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IPR Equation Of CBM Wells Using Palmer And Mansoori Model

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Abstract

IPR equation is important in designing well completion, production optimization, nodal analysis and artificial lifts on CBM wells. The technique for producing gas of coalbed methane is different from conventional gas because the production initially was dominated by water. The gas will flow as the reservoir reaches the desorption pressure. Permeability is very sensitive to the pressure reflected in the phenomenon of cleat compression and the corresponding matrix shrinkage in the cleat and coal matrix. This phenomenon causes the conventional IPR curve is not applicable in CBM wells. This paper presents a dimensionless IPR curve for CBM wells considering the Palmer and Mansoori (P & M) model. The equation of IPR illustrates the change in permeability due to the compression phenomenon and the shrinkage of the matrix in the coalbed methane reservoir. The equation model of IPR produces a graph illustrating the increasing permeability when the coalbed methane reservoir pressure depleted. The six reservoir parameters included porosity (ϕ), drainage area (A_D), thickness (h), S_{wc} and two P & M parameters (Young modulus (E) and the Poisson ratio (v) have been selected to make the IPR curve. Taking into account the P & M model in the development of the IPR curve, then the right method to predict the production performance of gas in coalbed methane will be obtained.

Keywords*: Pressure; gas flow rate; methane; IPR; CBM.*

1. Introduction

Coalbed methane (CBM) is a methane gas formed along with the establishment of coal. The gas is trapped and absorbed (adsorbed) inside the coal. The production of methane gas from the CBM reservoir is unique and different from the production process in the conventional reservoir (Fig. 1). In the early stages of production, when reservoir pressure is above the critical desorption pressure (CDP), usually only water flows from the cleats. After pressure reaches CDP, water and gas are produced simultaneously. When desorption pressure is reached, methane gas is released from the surface of the coal matrix and then begins to dominate the flow rather than water until it reaches the peak flow rate of gas (Fig. 2). As the gas flow rate reaches the peak, then the water production will reach zero so that only gas is produced.

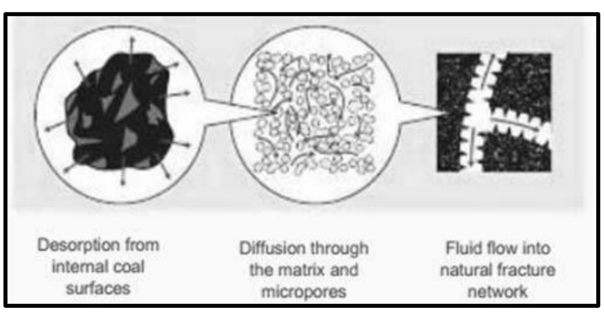

Fig. 1. Flow mechanism in CBM reservoir [11]

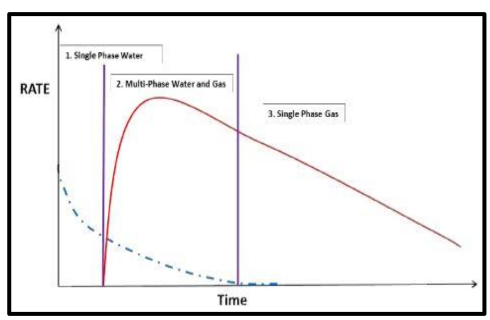

Fig. 2. Production profile of CBM well [11]

Palmer *et al.* [3] illustrate that the permeability of the CBM reservoir may change as it is influenced by changes of porosity due to the decrease of reservoir pressure. When reservoir pressure decreases, the overburden pressure forcing the cleat so that the cleat volume decreases resulting in a decrease in permeability. This phenomenon is referred as cleat compression (Fig. 3). But when reservoir pressure reaches below CDP, the gas is desorbed out from the coal matrix. This causes the volume of coal matrix will be reduced, but the cleats volume were enlarged so that the value of permeability increases (Fig. 4). Both these phenomena influence each other during pressure drop occurs.

