June 2010, Volume 4, No.6 (Serial No.31)
Journal of Energy and Power Engineering, ISSN 1934-8975, USA

Impact Factors on Fracturing Results of Coal Seams and Appropriate Countermeasures

X. Wang, Y.H. Ding, Y. Xu and Y.Y. Duan

Fracturing & Acidizing Technical Service Center, Research Institute of Petroleum Exploration and Development, China National Petroleum Corp. ,Langfang 065007, China

Received: December 17, 2009 / Accepted: March 2, 2010 / Published: June 30, 2010.

Abstract: Hydraulic fracturing is one of the efficient means for the abundant low-permeability CBM (coal-bed methane) reserves in China, however, due to the unique features of coal seams (i.e., low temperature, strong adsorption and abnormal development of natural fracture systems) as compared with the conventional reservoirs, the fractures propagate is difficult and the risk of damage to coal seam itself and the hydraulic fractures would be extremely high in the course of fracturing. As a result, losses would be suffered on the post-frac production of CBM wells.With the mean of numerical simulation, in this paper, the main factors have impact on the post-frac results as well as the extent to which the impact is brought were researched, and the technical solutions for the improvement of the fracturing performance was put forwards.

Key words: Coal-seam fracturing, hazard factors, yield loss rate, technical solutions.

1. Introduction

The reserves of CBM (coal-bed methane) in China generally fall within the category of low permeability. According to the well tests conducted to 23 target blocks within China, about 70% have the permeability less than 1 md, where about half ones having the value even lower than 0.1 md; without fracturing, almost no flow is present with the vertical holes, and fracturing constitutes the mainstream tool for stimulating the flow [1, 2]. Due to the unique features of coal seams (i.e., low temperature, strong adsorption, high plasticity and abnormal development of natural fracture systems) as compared with the conventional reservoirs, however, the risk of hazards (including those against coal seam itself and the hydraulic fractures) would be extremely high in the course of fracturing. Meanwhile, the fractures propagate in a regularity which is extremely hard to understand; unlike the case of conventional sandstone reservoirs (i.e., the single fracture, symmetrical in both wings, propagates in a regular manner), usually a complicated fracture network system would be involved, that is, the principal fracture extends along the maximal principal stress direction, and many multiple-fracture system would develop which connects with the principal fracture and extends in various directions；under such a fracture system, it is evident that the fracture propagation is very difficulty and the fracture length is rarely equal to the length of a single fracture; in other words, the coal-seam fracture is shorter [3-9]. Due to the sharing of fracturing fluid and proppant amongst multiple fractures, each fracture has a smaller width, or presents a lower flow conductivity; in addition, given the low temperature in the coal seams, it is hard for the gel fracturing fluid system to attain complete breaking, and the residual gel would subsequently reduce the flow conductivity of fractures, experiments show that the damage rate of gel can extend even as high as 80% or more [10]; after the closure of fractures, proppant would be imbedded due to the soft property and low Young's modulus of coal

Corresponding author: X. Wang, SE, research fields: oil and gas field development. E-mail: m-snower@163.com.

seam, which would further weaken the flow conductivity. Such variation in fracture length and flow conductivity would, in a broad sense, can cause loss to post-frac production. Plus, whereas coal seams are featured by high filter loss and strong adsorption, the fluid efficiency would be quite low in the course of fracturing treatment, and a quite large portion of fracturing fluid would be lost into reservoirs to an extremely big depth, which would have negative impacts on the post-frac results of CBM holes. Previous studies did not give a quantitative analysis of the impact of these factors on the production of coal-bed methane wells after fracturing and the relative magnitude of the impact. Principally based on numerical simulation, this paper probes into the extent to which such factors as fracture length, flow conductivity, hazard in filter loss zone of fracturing fluid, filter cake hazard, and residual gel hazard would influence the post-frac flow, in addition to putting forward the technical suggestions or countermeasures, for different scenarios, to reduce the potential hazards to be suffered.

