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Assessment of parameters effectiveness in the reserve estimation methods applicable to coal bed methane reservoirs

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ABSTRACT

The reserve estimation of coal bed methane (CBM) reservoirs is ascertained through the analytical methods (volumetric method, material balance equation and decline curve analysis). However, the adoption of reserve estimation methods depends on exploration stage and availability of the required parameters. This study deals with the analytical assessment of parameters that participate in effecting the reserve estimation of CBM reservoirs through the analytical techniques. The accurate measurement challenges always exist for the parameters which participate in the reserve estimation of the conventional and unconventional reservoirs because of the inclusion of limitations while measurement. Therefore, the impact of that measurement challenge must be assessed. The study specifies the impact of parametric change on the reserve estimation of CBM reservoirs so that the degree of parametric effectiveness is analyzed. Uncertain values are adopted which are associated during the evaluation of input parameters for each method to determine the overall impact on potential of CBM reserves. Results reveal that change in specific parameters considering each method provide relatively more effect on estimation of reserves. Thus, the measurement of parameters must be done accurately for assessing reserves of CBM reservoirs based on available methods.

1. Introduction

Coal bed methane (CBM) reservoirs, which are organic rich and naturally fractured, contains the natural gas reside in the micropores, matrix and cleats of coal and its recovery can be attained from the coal seams through desorption, diffusion and seepage (Seidle, 2011; Sampath et al., 2017; Thakur et al., 2020; Ni et al., 2021). The CBM reservoirs have the dual porosity system with low permeability in microdarcy in which matrix and fractures participate in the rock body of coal (Amott et al., 2016; Men et al., 2021). Low originally present porosity and permeability causes the difficulty in the drainage of gas through coal seams (Huang et al., 2022). Existing fractures in coal beds are classified into cleats (face cleats and butt cleats), faults and joints but cleats have the key contribution for the CBM production (Amott et al., 2016; Sampath et al., 2017). Desorption due to decline in pressure and diffusion because of concentration variation are the primary recovery mechanisms which contribute in methane production of CBM reservoirs (Sampath et al., 2017; Shi et al., 2018). The diffusion rate exists due to the difference in concentration between the pores and fractures which supports the gas movement form the matrix micropores to cleats and fractures (Seidle, 2011; Sampath et al., 2017; Thakur et al., 2020).

Coal seams for methane existence are typically classified into dry seams and water saturated coal seams (Sampath et al., 2017). Dry seams with no presence of water have only gas pressure gradient which supports the methane production while water saturated coal seams with water presence in coal seam provides the additional pressure gradient of water for production (Seidle, 2011; Sampath et al., 2017; Thakur et al., 2020).

CBM reservoirs, when compared with conventional gas reservoirs, represent some dissimilarities. In conventional gas reservoirs, inorganic rock body retains the methane presence while coal itself is an organic material which behaves as combustible material (Zou, 2013; Sampath et al., 2017). The water production profile of CBM

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reservoirs is different form the conventional gas reservoirs because in water saturated CBM reservoirs water is initially produced and methane production starts due to the decline in pressure after the stage of dewatering (Seidle, 2011; Zou, 2013). CBM reservoirs have several processes which contribute in fluid flow from coal beds to well bore i.e., i) the desorption of methane gas ii) movement of methane occurs due to Langmuir-type equations from micro pores to matrix iii) diffusion eventuates in the matrix considering the concentration difference following Fick's law and iv) Darcy's law is applicable in the movement occurring in cleats and fractures of coal beds (Sampath et al., 2017).

Reserve estimation of CBM is an imperative attribute for field development decisions and economic analysis or to estimate reserves, accurate formation evaluation and production profile are always vital to be assessed accurately, however, higher degree of uncertainty can be associated with the formation evaluation. For prospecting the accurate and precise determination of the initial gas in place in CBM reservoirs, there are different methods which exist for the reserve estimation of CBM reservoirs (Aminian, 2020a) such as: Volumetric method, material balance equation and decline curve analysis (Altowilib et al., 2020). To the best of our knowledge, no previous studies has made the attempt to evaluate the minor and major effective parameters associated with reservoir estimation methods.

The aim of this study is to carry out the uncertainty analysis of parameters that participate in the reserve estimation of CBM reservoirs through the analytical methods to determine the overall impact on potential of CBM reserves.

2. Background

2.1. Langmuir isotherm equations

Gas sorption capacity and storage volume of CBM reservoirs strongly rely on the specific isotherms named as Langmuir isotherm equations. These equations specifically describe the phenomena of gases adsorption behaviour and therefore support for the reserve estimation of the CBM reservoirs. Pressure and temperature affect the gas sorption which is governed by the sorption isotherm equations (Seidle, 2011; Alafnan et al., 2021). Langmuir isotherm equations provide and describe the relationship of gas content (V) with pressure (P) considering the gas sorption capacity.

$$V = V_L \frac{P}{P + P_L} \tag{1}$$

where V_L and P_L are Langmuir volume constant (scf/ton) and Langmuir pressure constant (psia) respectively. The Langmuir volume constant describes as the gas sorption volume due to the insertion of infinite pressure whereas the Langmuir pressure constant is the half saturation pressure from which the half of the maximum sorbed volume is achieved.

The limitations associated because of assumptions in Langmuir isotherms restrict the accuracy of the reserve estimation methods. The complexity concerned in the unconventional reservoirs set the potential constraint for reserve estimation. Modifications had been done in the estimation methods for incorporating the accuracy level and reducing the effect of the limitation. The parameters, which are participating in the reserve estimation methods, can be assessed considering the sorption models to analyze the effectiveness (Alafnan et al., 2021).

2.2. Volumetric method

Volumetric method is the primary technique, applied at the initial phase, for the reserve estimation of the CBM reservoirs which requires less data for finding the initial gas in place. Thickness, area, porosity, water saturation, coal density, initial gas formation volume factor Langmuir constants of volume and pressure are the contributing parameters in volumetric method, which is modified according to the unconventional CBM reservoirs (Altowilib et al., 2020; Aminian, 2020a,b). The finalized form of the volumetric method for the coal seam gas is as follow:

$$G_i = Ah\left(\frac{43560 \times \varphi_f \times (1 - S_{wi})}{B_{gi}} + 1.3597\rho_c G_c\right) \tag{2}$$

Where the equation has initial gas in place in scf (G_i), drainage area in acres (A), thickness in ft (h), porosity (φ_f), initial formation volume factor for gas in ft^3/scf (B_{gi}), initial saturation of water (S_{wi}), coal density in kg/m^3 (ρ_c), gas content which is adsorbed in scf/ton (G_c), free gas in scf/ton (G_f), reservoir pressure in psia (P), Langmuir pressure constant in psia (P_L) and Langmuir volume constant in scf/ft^3 (V_L).