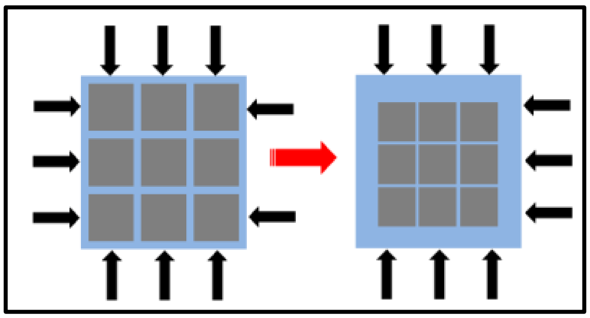

Fig. 3. Cleats compression *(Zulkarnain [9])*

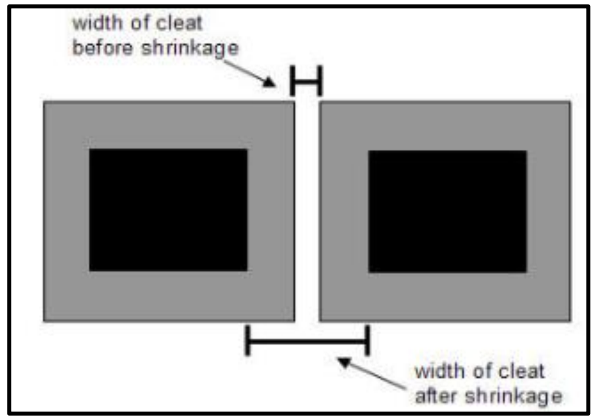

Fig. 4. Matrix shrinkage *(Zulkarnain [9])*

Palmer and Mansoori model [3] arranged the following equation:

$$\frac{\phi}{\phi_i} = 1 + \frac{c_m}{\phi_i}(p - p_i) + \frac{c_o}{\phi_i}\left(\frac{K}{M} - 1\right)\left(\frac{Bp}{1+Bp} - \frac{Bp_i}{1+Bp_i}\right) \quad (1)$$

where Modulus axial constraint constant comes from :

$$M = \frac{(1-v)E}{(1+v)(1-2v)} \quad (2)$$

Poisson's ratio (v) states the change in the shape of material if force is applied in one direction. The Young Modulus (E), also known as the elastic modulus, is expressing the magnitude of the failure or the change of shape of material when the material is subjected to force. When expressed in cm and the relation of K/M is expressed by the following equation:

$$\frac{K}{M} = \frac{1}{3}\left(\frac{1+v}{1-v}\right).. \quad (3)$$

then the Palmer and Mansoori equation can be written as follows :

$$\frac{\phi}{\phi_i} = 1 + \frac{(1+v)(1-2v)}{(1-v)E\phi_i}(p - p_i) + \frac{c_o}{\phi_i}\frac{2(1-2v)}{3(1-v)}x.. \quad (4)$$

$$\left(\frac{Pi}{Pi+P_L} - \frac{P}{P+P_L}\right). \quad (5)$$

The center part of the above equation shows porosity change due to the effects of stress on coal, while the last part shows the influence of shrinkage porosity against the matrix. Assuming the change of permeability depends on the value of the porosity, then obtained the equation as follows:

$$\frac{k}{k_i} = \left(\frac{\phi}{\phi_i}\right)^3.. \quad (6)$$

As discussed earlier, permeability is very sensitive to the effective stress (reservoir pressure). Palmer and Mansoori [3] (Fig. 5) show a phenomenon of permeability change as a function of effective stress. A decrease in pressure at the early of production will cause the effective stresses on cleats start to increase so that the cleats will be compressed and cause a decrease in permeability. In the next stage, the effect of effective stress on cleats will diminish so the permeability tends to increase.