2. Impacts of Various Hazard Factors on Post-Frac Flow of CBM Holes

2.1 Methodology

Herein, numerical simulation is principally employed for getting an understanding of the impacts brought by various hazard factors against the post-frac flow in CBM holes [11, 12]. To this end, the CBM module of the numerical simulation program-ECLIPSE is used for the coal-seam modeling, and the Coal Bed Methane model uses a modified Warren and Root dual porosity model to describe the physical processes involved in a typical coal bed methane project. The adsorbed concentration on the surface of the coal is assumed to be a function of pressure only, described by a Langmuir Isotherm. The Langmuir Isotherm is input as a table of pressure versus adsorbed concentrations. Different isotherms can be used in different regions of the field. Upon which three systems are taken into account: coal matrix, coal-seam cleat fracture system and hydraulic fracture. The hydaulic fracture is simulated by local grid refinement and equivalent conductivity. Using “equivalent conductivity” approach to deal with fracture, namely, the fracture width is generally only a few millimeters while the fracture lenghth and spacing are the amount of several hundred meters. If the grid is divided according to the actual data, the grids will be very large so that the simulation work is very time-consuming or even impossible. The so-called equivalent conductivity refers to appropriate expand the fracture width while proportional to reduce the fracture permeability to keep the fracture conductivity (the product of permeability by fracture width) unchanged. This method has been confirmed that the error was within 3% [13]. The simulation data are taken from the typical coal seams of Qinshui Basin in Shanxi Province. 0.5 md is taken as the value of permeability since a great majority of china’s coal seams are of low permeability, and the basic reservoir parameters employed are given in Table 1.

2.2 Impact of Fracture Length Hazard on Yield

Whereas cleat crevices develop in coal seams, the fractures usually tend to form a complicated network, and the propagation in the direction of length is rarely satisfactory. Presently, it is a normal practice for the CBM fields to adopt 200 ~ 300 m as the well spacing for the purpose of development, with the optimal fracture half-length being generally 100 ~ 120 m; since, among others, it is hard for multiple fractures to propa-

Table 1 Main parametric inputs for the numerical simulation model.

Parameter	Value
Depth, m	520
Thickness, m	5.5
Porosity, %	2.9
Permeability, md	0.5
Formation pressure coefficient, MPa/100 m	0.9
Gas content, m^3/t	26
Gas saturation, %	92
Time span for simulation, year	15

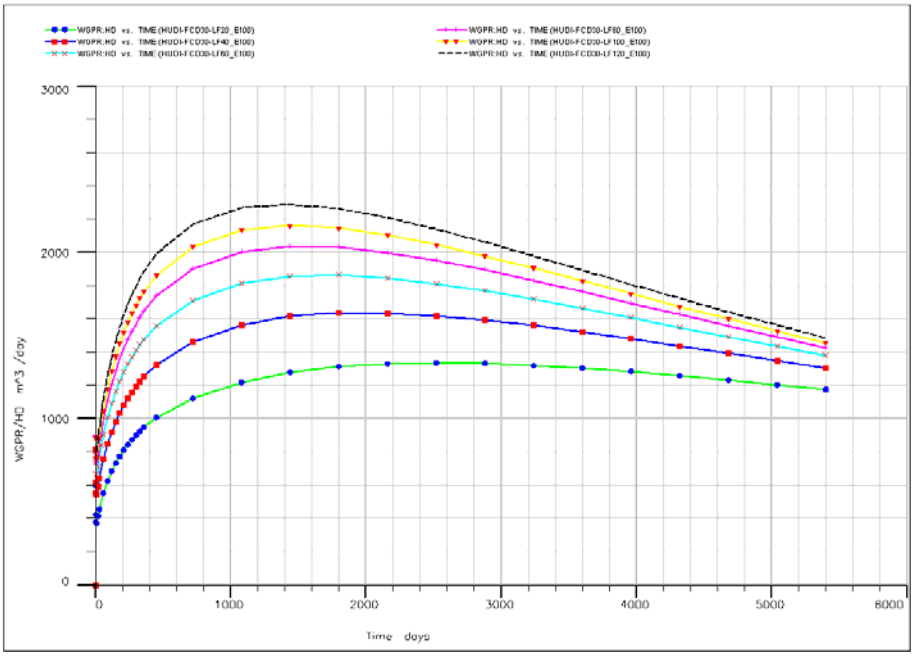

Fig.1 Impact of fracture length hazard on gas yield.

(The corresponding hazard rates of fracture half-length are, from up to down, 0, 17%, 33%, 50%, 67% and 83%.)