2.3. Material balance equation

The material balance equation (MBE) is a generalized practice for assessing the reserve estimation, prediction of the performance associated with the reservoir and the understanding of the driving mechanisms which contribute to the recovery (Ahmed, 2018). Material balance equation is one of the performance methods which depends on the production data of methane gas (Altowilib et al., 2020). The material balance equation for conventional gas reservoirs is an essential tool to reserve estimation and performance prediction utilizing the consideration of p/z plots. However, it is extended to achieve the evaluation of concerned aim for the unconventional CBM reserves (Ahmed et al., 2006).

There are number of material balance equations which are generated for the unconventional CBM reservoirs. The generalized material balance equation is developed (Ahmed et al., 2006) for the coal seam gas reservoirs which eliminates the iterative approach for estimating the initial gas in place. The material balance equation integrates the generated Langmuir isotherms, the participation of initial free gas present in the dual porosity structure of the coal beds, expansion of water and compaction attached with the formation (Altowilib et al., 2020). The finalized form of the equation presented by (Ahmed et al., 2006) is as follow

$$G_p + \frac{B_w W_p E_g}{1 - \left(c_f\,\Delta P\right)} = Ah\left[1359.6\rho_B (G_c - V) + \frac{7758\varphi\left[\Delta P\left(c_f + S_{wi}c_{wi}\right) - (1 - S_{wi})\right]E_g}{1 - \left(c_f\,\Delta P\right)}\right] + 7758Ah(1 - S_{wi})E_{gi} \tag{3}$$

Where G_p is representing the cumulative gas produced in scf, B_w is formation volume factor of water in bbl/STB, W_p is the cumulative water produced in STB, E_g is the gas expansion factor which is taken in scf/bbl, c_f is the isothermal compressibility of formation in psi^{-1}, $\Delta\ P$ is showing the change in pressure in psi from the initial reservoir pressure after the depletion of the pressure in reservoir, A is the area having acres unit, h is the thickness in ft, ρ_B is the bulk density of coal in gm/cm^3, G_c is showing the gas content in scf/ton, V is the volume of the gas which is adsorbed at pressure “P” having the units in scf/ton, S_{wi} is representing the initial water saturation, c_{wi} is the isothermal compressibility at the initial reservoir pressure in psi^{-1}, φ is porosity in fractions and E_{gi} is depicting the gas expansion factor at the initial pressure where its unit is in scf/bbl.

2.4. Decline curve analysis

Different models based on decline curve analysis are established for deciding the gas present in CBM reservoirs utilizing the sufficient production history (Altowilib et al., 2020). Unchanged production conditions for future performance and the boundary dominated flow are specific limitations which are attached with the conventional decline curve analysis (Ahmed, 2018). In the low permeability gas reservoirs like tight sandstone gas, tight shale gas and CBM reservoirs, the limitation exists for achieving the boundary dominated flow (Sun, 2015).

The modified hyperbolic decline model transforms the hyperbolic model into the exponential decline curve for matching the existing transient flow regime production data (Altowilib et al., 2020). Power law function analysis presents the solution for removing the restriction due to low permeability. This Power-Law decline model also nominated as Ilk model offers the appropriate method for estimation of unconventional low permeability CBM reservoirs (Sun, 2015). This model is as follow

$$q(t) = \hat{q}_i e^{\left[-\hat{D}_\infty t - \hat{D}_i t^n\right]} \tag{4}$$

Where $q(t)$ is the production rate at the time of t in Mscf/day, q_i is indicating the rate intercept in Mscf/day, $\hat{D}_i$ is the initial decline constant, $\hat{D}_\infty$ is decline constant at infinite time i.e., $t = \infty$, t is the time of production in days and n is demonstrating the time exponent.

2.5. Simulation

Reservoir simulation can be employed for the reserve estimation of unconventional reservoirs in the early stages as well as after the initialization of production. The confidence level increases by taking the support of simulation for the estimation of certain potential reserves through the development of reservoir model. (Radwan et al., 2022). Analytical and semi analytical models for the reserve estimation and performance prediction of CBM reservoirs do not focus on all the complexities associated with the unconventional reservoirs. The certainty for the useful estimation of performance and reserves through the analytical models requires large amount of reservoir and production data (Thakur et al., 2020). Gas sorption capacity with low permeability and intrinsic complex geometry in unconventional reservoirs can be modeled through the reservoir simulation (Segatto and Colombo, 2011). The complete life cycle performance with the strong attachment with the reserves estimation of the reservoir is analyzed through the simulation (Radwan et al., 2022). Reservoir simulation supports for the accurate prediction of reserves and production performance through the rigorous development of the unconventional reservoir models. The studies attached with the numerical simulation enhances insight for the critical factors in the accurate prediction of reserve estimation (Al-Fatlawi, 2018). Mostly, coal beds have low permeability, less reservoir pressure and fractures with dual porosity. The factors of permeability, dual porosity, Langmuir pressure constant and gas saturation creates an impact on the flow mechanisms and recovery via coal seams. These factors are incorporated through the careful development of numerical model of coal bed methane reservoirs (Zhang, 2014). Numerical Simulation is implemented for the accurate reserves estimation using the ECLIPSE software which assimilates flow capacity considering low permeability, gas adsorption, dual porosity, diffusion and rock compaction are included in the simulation for accurate reserve estimation (Al-Fatlawi, 2018). There are certain parameters which are involved in the reserve estimation of CBM reservoirs are summarized in Table 1.

3. Methodology

Parametric studies can be performed to assess the impact of uncertain data on the reserve estimation by selecting the expected

Table 1
Reservoir data acquisition (Lee, 1982; Bateman, 2012).

Symbol	Parameter	Primary Source
φ	Reservoir Porosity	Petrophysical Analysis and Well Logging
h	Pay Zone Thickness	Well Testing, Well Logging, Seismic Survey and Petrophysical Analysis
A	Area (Areal Extent of Reservoir)	Seismic Data
B_o	Gas Formation Volume Factor	Correlations, Laboratory Analysis
S_g	Gas Saturation	Petrophysical Analysis, Well Logging
k	Reservoir Permeability	Well testing
ρ_c	Coal Density	Petrophysical Analysis, Well Logging
G_c	Gas Content	Gas Content Analysis
G_p	Cumulative Gas Production	Production Data
B_w	Formation Volume Factor of Water	Correlations, Laboratory Analysis
W_p	Cumulative Water Produced	Production Data
E_g	Gas Expansion Factor	Correlations, Laboratory Analysis
Cf	Isothermal Compressibility of Formation	Correlations, Laboratory Analysis
V	Adsorbed Volume of Gas	Gas content analysis
S_{wi}	Initial Water Saturation	Petrophysical analysis, well logging
Cwi	Initial Isothermal Compressibility of Water	Correlations and laboratory analysis

range of parameter (Aminian, 2020b). This study incorporates the reserve estimation of CBM reservoirs by integrated analytical methods and numerical simulation as shown in Fig. 1. The analytical methods are comprised of volumetric method, material balance equation and decline curve analysis. The objective of the study is to perform the parametric assessment for the reserve estimation of CBM reservoirs considering each technique. In techniques, there are several parameters which take part in deciding the quantitative extent of gas initially in place in the coal seams of the reservoirs and the assessment is done with different formation evaluation techniques summarized in Table 1.

