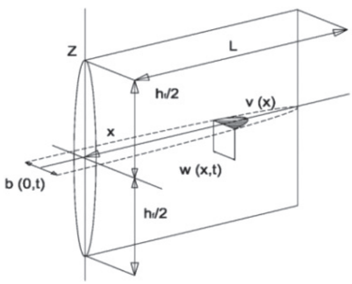

Fig. 2. PKN Model

The equation for the fracture half length in PKN model becomes:

$$x_f = 0.68\left[\frac{Gq^3}{(1-\nu)\mu h_f^4}\right]^{\frac{1}{5}} t^{\frac{4}{5}} \tag{3}$$

Formula on the average width of the fracture was developed as [4]:

$$\overline{w} = 0.3\left[\frac{\mu q_i (1-\nu) x_f}{G}\right]^{\frac{1}{4}}\left(\frac{\pi}{4}\gamma\right) \tag{4}$$

where γ is assumed to be 0.75.

The first two models considered the propagation of vertical fracture with a given height. The Radial model is considered more accurate for the fractures propagating in the inclined or horizontal direction (Table 2). The shape of the fracture is circular and the maximum width is at its centre.

Fracture radius R has been formulated as [11]:

$$R = 0.548\left[\frac{Gq^3}{\mu}\right]^{\frac{1}{9}} t^{\frac{4}{9}} \tag{5}$$

And for radial PK model:

$$R = \left[\frac{3qt}{2\pi \overline{w}} \right]^{\frac{1}{2}} \tag{6}$$

where R – fracture radius [ft].

Formula on the average width of the fracture was developed as [4]:

$$\overline{w} = 0.85 \left[\frac{\mu q_i (1-\nu) R}{E} \right]^{\frac{1}{4}} \tag{7}$$

where:

$\overline{w}$ – average fracture width [ft],

E – Young's modulus [psi].

And for radial PK model:

$$\overline{w} = 1.42 \left[\frac{\mu^2 q^3 (1-\nu)^2 t}{\pi g^2} \right]^{\frac{1}{9}} \tag{8}$$

Table 2

Comparison between different fracture propagation models

Model	Assumptions	Shape	Application
KGD	constant height, plain strain in horizontal direction	rectangular cross section	length < height
PKN	fixed height, plain strain in vertical direction	elliptical cross section	length > height
Radial	propagate in given plane symmetrical to the wellbore	circular cross section	radial

4. MODEL APPLICATION

Based on the above mentioned data on various reservoirs in the U.S and considering a injection rate of 10 bbl/min, fluid viscosity of 10 cP, fracturing height of 100 ft, the estimated half-fracture length of all the above given reservoirs are calculated based on the given three 2D fracture propagation models. The calculated results (the estimated fracture width and fracture half length) based on the model equations are presented in Table 3.

Table 3

Comparison of different fracture properties

Fracture Propagation Model	Reservoir	Estimated average fracture width [ft]	Fracture half length [ft]
KGD Model	Woodford Shale	0.0023	1,111
	Haynesville Shale	0.0022	960
	Marcellus Shale	0.0021	1,012
	Barnett Shale	0.0019	1,160
	Eagle Ford Shale	0.0022	959
PKN Model	Woodford Shale	0.0011	1,942
	Haynesville Shale	0.0011	1,630
	Marcellus Shale	0.0011	1,737
	Barnett Shale	0.0010	2,045
	Eagle Ford Shale	0.0011	1,628
Radial Model	Woodford Shale	0.0051	398
	Haynesville Shale	0.0062	361
	Marcellus Shale	0.0057	374
	Barnett Shale	0.0048	409
	Eagle Ford Shale	0.0062	361

Lublin basin has been chosen as there has been ongoing drilling operations. Results of calculation are shown in Table 4.