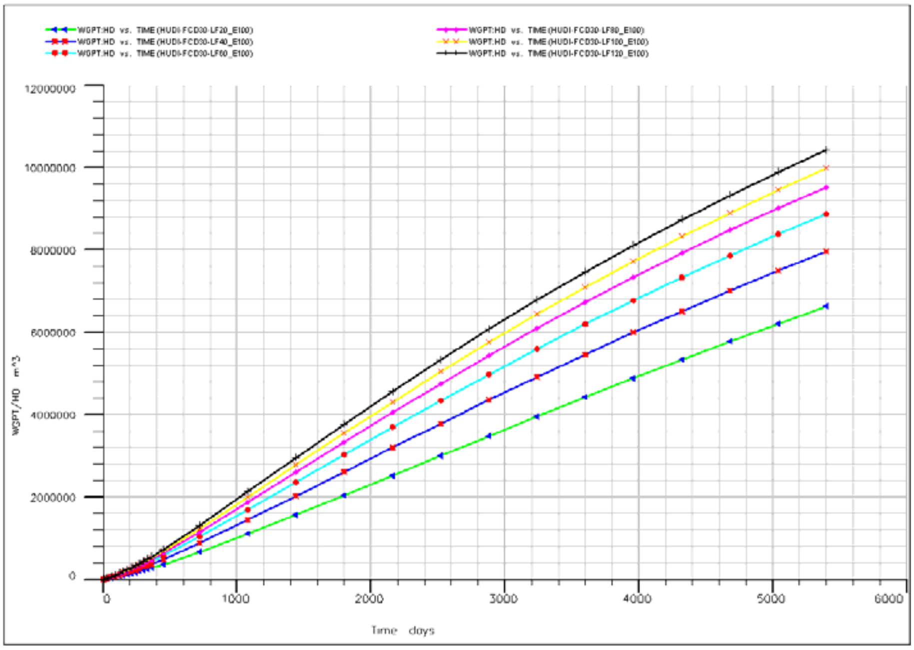

Fig. 2 Impact of fracture length hazard on cumulative gas yield.

(The corresponding hazard rates of fracture half-length are, from up to down, 0, 17%, 33%, 50%, 67% and 83%.)

gate (which, in our view, is one type of hazard), Figs. 1 and 2 respectively depict the impacts of fracture length hazards (at 17%, 33%, 50%, 67% and 83%) on the gas yield and on the cumulative gas yield; no information on water production is provided in the simulation results, because the impact on water production is similar to the case of CBM, and the water production deserves no high consideration.

Here and throughout this paper, yield loss rate = (yield under no hazard-post-hazard yield) × 100/yield

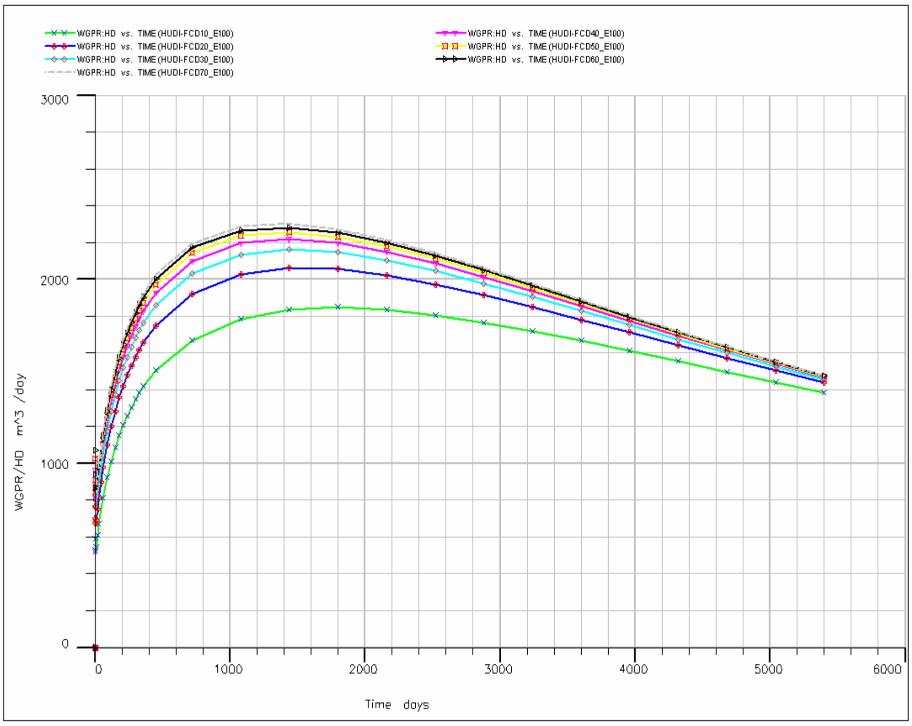

Fig. 3 Impact on gas yield as brought by hazard of flow conductivity.