The identification of modified methods associated with the reserve estimation of unconventional CBM reservoirs and the requirement of data acquisition for implementing the methods are acquired. The reserves of CBM reservoirs are estimated by implementing the volumetric method, material balance equation and

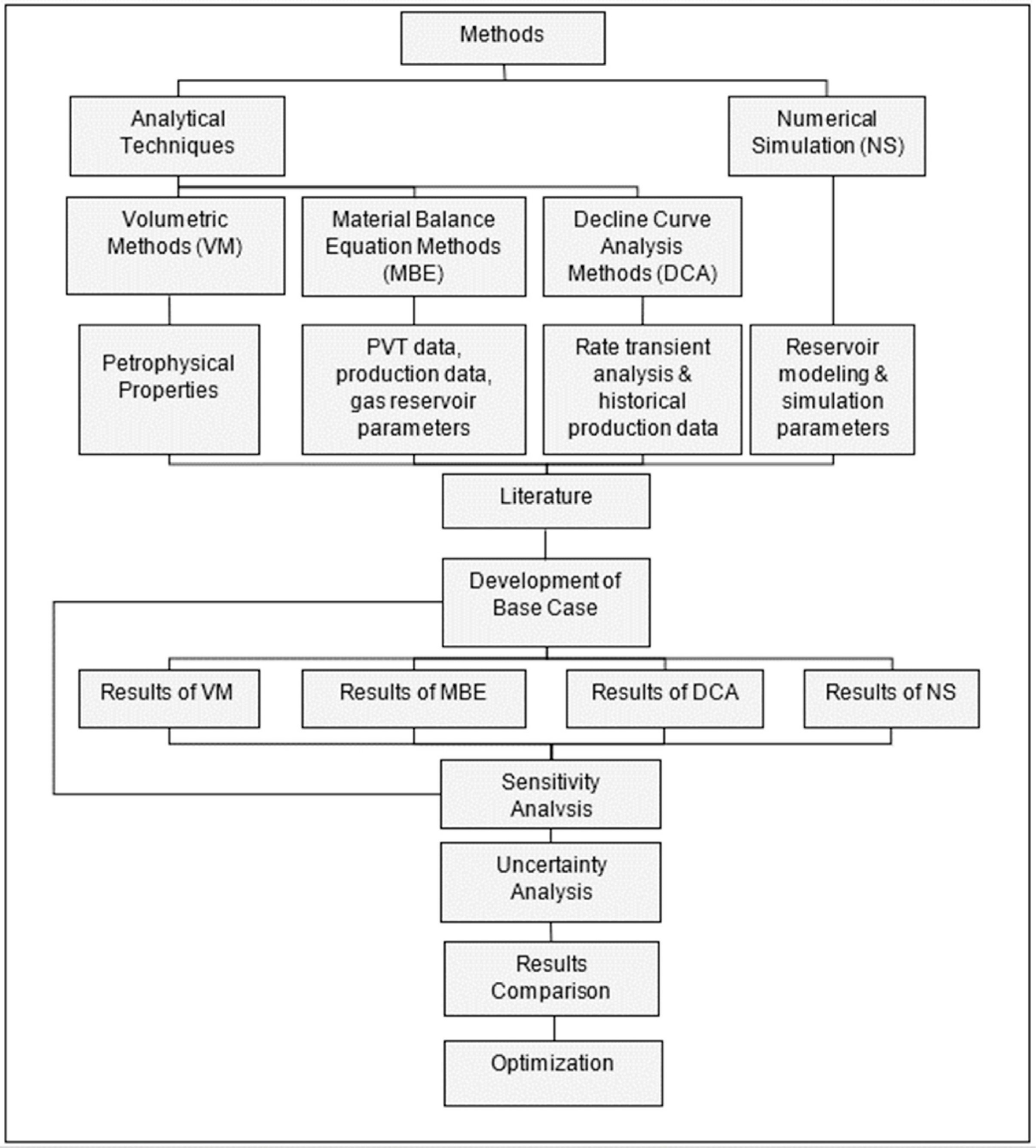


Fig. 1. Methodology's flow chart.

Table 2
Parameters and their values used in the volumetric method (Scott and Luppens, 2013).

Parameters	Values	Units
Area (A)	13440000	acres
Thickness *(h)*	10	ft
Porosity (ϕ_f)	0.1	–
Initial Water Saturation (S_{wi})	0.8	–
Initial Gas Formation Volume Factor (B_{gi})	0.01037574	–
Coal Density (ρ_c)	1.34	g/cm^3
Reservoir Pressure P	153	psia
Langmuir Pressure Constant (P_L)	394	psia
Langmuir Volume Constant (V_L)	117.2	scf/ton
Gas Deviation Factor (z)	0.863	–

Table 3
Values of input parameters used in the material balance equation (Ahmed et al., 2006).

Parameters	Values	Units
Area (A)	322.25	acres
Thickness *(h)*	50	ft
Porosity (ϕ_f)	0.01	–
Initial Water Saturation (S_{wi})	0.95	–
Water Volume Factor (B_w)	1	–
Coal Density (ρ_B)	1.7	g/cm^3
Initial Water Compressibility(c_{wi})	0.000003	–
Formation Compressibility (c_f)	0.000006	–
Gas Content (G_c)	345.1	–
Initial Gas Expansion (E_{gi})	599.21	–

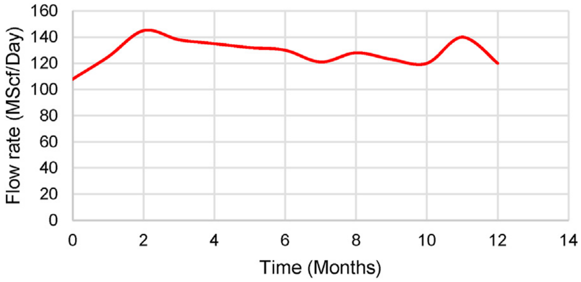


Fig. 2. Production history for decline curve analysis (Zhou et al., 2017).

decline curve analysis. The parametric assessment is performed considering the uncertain values up to 20% which associate with the parameters that can be attached during the evaluation. The impact of that parametric uncertain evaluation on the reserve estimation of CBM reservoirs is measured. For this purpose, each analytical method is adopted and then the evaluation is performed for sorting out the comparatively high impact causing parameters for each method on the reserve estimation. After the assessment of each involved parameters effectiveness the optimization of parameters is accomplished by the assessing the reserve estimation of unconventional CBM reservoirs.