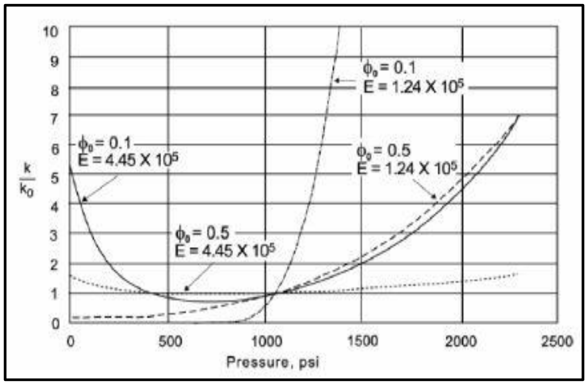

Fig. 5. Effect of stress on the permeability of Palmer & Mansoori model [3]

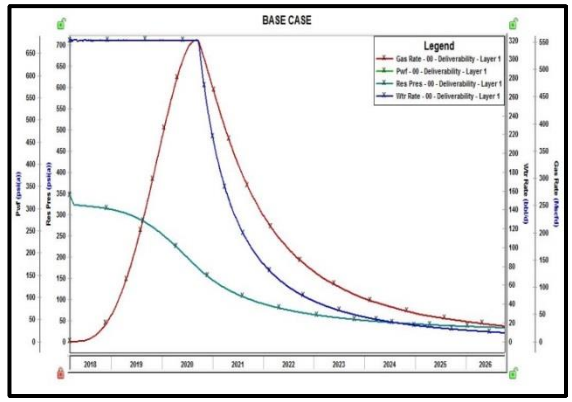

Fig. 6. The relationship of P_r, Q_g, and Q_w

This phenomenon affects the gas production of reservoir CBM because permeability increases one to four times greater than initial permeability. This should be increasing of gas recovery.

2. Material and methods

2.1 Development of IPR equation

Method of producing gas of coalbed methane is different from the conventional gas reservoir. In the beginning, production is dominated by water where the gas will flow when the pressure reaches a critical point. In addition, the permeability is very sensitive to the pressure indicated by the phenomenon of cleat compression and shrinkage of the matrix. Therefore, conventional IPR methods cannot be used for CBM wells.

Vogel's IPR [8] is well known and commonly used to describe fluid flow in oil wells. Vogel's IPR is performed by using simulations of single wells for various characteristics of gas and oil reservoirs. IPR for coalbed methane was initially developed with the assumption of conventional gas wells. Seidle and Erickson [6] used Vogel's IPR to construct IPR for gas of coalbed methane. Furthermore, there is a general form of Vogel's IPR equation developed by Richardson and Shaw [4].

$$\frac{Q}{Qmax} = 1 - V\frac{Pwf}{Pr} - (1-V)\left(\frac{Pwf}{Pr}\right)^2.. \quad (7)$$

Shaw [4] develops the same equation as Vogel's IPR by using the variable Vogel coefficient denoted by *V*. The IPR equation needs to be adjusted to the CBM reservoir characteristics. The new IPR equation is needed to provide the CBM wells performance more accurately than Vogel IPR.

2.2. Reservoir data

In this research, Fekete F.A.S.T CBM software is used to develop a reservoir model. This study uses vertical good models where the pressure response is a rectangular, homogeneous or double porosity reservoir. The hypothetical under saturated reservoir model is used with the assumption of 1 layer reservoir, homogeneous isotherm, no water entry, 100% water saturation in cleats, the abandon pressure 20 psia and the composition of the gas methane 100%. It is also assumed that the A_D value is 80 acres. The following is the data used for base case model of wells T-01.

The effect of the shrinkage matrix of P & M model was tested first with a reservoir simulation. In the simulation, the shrinkage parameter of the Poisson ratio matrix (*v*), Young's modulus (*E*) is recommended parameter as the input, and greatly affects the shrinkage of the matrix.