(The corresponding hazard rates of fracture flow conductivity are, from up to down, 0, 17%, 33%, 50%, 67% and 83%.)

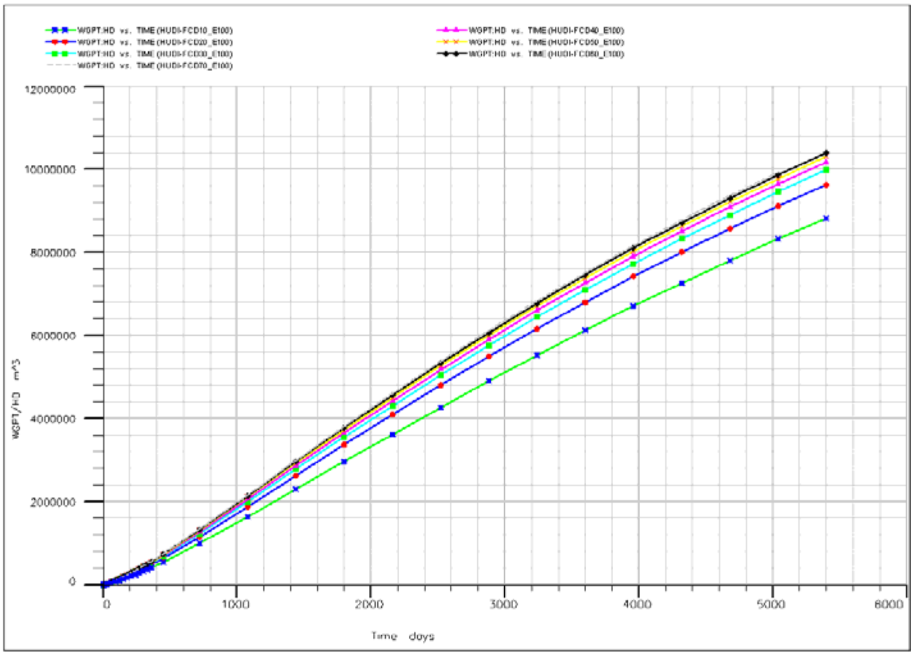

Fig. 4 Impact on cumulative gas yield as brought by hazard of flow conductivity.

(The corresponding hazard rates of fracture flow conductivity are, from up to down, 0, 17%, 33%, 50%, 67% and 83%.)

under no hazard. For respective hazard rate of fracture length, Table 2 provides the cumulative yield and the yield loss rate in the time span of 15 years.

As indicated by the simulation result, given the hazards of fracture length ranging between 17% ~ 83%, the yield loss would be 4.3% ~ 36.4%.

Table 2 Impact of fracture length hazard on post-frac yield.

Hazard rate of fracture length (%)	Cumulative gas yield (10^4 m^3)	Yield loss rate (%)
0	1 042.3	0.0
17	997.7	4.3
33	953.1	8.6
50	887.6	14.8
67	796.8	23.6
83	663.2	36.4

Table 3 Impact of hazard of fracture flow conductivity on post-frac flow.

Hazard rate of fracture flow conductivity (%)	Cumulative gas yield (10^4 m^3)	Yield loss rate (%)
0	1 038.9	0.0
17	1 030.1	0.9
33	1 017.4	2.1
50	997.7	4.0
67	962.6	7.4
83	881.6	15.1

2.3 Impact on Yield Brought by Hazard of Flow Conductivity

Whereas cleat crevices develop in coal seams, the fractures usually tend to form a complicated network; by ignoring the other factors, the low Young's modulus of coal seams would result in a relatively large width; here, the impacts on both gas yield and water production are simulated as brought by such hazard factors as residual gel, multiple fractures, etc. When the flow conductivity of fracture decreases from the original 60 dc.cm to 50, 40, 30, 20 and 10 dc.cm, respectively, Fig. 3 and Fig. 4 depict, respectively, the impacts of the hazard of flow conductivity on the gas yield and the cumulative gas yield.

Table 3 provides the cumulative yield and the yield loss rate, corresponding to various hazard rates of fracture flow conductivity, resulted from the simulation in a time span of 15 years.