The reservoir details necessary for the validation and implementation of volumetric reservoirs needs to be based on the application example. Therefore, the reservoirs details which participate in the reservoir of Powder River Basin, are adopted for the volumetric method (Scott and Luppens, 2013). The reserve estimation from volumetric method includes the parameters of area, reservoir thickness, porosity, initial water saturation, initial gas formation volume factor, Langmuir constants for pressure and volume. The relative evaluation is done by the separate selection of each uncertain parameter to assess the sensitivity effect on the reserve estimation through volumetric method. The values of input parameters are given in Table 2. Material balance equation includes greater number of parameters required for reserve estimation of CBM reservoirs when compared with the volumetric method and decline curve analysis. A material balance equation for unconventional CBM reservoirs was proposed by (Ahmad, 2006) which eliminated the iterative approach for estimating the reserves. Implementation of the material balance equation needs the reservoir performance to get the production history. Reserve estimation of CBM reservoirs through material balance equation needs the gas reservoir parameters, PVT properties and dynamic parameters which represent the performance of reservoir. The performance parameters and reservoir input parameters details for the implementation of the MBE technique is taken from the reservoir coupled with the simulated data (King, 1993; Seidle, 1999; Ahmed et al., 2006). The input and performance parameters are given in the Table 3 & Table 4 respectively. For the decline curve analysis, the daily production rate of the CBM reservoir wells along with forecasted production data is used (Zhou et al., 2017). The trend of the decline curve justifies the validity of production rate because the decline curve is following the same behaviour as it is suggested in the modified power law decline curve analysis for the implementation (Mattar and Moghadam, 2009).

Modified power law decline curve analysis is performed for CBM reservoirs. The modified decline curve resolves the long residence of pressure behavior in transient state due to low permeability of coal seams and it is applicable on short production history. The performance of CBM reservoir for the implementation of the decline curve is shown in Fig. 2.

Reservoir parameters of the southern Qinshui Basin are included for performing the analysis through numerical simulation. The further specific essential details required for numerical modeling are adopted from results of previous numerical simulations which has been done on the same reservoir (Zhang et al., 2011; Fang et al., 2019). The data file representing the model compatibly is prepared based for CBM reservoir. The reservoir parameters represent the

Table 4
Values of performance parameters used in the material balance equation (Ahmed et al., 2006).

Parameters	Gp	Wp	Eg	V	Eg	P	ΔP
Values	0	0	599.21	345.097	599.21	1500	0
	265.086	0.15749	526.8682	335.903	526.86825	1315	185
	968.41	0.290238	399.0446	316.233	399.04461	1021	479
	1704.033	0.368292	312.1063	296.5301	312.10625	814.4	685.6
	2423.4	0.425473	251.0419	277.33	251.0419	664.9	835.1
	2992.901	0.464361	213.566	262.1436	213.566	571.1	928.9

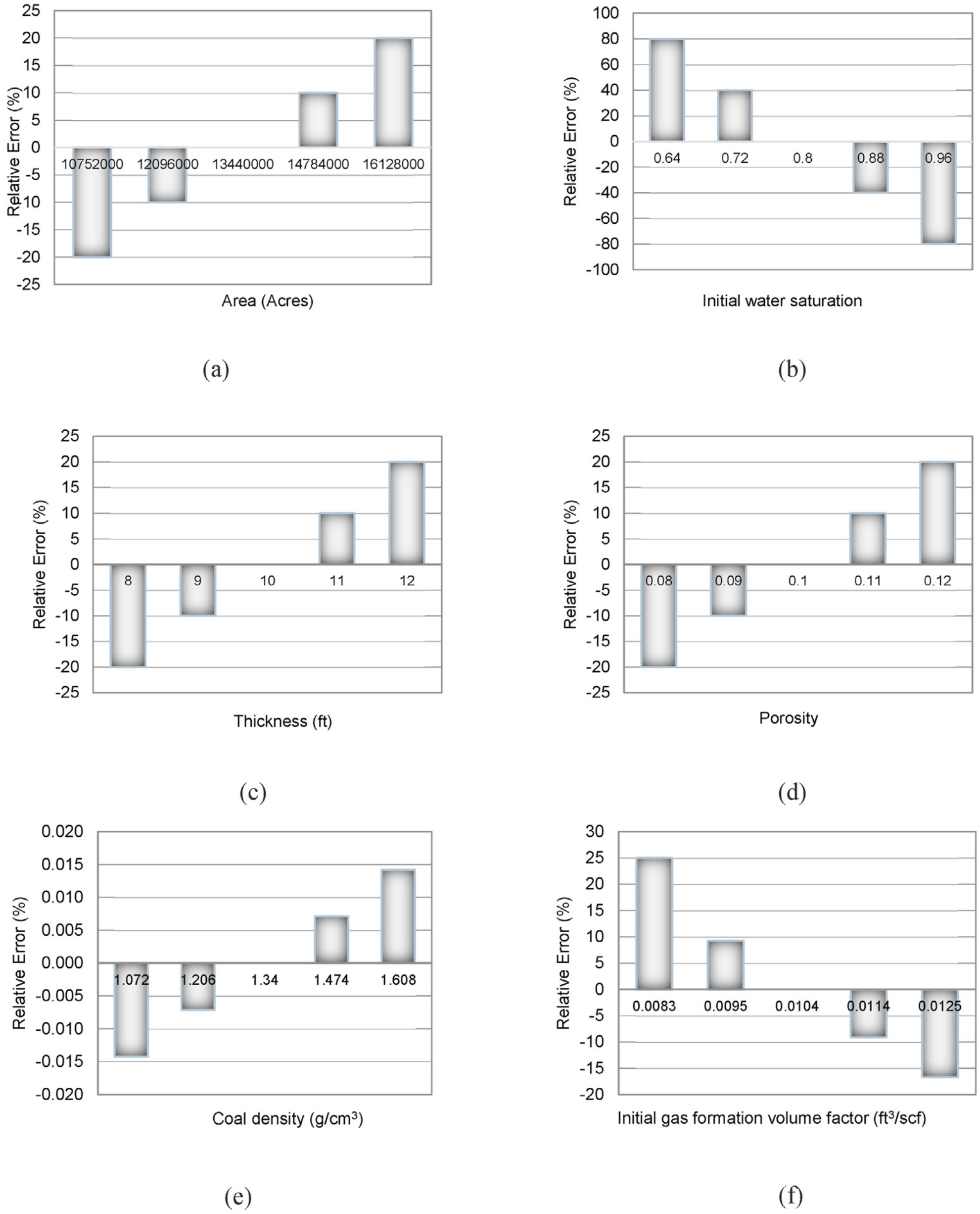
Table 5
Reservoir description for model development (Fang et al., 2019).

Parameters	Values	Units
Fluid Phases	2 phases (gas and water)	–
Dimensions (Grid Blocks)	44 × 44 × 2	–
Coal Density	1380	kg/m^3
Permeability	0.26	mD
Porosity	8.4	–
Reservoir Temperature	50	°C
Initial Reservoir Pressure	1109.5	psi
Initial Gas Saturation	0.592	–
Langmuir Volume Constant (CH_4)	0.03832	m^3/kg
Langmuir Volume Constant (CO_2)	0.06329	m^3/kg
Langmuir Pressure Constant (CH_4)	0.51	MPa^{-1}
Langmuir Pressure Constant (CO_2)	1.92	MPa^{-1}

closest originally based reservoir of coal bed methane. This model's best compatible data for the reserve of coal bed methane is summarized in Table 5. The analysis is performed to analyze the impact of uncertain parameters on original gas in place. Various cases are established for the simulation study for the evaluation of reserve estimation. The reserve estimation from each case is achieved by considering the uncertainty with the concerned case.