Table 1. The Base data of well T-01

Layer		1	Moisture content (Wc),	%	38.8
Initial pressure (Pi),	psia	714	Ash content (a),	%	4.43
Langmuir volume (VL),	scf/ton	258.6	Bulk density (ρb),	gr/cc	1.31
Langmuir pressure (PL),	psia	492.89	Skin damage (Sd)		0
Temperature reservoir (TR)	°F	110	Permeability		84.5
Gas saturation (Sg),	%	10	Well radius (rw),	ft	0.3
Connate gas saturation (Sgc),	%	1	Φi,	(%)	1.9
Connate water saturation (Swc),	%	20	AD assumption	Acre	80
Thickness (h),	ft	62.4	Pabd assumption	Psia	20
Initial water saturation (Swi),	%	1			

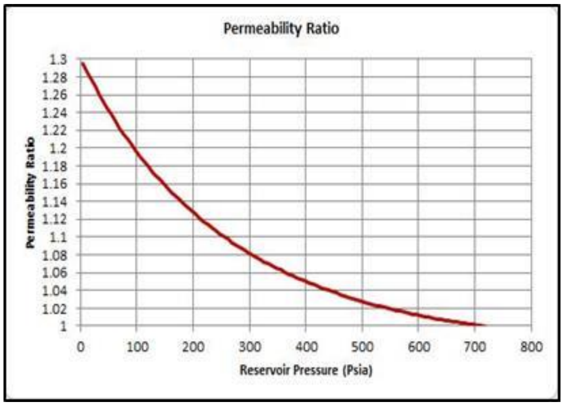

Fig. 7. Permeability ratio of P&M model

The value of Poisson's ratio (v) is set at 0.35, and young's modulus (E) is 350,000 psi. After the data is inputted into the simulator, the Langmuir desorption pressure graph shows a value of 321 psia. The effects of desorption pressure can be seen in the profile of production rates as shown in the Fig. 6.
Fig. 7 shows that a decrease in pressure will cause the permeability to increase, even when pressure below the critical desorption pressure. The shrinking of the coal matrix will lead to cleat opening so that the permeability increase will be greater.

2.3. Methodology

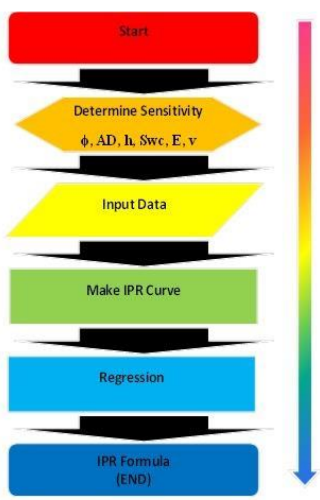

Fig. 8. Flowchart for the development a dimensionless IPR curve

IPR curve is defined as the relationship of flowing bottom hole pressure versus gas flow rate. The flowing bottom hole pressure are measured simultaneously with the gas flow rate under the conditions of pseudo steady state (PSS). In developing of IPR curve for gas of coalbed methane can be done by first specifying the constant flow rate. Furthermore, the flowing bottom hole pressure is calculated when it reaches the pseudo steady state condition. The calculation is done by sensitivity to several variables of coalbed methane reservoir. The relationships of flowing bottom hole pressure against the production rate are then changed into the form of a dimensionless variable of $\frac{pwf}{Pr}\ vs\ \frac{Q}{Qmax}$. The flowchart of development the dimensionless IPR for gas coalbed methane is shown in Fig. 8.

In the first stage, the sensitivity analysis of parameters ϕ, A_D, h, Swc, v and E is conducted. The data is then inputted into the simulator which includes sorption data model, shrinkage of matrix and deliverability. The water flow rate constraint is set to constant at 320 bbl/d. The results of simulation show that in the second year of production time, the reservoir pressure reaches critical desorption and gas begin to flow.

The predicted result of gas production rate (Q_g) and flowing bottom hole pressure (P_{wf}) is taken to create the IPR curve (Fig. 9). Furthermore, based on these data, it is used to create the dimensionless IPR equation for T-01 well.