Table 4

Estimation of fracture width and half length for Lublin shale from 2D fracture propagation models

Fracture Propagation Model	Reservoir	Estimated average fracture width [ft]	Fracture half length [ft]
KGD Model	Lublin Shale	0.0014	1163
PKN Model		0.001	2052
Radial Model		0.0048	410

The above Table 4 gives the estimated fracture length and width of the Lublin reservoir in Poland, where the values for the calculations are given as $E = 55 \cdot 10^6$ psi, Poisson's ration $\nu = 0.23$, viscosity $\mu = 10$ cP and injecting fluid at the rate of 10 bbl/min for hydraulic fracturing over an injection time of 1 hr. The results from the three 2D fracture propagation models are presented and a general conclusion can be drawn from this initial preliminary findings based on the hydraulic fracture thickness comparison between U.S. and Polish shale reservoirs.

5. CONCLUSION

This paper presents a comparative study on the hydraulic fracture thickness between a U.S. and Polish shale basin based on the zone thickness and geo-mechanical characteristic of the rocks. The results are derived from three basic 2D fracture propagation models to estimate the fracture width comparison between different models. The fracture width estimation obtained from these models for different shale basins across the U.S. and Poland gave similar results and with little changes from each other's. The results show that the reservoir characteristics between U.S. and Poland shale are similar in nature but a new problem that would arise in Polish shale would be depth and geo-thermal gradient. As the same type of shale rocks characteristics which are at greater depth than the U.S. would mean technological and economical enhancement to recover shale gas in Poland. The findings are preliminary and it is too early to conclude and stop our investigations half way, therefore this step is a way forward to go for a detailed and comprehensive research study of Polish shale and derive a complete roadmap to explore shale gas with greater reliability, cost and environmental concern for the energy security of the country.

SI METRIC CONVERSION FACTORS

ft · 3.048 E – 01 = m
psi · 6.894757 E – 03 = MPa
cP · 1 E – 03 = Pa·s
bbl/min · 2.649788 E – 03 = m^3/s

REFERENCES

[1] Dimitrijevic B., Pinka J., Mitrovic V.: *Selection of technological parameters in borehole mining production by technical deep drilling and hydro-exploitation*. Acta Montanistica Slovaca 2004.

[2] Economides M.J., Nolte K.G.: *Reservoir Stimulation.* Second Edition. Prentice Hall, Englewood Cliffs 1989.

[3] Gidley J.L., Holditch S.A., Nierode D.E., Veatch R.W. Jr.: *Recent Advances in Hydraulic Fracturing*. Society of Petroleum Engineers, Richardson, Texas 1990. SPE Monograph Series, vol. 12.

[4] Boyun G., W.C. Lyons, Ghalambor A.: *Petroleum Production Engineering*: *a Computer-Assisted Approach*. Elsevier Science & Technology Books, 2007.

[5] Hall C.D.: *A Comparison of Gas Shale Reservoir Properties – Muskwa, Marcellus, Barnett, Montney, Haynesville, and Eagle ford, Integrated Reservoir Solutions Division*: *Core Laboratories, Houston, Texas*. 4th B.C. Unconventional Gas Technical Forum, Victoria, British Columbia 2010.

[6] Matyasik I.: *Geological-geochemical assessment of occurrence and extraction of shale gas in Poland*. Oil and Gas Institute, Krakow 2011.

[7] Perkins T.K., Kern L.R.: *Widths of Hydraulic Fractures*. Journal of Petroleum Technology, vol. 13, no. 9, 1961, pp. 937–949.

[8] Stryczek S., Wiśniowski R.: *The method of gravity injection to the mining voids in salt mines*. Archives of Mining Sciences, vol. 49, no. 1, 2004, pp. 55–69.

[9] Sneddon I.N., Elliot A.A.: *The Opening of a Griffith Crack Under Internal Pressure*. Quarterly of Applied Mathematics, vol. 4, 1946, pp. 262–267.

[10] Sneddon I.N., Green E.A.: *The Distribution of Stress in the Neighborhood of a Crack in an Elastic Solid*. Proceedings of the Cambridge Philosophical Society, vol. 46, issue 1, 1950, pp. 229–260.

[11] Yew Ching H.: *Mechanics of Hydraulic Fracturing*. Gulf Publishing, 1997.