4. Results

The reserve estimation of the reservoir situated in the Powder River Basin has been done through the volumetric method specifically associated with the CBM reservoirs. Volumetric method depends on less input parameters comparatively to other analytical

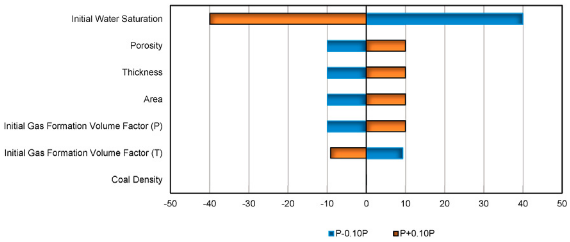


(a) (b)

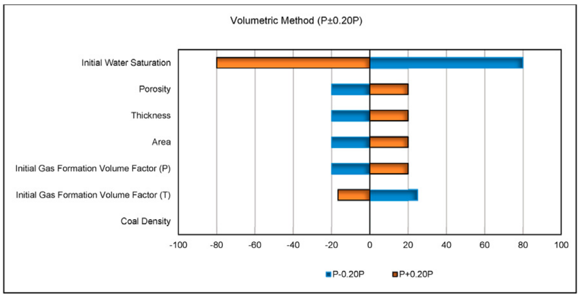
(c) (d)

(e) (f)

Fig. 3. Relative error in reserve estimation from volumeteric method due to change in parameters.



(a) Comparision of participating parameters in volumetric method due to 10% change



(b) Comparision of participating parameters in volumetric method due to 20% change

Fig. 4. Percentage change in reserves estimation due to measurement of participating parameters in volumetric method.

methods. Area, thickness, porosity, initial water saturation, pressure and temperature create an impact on the reserve estimation while applying the volumetric method. The impact of parametric change for volumetric method reveals that all participating input parameters strongly show an impact in the calculation of reserve estimation. However, coal density and initial water saturation indicate more deviated estimation of reserves. The coal density is the weakest parameter for causing an impact on the reserve estimation because change in its values creates a minute effect on the reserve estimation. Contrarily, reserve estimation is greatly influenced by the initial water saturation during the adoption of volumetric method as shown in Fig. 3 & Fig. 4.

The results for material balance equation reveal that evaluation of parametric change does not strongly influence on the reserve estimation of CBM reservoirs as shown in Fig. 5 & Fig. 6. The material balance equation does not show high grade of dependence on the variation associated with the parameters and their evaluation. Initial water saturation relatively provides more uncertain reserve estimation as compared to the other input parameter involved in the material balance equation.

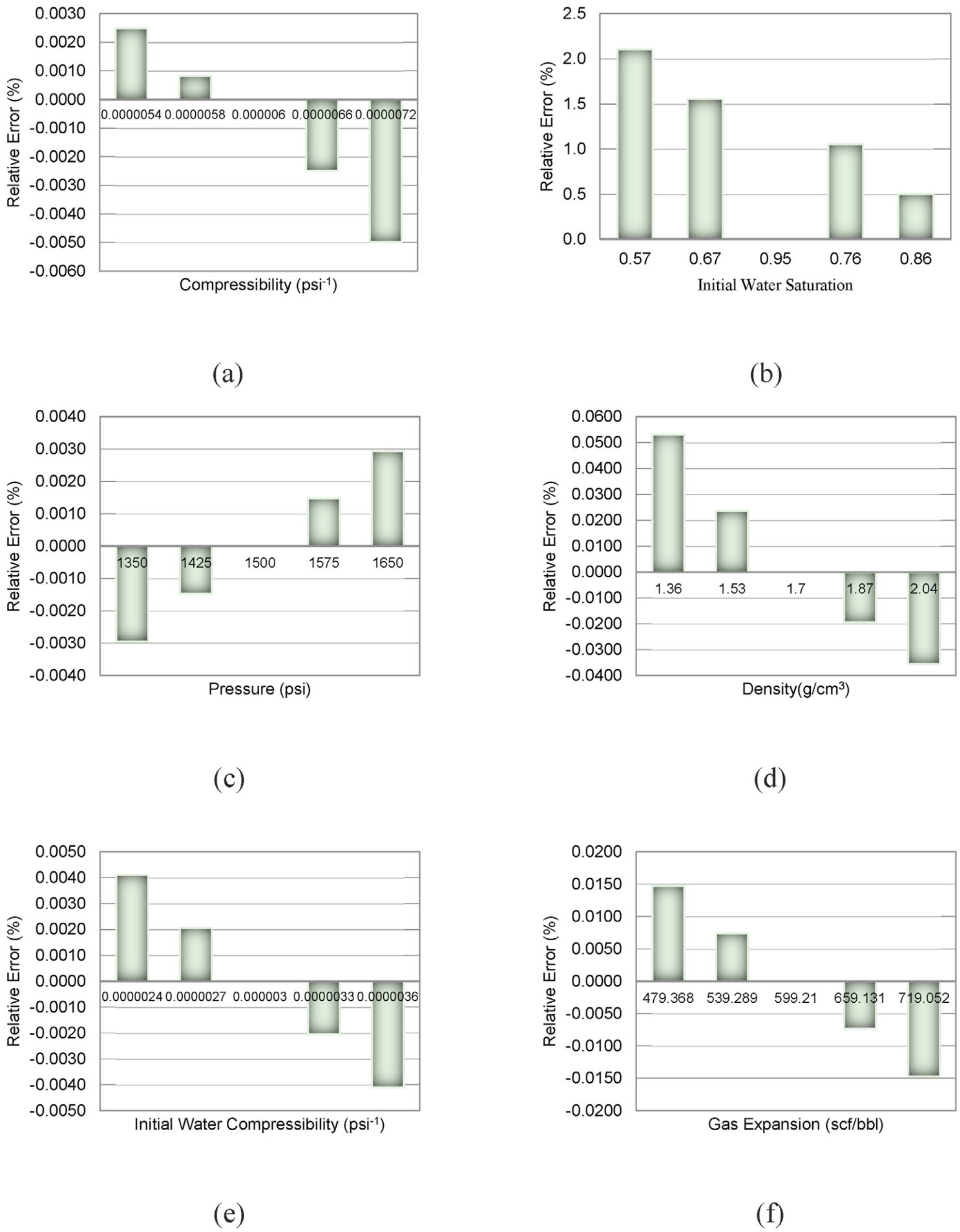
Power law decline curve analysis depends on the production data which plays a supportive role in estimating the parameters of time exponent, decline rate and initial or maximum flow rate. These parameters are calculated by utilizing the decline curve analysis based on the production history. The production history directs these prominent parameters. The change in the participating parameters associates with the erroneous measurement of production data or calculation of parameters. The variation of parameters is performed by adopting the time exponent, decline rate and initial or maximum flow rate. The uncertain values of the participating parameters influence on the reserve estimation of CBM reservoirs. Decline rate and time exponent show an inverse relation with the reserve estimation. Decrease in decline rate and time exponent overestimates the reserve while increase value of decline rate underestimate the reserves as shown in Fig. 7 & Fig. 8. Maximum flow rate and time exponent give comparatively high grade of relative error as compared to the decline rate.