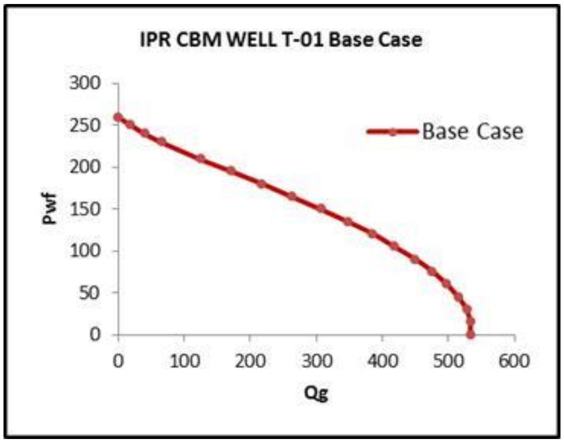

Fig. 9. Inflow performance relationship curve of base case

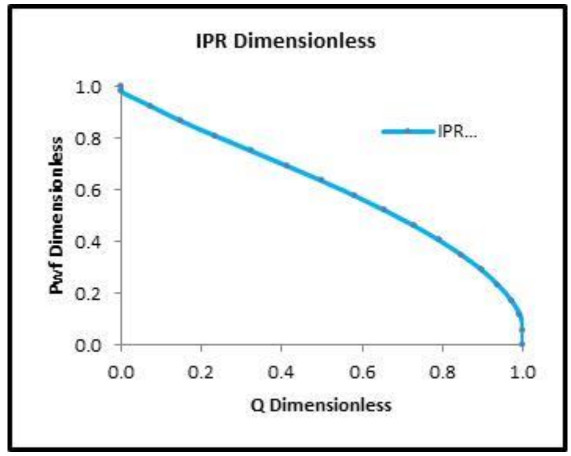

Fig. 10. Dimensionless IPR curve of base case

As discussed earlier, the sensitivity analysis of input parameters *ϕ, A_D, h, S_{wc}, v* and *E* is conducted in the simulation. Sensitivity analysis of Langmuir Volume (*VL*) parameters, Langmuir Pressure (*PL*) and Reservoir Pressure (P_i) cannot be performed because these three parameters influence one with the other. Changing one variable will change the other parameter. Sensitivity analysis was conducted on various parameters such as following:

Table 2. Sensitivities analysis data

φi (%)	1 : 3 : 5 : 9
AD(Acre)	60 : 80 : 100 : 120
E (Psia)	100000 : 200000: 300000: 400000
v	0.35 : 0.4 : 0.45
h	50 : 60 : 70 : 80
Swc	10 : 20 : 30 : 40

Based on the sensitivity analysis of these six parameters (Table 2), the dimensionless IPR curve and IPR equation for coalbed methane are obtained (Fig. 10).

3. Result and discussion

3.1. Sensitivity analysis and IPR curve

Six reservoir parameters such as porosity (*ϕ*), drainage area (A_D), thickness (*h*), S_{wc}, young modulus (*E*) and poisson's ratio (*v*) are selected to construct the IPR curve. The value of porosity 1.9 % is chosen as base of porosity. Furthermore, the sensitivity test for porosity of 1, 3, 5 and 6 % was performed. The resulting IPR curve can be seen in Fig. 11. Fig. 11 shows the effect of porosity to gas production rate. The larger porosity will result in lower gas production rates compared to lower porosity. The next sensitivity analysis was conducted for the drainage area. The base value of the drainage area used is 80 acres. While the sensitivity analysis carried out for the drainage area 60, 80, 100 and 120 acre. The resulting IPR curve is shown in Fig. 12. Fig. 12 shows the effect of the drainage area on the gas production rate. The larger drainage areas will result in larger gas production rates. The sensitivity test for thickness indicates that rate of gas production is linear with reservoir thickness (Fig. 13). The thicker the reservoir thickness will result in a larger of gas production rate.