According to the simulation results, given the hazard of flow conductivity at 17% ~ 83%, yield would suffer a loss of 0.9 %~ 15.1%.

Due to the low temperature in coal seams, it is hard for the gel (if used for the fracturing) to break; in addition, a large portion of low-molecular weight gel breaker would be lost into coal seams together with filtrate, making it hard for the cross-linked gel to break completely in the hydraulic fractures, and a certain quantity of residual gel lingering in the fracture fractures would also weaken the flow conductivity of fractures. Therefore, another scenario has been simulated, where despite, upon gel fracturing, the anticipated fracture length is attained, the gel has no way to break completely due to low temperature and breaking technique, and intermittent distribution of flow conductivity occurs within the length of the principal fracture, (Fig. 5). The simulation involves the cases where the flow conductivity of fracture in the hazard segment is reduced from 60 dc.cm to 40, 30, 20 and 10 dc.cm, respectively, as well as the case of extremity, i.e., the flow conductivity of fracture decreases to 0 dc.cm due to the effect of residual gel. The results of simulation for the impacts on yield can be seen in Figs. 6 and 7.

Table 4 provides the cumulative yield and the yield loss rate, corresponding to various hazard rates of residual gel, resulted from the simulation in a time span of 15 years.

As indicated by the simulation result, if the gel has no way at all to break completely in the residual gel segment, i.e., the flow conductivity therein decreases to 0 dc.cm, and the yield loss rate would reach 46.8%; so long a certain flow conductivity is retained for the fractures (for instance, kept above 17%), the loss rate would fall below 15%.

2.4 Hazard of Permeability in Filter Loss Zone

As we all know, in the case of a conventional tight reservoir, normally the filter loss zone is, due to the low permeability, merely several or tens of centimeters,

Fig. 5 Uneven hazard of fracture flow conductivity as resulted from residual gel.
(In the figure, the residual gel hazard zones are highlighted with deep color).

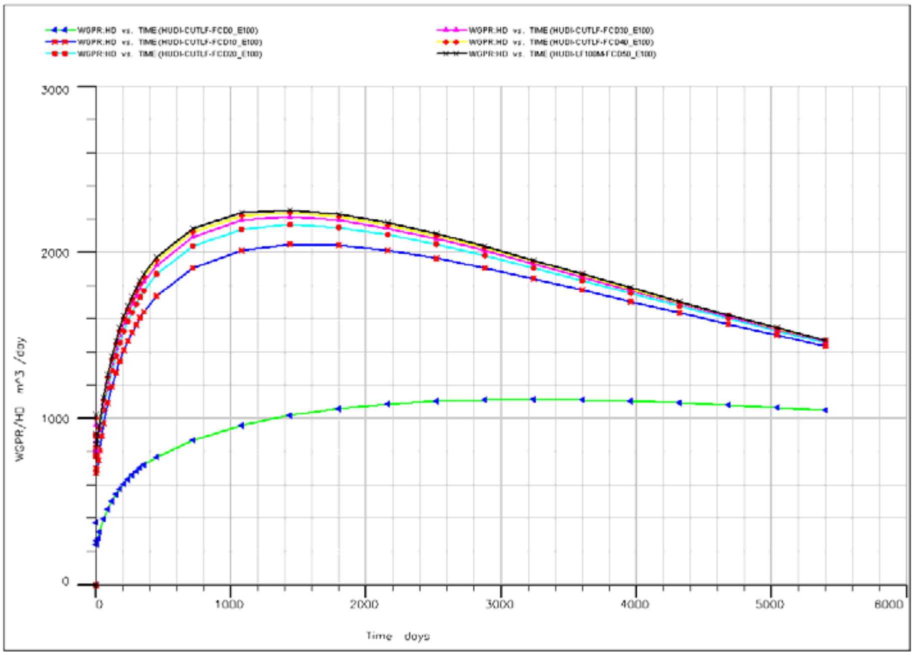

Fig. 6 Impact on gas yield as brought by hazard of residual gel in fractures.
(The corresponding hazard rates of flow conductivity in the hazard zone of residual gel are, from up to down, 17%, 33%, 50%, 67%, 83% and 100%.)