Reserve estimation of CBM reservoirs through the volumetric method is associated with certain parameters. The comparative effect of those parameters shows that initial water saturation is comparatively more sensible for effecting the reserves estimation. Porosity, thickness, area and formation volume factor represent the equal variation in the estimation due to change. Coal density is the least effective parameter considering the volumetric method. MBE proves that this method is the least sensitive method when it is associated with the CBM reserve estimation. The initial water saturation provides the uncertain behaviour, and it is the one in which measurement precautions must be taken while implementing the MBE method. The other parameters which are incorporating in the MBE do not require the high scale certain measurement approach because of the less effectiveness which exists in CBM reserve estimation through MBE. When the reserve estimation is done by utilizing the DCA then initial flow rate and exponent n should be adopted for certain reserve estimation. Although all the participating parameters in DCA are affecting the estimation due to measurement change but comparatively initial flow rate and n provide more sensitive effect on reserve estimation. Considering the results, almost each method is showing impact on reserve estimation because of change but MBE is only sensitive to the initial water saturation. Therefore, MBE with the certain measurement of initial water saturation provide the accurate results of CBM reserve estimation when implemented for the reserve estimation.

Analysis of the study adopting the numerical simulation utilizes the reservoir features which is positioned in the southern Qinshui Basin of China. Numerical simulation evaluates the reserve estimation of unconventional CBM reservoirs. Simulation study is completed to measure the degree of effectiveness of parameters which contributes to the reserve estimation as shown in Fig. 9 & Fig. 10. Coal density, permeability, porosity, pressure, reservoir temperature, water saturation, gas saturation and thickness are the participating factors for the reserve estimation through the numerical simulation. Reservoir temperature and permeability create least influence on the reserve estimation. Fundamentally, considering the pressure and temperature of the reservoir, pressure is additionally strong function of the sorption, adsorption, and desorption which causes supplementary impact on the reserve estimation. In the numerical simulation, coal density, pressure and thickness diverge the estimation of reserves to greater extend which indicates that these parameters additionally contribute to cause the uncertain effect. From the numerical simulation, coal density and pressure act as a decisive factors for the reserve estimation.

5. Discussion

The reserve of unconventional CBM reservoir using the integrated analytical technique is estimated by adopting the uncertainty analysis to analyze and quantify the effect of all parameters on the reserve estimation. Static parameters participate in the execution of volumetric method while dynamic parameters contribute to implement the material balance equation and decline

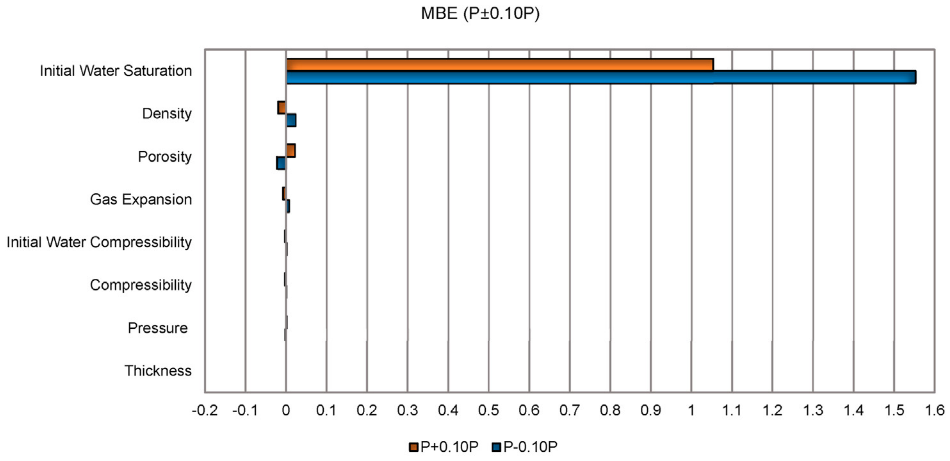


(a) (b) (c) (d) (e) (f)

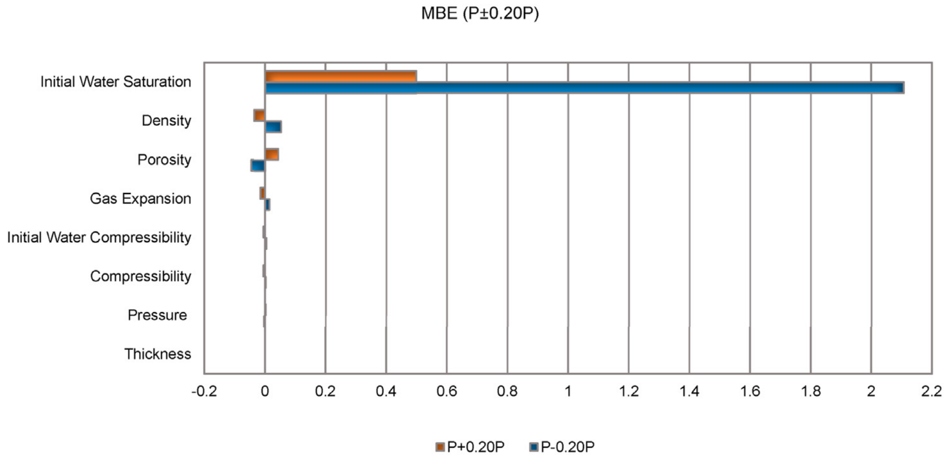
Fig. 5. Relative error in reserve estimation from MBE method due to change in parameters.

curve analysis (Aminian, 2020a; Sampath et al., 2017; Thakur et al., 2020).

It is examined from the results that initial water saturation comparatively creates a greater impact on the estimation of reserves because of its change. Methane gas, in dissolved form, also resides in the water present in coal seams. Therefore, initial water saturation represents an effect on the gas production and dewatering phenomenon. High pressure in coal beds supports the residence of methane gas and reduces the chance of being escape through coal seams. Initial water saturation is related to the reserve estimation because it comes in coal seams during the generation process of methane gas. Water is generated as a by-product during the methane gas generation. Water also traps the methane gas because of its hydrodynamic characteristics and by creating the formation pressure which leads to the residence of methane gas in coal seams and increasing the reserve of methane gas in coal seams. Along with that geometry of coal, pores and cleats also support for the methane residence and water occurrence in the coal seams. Initial water saturation directly describes the pressure of CBM reservoir which plays a supportive role in defining the quantity of



(a) Comparision of participating parameters in MBE due to 10% change



(b) Comparision of participating parameters in MBE due to 20% change

Fig. 6. Percentage change in reserves estimation due to measurement of participating parameters in MBE method.

initial gas in place. Therefore, initial water saturation gives the erroneous results for the reserve estimation while implementing the volumetric method.