The sensitivity analysis of residual water saturation (S_{wc}) shows that the greater the value of S_{wc}, the greater the gas production rate (Fig. 14). Another sensitivity analysis is to test the matrix shrinkage parameters of young's modulus (*E*) and Poisson's ratio (*v*). The base value of 300,000 psi is used as an assumption of the young's modulus. The sensitivity analysis was performed for the value of young's modulus of 100,000, 200,000 300,000 and 400,000 psi.

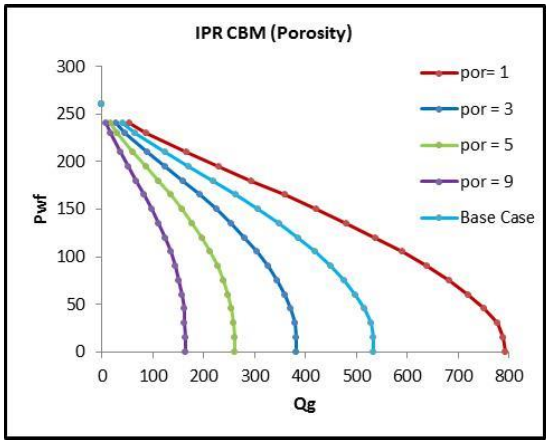

Fig. 11. The influence of porosity on IPR curve

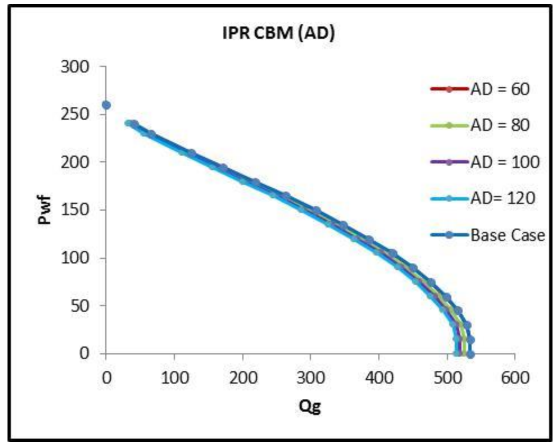

Fig. 12. The influence of drainage area on IPR curve

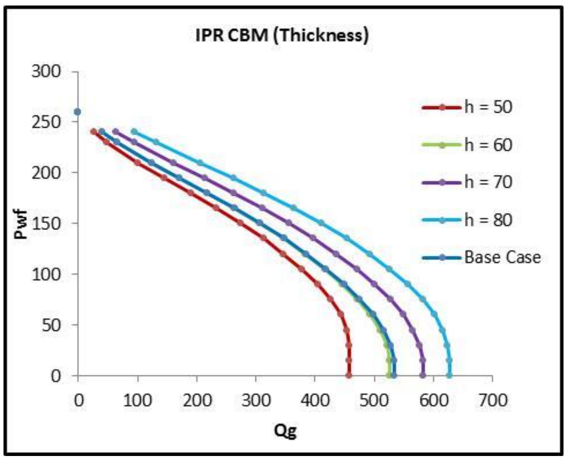

Fig. 13. The influence of reservoir thickness on IPR curve

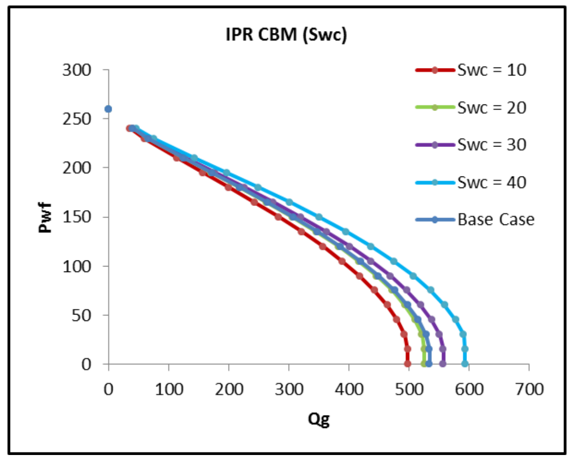

Fig. 14. The influence of S_{wc} on IPR curve

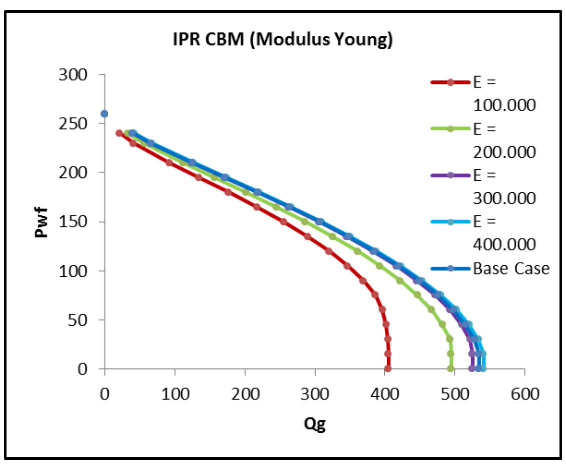

Fig. 15. The influence of Young's Modulus on IPR curve

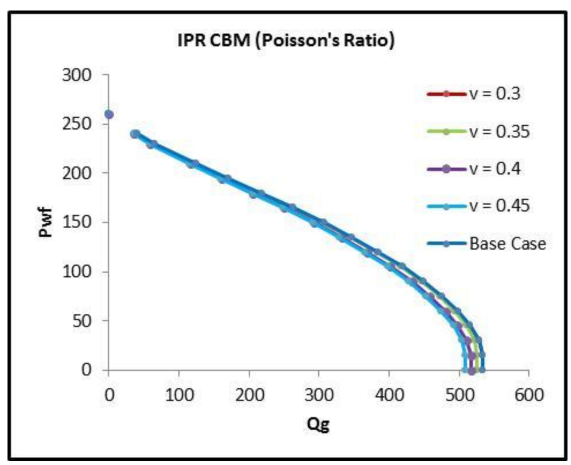

Fig. 16. The influence of Poisson's Ratio on IPR curve

Fig. 15 shows that the greater the young's modulus, the greater the gas production rate. In contrast, the sensitivity of Poisson's ratio indicates that decreasing the Poisson's ratio will provide greater gas flow rate (Fig. 16). As we know, Palmer and Mansoori show that young's modulus, Poisson's ratio, and porosity are part of the matrix shrinkage phenomenon. Thus, these three parameters will have the greatest impact on the gas production rate. In the event of shrinkage of the matrix, the permeability of the coalbed methane reservoir increases as the pressure falls below the critical desorption pressure. At that time, there will be shrinkage of cleats so that porosity fissures (cleats) filled by water also shrinking. The lower porosity indicates that less water fills the cleats, so the gas permeability is getting enlarged. In addition, gas production may increase due to young's modulus and Poisson's ratio; the greater the young's modulus and the smaller Poisson's ratio, the more difficult the coal to be compressed.

3.2. Dimensionless IPR curve of coalbed cethane

The dimensionless IPR curve equation is developed by combining the IPR curve resulting from the sensitivity analysis. The sensitivity analysis of six CBM reservoir parameters such as porosity (ϕ), drainage area (A_D), thickness (h), S_{wc}, young modulus (E) and Poisson's ratio (v) yields 1 dimensionless IPR curve for each parameter. The six curves are then combined to obtain a dimensionless IPR curve equation (Fig. 17).

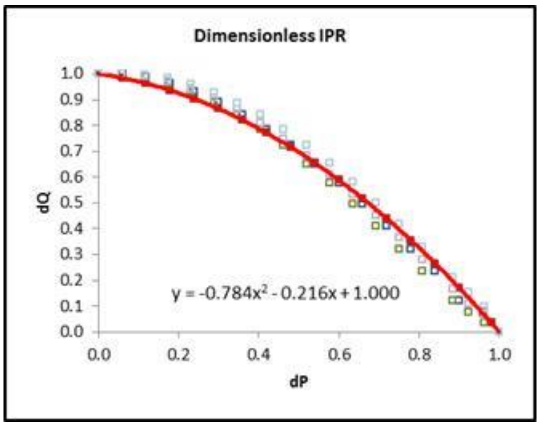

Fig. 17. The polynomial regression of dimensionless IPR curve

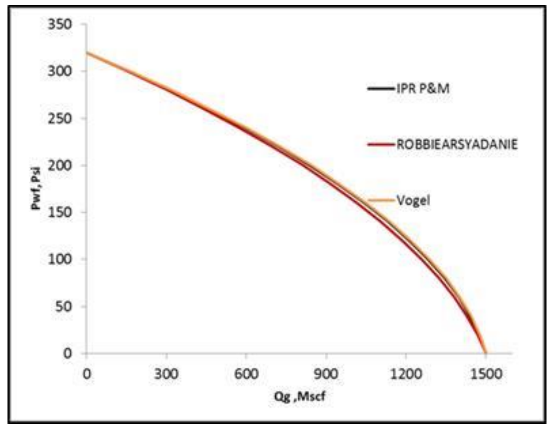

Fig. 18. Comparison of the IPR of P & M, Vogel and Robbie Arsyadanie

To obtain the general equation of the dimensionless IPR curve is done by using the second order polynomial regression method as follows:

$$\frac{Q}{Qmax} = 1 - 0.216\frac{Pwf}{Pr} - 0.784\left(\frac{Pwf}{Pr}\right)^2. \quad (8)$$

Fig. 18 shows the comparison of IPR for CBM derives by using the P & M method (eq. 7), Robbie Arsyadanie's methode and Conventional Vogel IPR. The IPR curve derives by using the P & M method is relatively similar to Vogel IPR but more optimistic than IPR of Robbie Arsyadanie's because the IPR P & M is considering the permeability changes in CBM reservoir. Thus the P & M IPR curve will be appropriate when applied to predict the gas production performance of coalbed methane.

4. Conclusion

1. The dimensionless IPR equation has been successfully arranged and provides accurate prediction results of IPR curve. This equation can be used to estimate the peak gas production rate of CBM wells.
2. The matrix shrinkage has a major impact on the permeability of CBM reservoir. The effect of matrix shrinkage can increase permeability up to 2 times than before.
3. The changes in permeability were strongly influenced by the reservoir pressure in dewatering stage when matrix shrinkage effect is taking the role after reservoir pressure reached CDP.
4. Porosity is the most influential parameter to the IPR curve of CBM reservoir.

5. Recommendation

1. Need to consider the influence of other variables that may affect the deliverability of CBM reservoir.
2. It is necessary to validate this dimensionless IPR equation in the field to verify its accuracy.

List of symbols

c_m	*1/M, psia^{-1}*	*Pr*	*reservoir pressure, psia*
c_o	*volumetric strain coefficient, psia^{-1}*	*Pi*	*initial pressure, psia*
B	*reciprocal of Langmuir pressure, psia^{-1}*	*TR*	*reservoir temperature, F*
M	*constrained axial modulus, psia*	*Sg*	*gas saturation, fraction*
K	*bulk modulus, psia*	*Sgc*	*connate gas saturation, fraction*
v	*Poisson's ratio, fraction*	*Swc*	*connate water saturation, fraction*
E	*modulus Young, psi*	*h*	*thickness, ft*
ϕ	*porosity, %*	*Swi*	*initial water saturation, fraction*
ϕi	*initial porosity, %*	*Wc*	*moisture content, fraction*
P_L	*Langmuir pressure, psia*	*a*	*ash content, fraction*
V_L	*Langmuir volume, scf/ton*	*pb*	*bulk density, gr/cc*
Qw	*water flow rate, bbl/d*	*rw*	*well radius, ft*
Qg	*gas flow rate, mscf*	*AD*	*drainage area, acre*
Pwf	*well flowing bottom hole pressure, psia*	*Pabd*	*abandonment pressure, psia*

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