Fluid flow behavior and recovery mechanisms for CBM reservoirs require some modifications in conventional material balance equation (Thakur et al., 2020). Material balance equation is based on different parameters which are calculated from the PVT analysis or from the performance evaluation. Ahmad (2006) presents the material balance equation for CBM reservoirs which follows the exact approach for providing the initial gas present in place. Porosity, initial water saturation, reservoir pressure, compressibility, gas expansion, density, thickness and initial water compressibility are the major parameters which participates in the material balance equation and the potential impact of these parameters are assessed by the adopting the change in the measured values. Thickness does not show an influence on the estimation of reserves although it is physically considered to be an impactful parameter for the reserve estimation but the material balance approach of developing a relation between slope, area and thickness minimize the effect of change in thickness on the reserve estimation. Initial water saturation shows an impact in the utility of the material balance equation. Precise, certain and accurate measurement of initial water saturation is necessary for reserve estimation of CBM reservoirs because it is creating potential impact while considering the volumetric method and material balance equation. Therefore, initial water saturation must be assessed accurately.

Accurate availability of the production data facilitates in the implementation of decline curve analysis with exact reserve estimation and production forecasting. The accurate metering of flow rate and proper calculation of time exponent and decline rate led to get the certain estimation of reserves (Altowilib et al., 2020; Paryani et al., 2016). The measurement of initial or peak flow rate is necessary for the implementation of decline curve analysis. The results attachment of gas well testing for CBM reservoir improves the parameters measurement and adoption of decline curve analysis. The abundance of production data also facilitates the reserve estimation accuracy using the decline curve analysis.

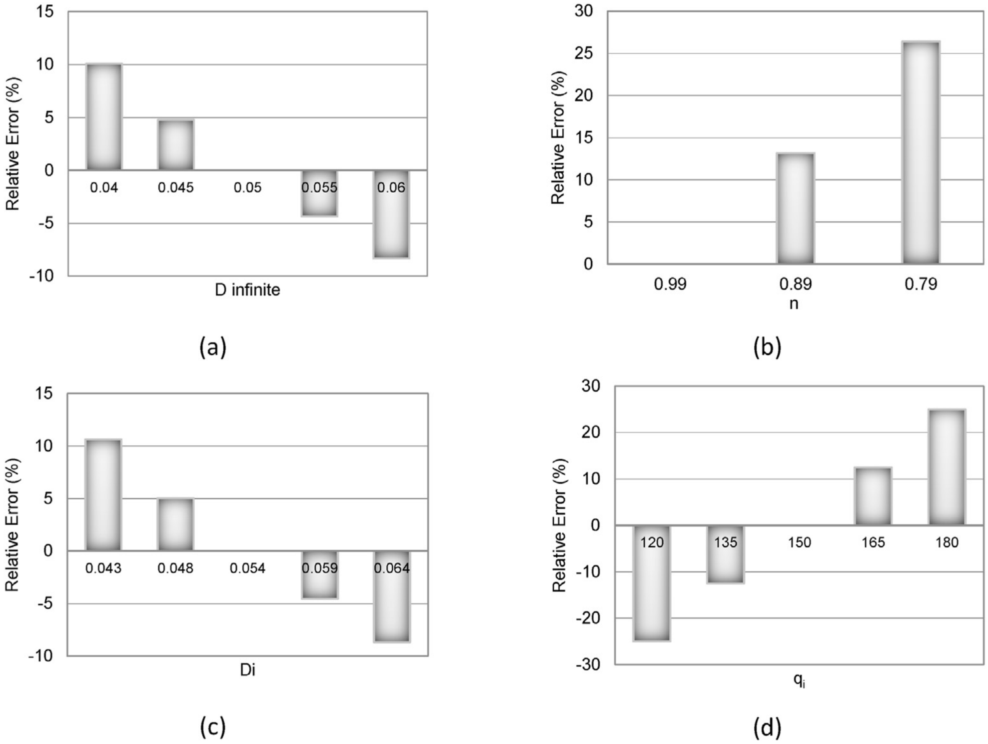
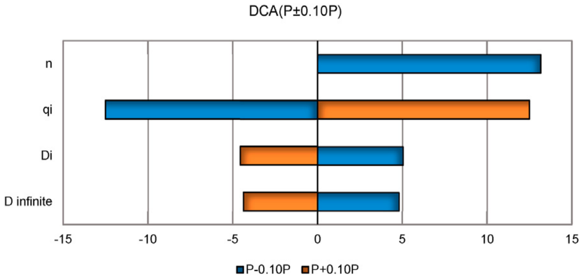
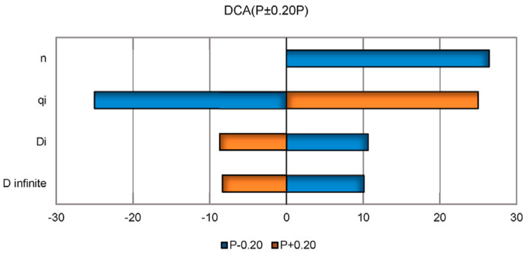


Fig. 7. Relative error in reserve estimation from DCA method due to change in parameters.



(a) Comparision of participating parameters in DCA due to 10% change



(b) Comparision of participating parameters in DCA due to 20% change

Fig. 8. Percentage change in reserves estimation due to measurement of participating parameters in DCA method.

Integrated analytical techniques are the existing methods for accurate measurement of reserve estimation until the certain measurement of parameter could be done. Each technique represents the some extremely sensitive parameters which impact on the reserve estimation of unconventional CBM reservoirs. Therefore, accurate measurement of the pointed parameters should be done while adopting specific technique for reserve estimation.

In the numerical simulation, temperature has least effect because it associates with the composition of fluids present in the reservoir and in case of CBM reservoirs only methane and water reside in the coal seams. The composition does not have strong relation with the gas reserves. Therefore, temperature shows less influence on the reserve estimation. Coal density directly associates with the pressure and compaction. The coal density affects the rank of coal and makes itself dynamic function of the coalification. The coalification modifies the sorption and maturity of the coal and for the reason, coal density is directly influenced by this phenomenon, so the coal density is measured as effective parameter for reserve estimation. Pressure affiliates with the quantitative estimation of sorption, diffusion and dissolved methane. It is clearly understood that in numerical modelling low permeability, gas adsorption, desorption, dual porosity and diffusion are incorporated for reserve estimation therefore, associated parameters like pressure and coal density create strong impact on results.

The application of the purposed study is based on the implementation of reserve estimation techniques on CBM reservoirs. The applicability approves its validity through the adaptation of practically existing reservoirs. The Powder River Basin and southern Qinshui Basin are the reservoirs which are used for the volumetric method and numerical simulation respectively(Zhang et al., 2011; Scott and Luppens, 2013; Fang et al., 2019). The volumetric method and numerical simulation of the existing reservoirs increase the reliability of the estimation of reserves. Analysis based on these reservoirs approves the sensitive extent of participating parameters for the real existing reservoirs. The required input parameters for

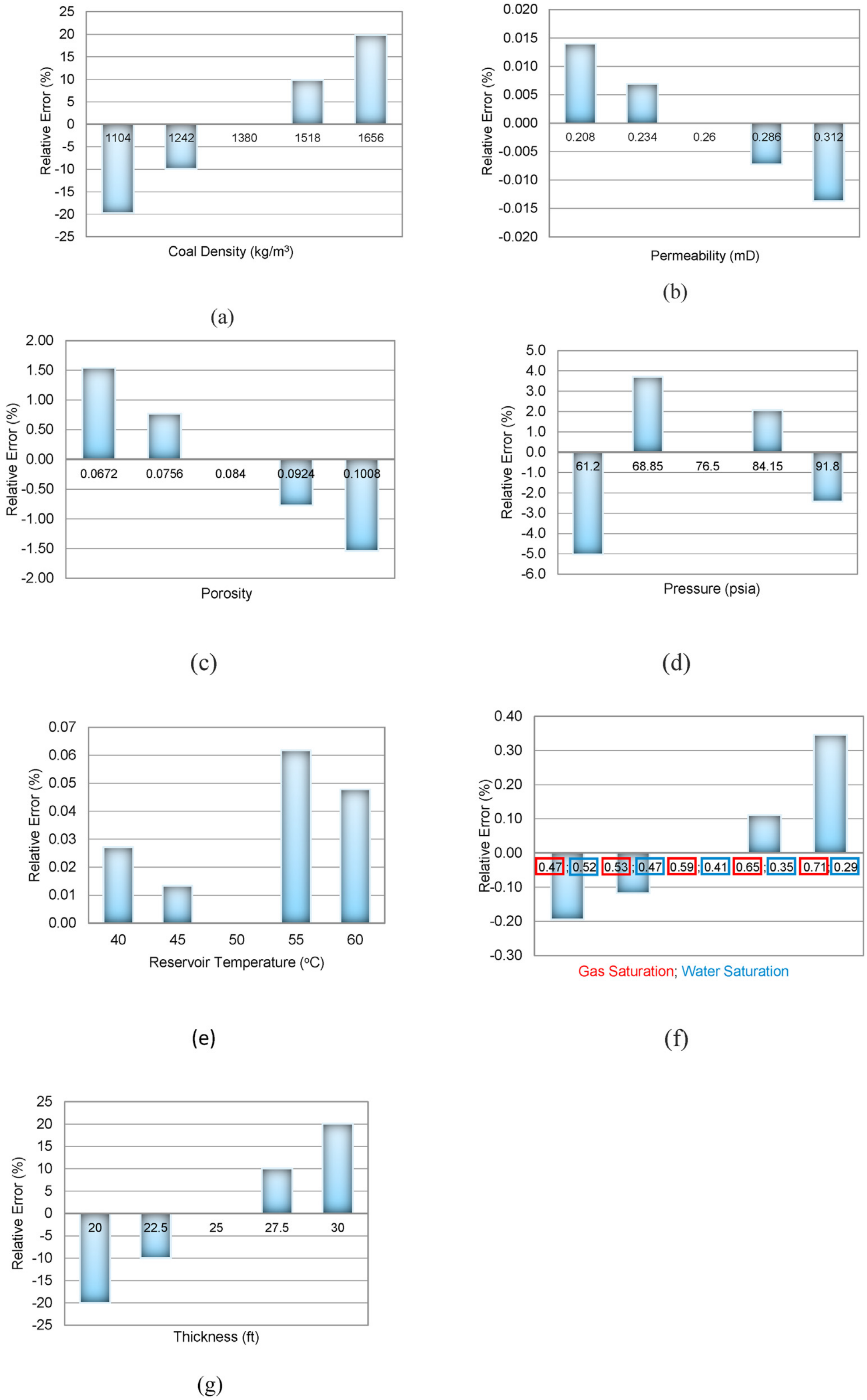
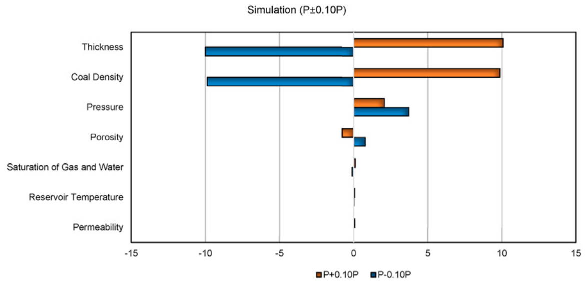
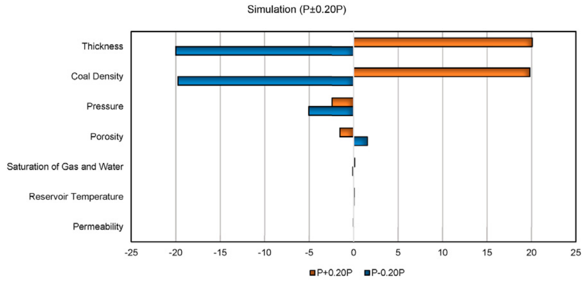


Fig. 9. Relative error in reserve estimation from numerical simulation due to change in parameters.

MBE and DCA are based on the simulated data developed from the basic reservoir parameters through the reservoir modeling (King, 1993; Seidle, 1999; Ahmed et al., 2006; Mattar and Moghadam, 2009; Zhou et al., 2017). The forecasting of performance parameters on the reservoir data enables the implementation of MBE. The simulation and forecasting are done on the production data of CBM wells for executing the decline curve analysis using the modified power law decline curve.



(a) Comparision of participating parameters in numerical simulation due to 10% change



(b) Comparision of participating parameters in numerical simulation due to 20% change

Fig. 10. Percentage change in reserves estimation due to measurement of participating parameters in numerical simulation.

6. Conclusions

This study investigates different reserve estimation methods applicable to unconventional CBM reservoirs in concomitant with effective parameters. It is found that change in the initial water saturation shows additional impact on the reserve estimation for volumetric method and material balance equation. In addition, all parameters except coal density are influencing the reserve estimation in volumetric method. On the other hand, material balance approach is relatively less affected due to the uncertainty in participating parameters. It is noted that peak flow rate must be measured accurately along with the production data for impactful implementation of decline curve analysis considering the measurement of reserves of unconventional CBM reservoirs. Although, parameters govern impression on reserve estimation using numerical simulation, but coal density is the prominent parameter which needs to be measured accurately while implementing the method. Therefore, before the implementation of any approach to estimate the unconventional CBM reserves, the certain measurement of notified and potentially impactful parameters must be evaluated accurately through the existing measurement techniques. High degree of accuracy must be adopted in measuring the nominated parameters to achieve the actual estimation of CBM reserves. Moreover, the low impact causing parameters has less capability to deviate the estimation of CBM reserves form accuracy. However, the accuracy of these parameters can be compromised in measurement evaluation for the reserve estimation of CBM reservoirs. The segregation of impactful parameters from the non-impactful parameters participating in reserves estimation methods of CBM reservoirs underpins the applicability of adopted approach to select method for reserve estimation based on the accuracy of available data.

Declaration of competing interest

The authors declare that they have no competing interests.

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