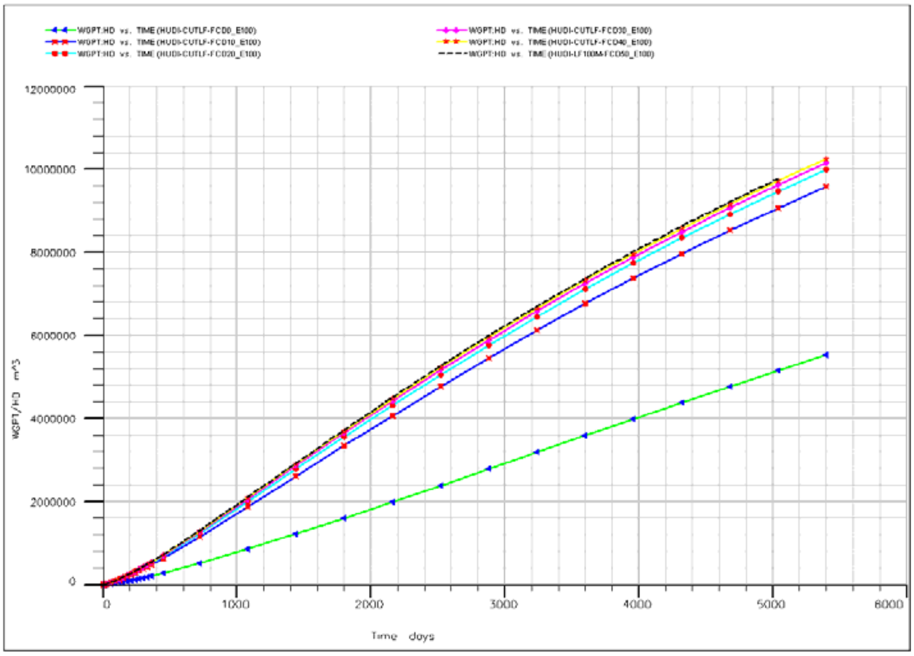

Fig. 7 Impact on cumulative gas yield as brought by hazard of residual gel in fractures.
(The corresponding hazard rates of flow conductivity in the hazard zone of residual gel are, from up to down, 17%, 33%, 50%, 67%, 83% and 100%.)

and, subsequently, the impact of permeability hazard resulted from filter loss is relatively small within the entire percolation field. Coal seam is the opposite, nevertheless, where the natural fracture system develops, the filter loss of fracturing fluid in the course of fracturing treatment is large, and the zone affected

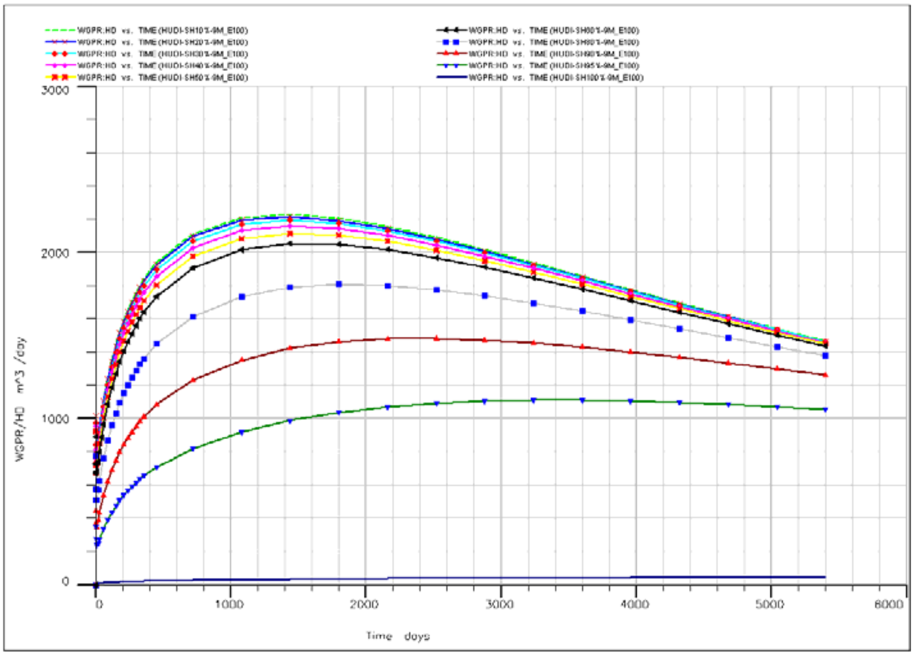

Fig. 8 Impact on gas yield as brought by permeability hazard in the filter loss zone.
(The corresponding hazard rates of permeability in the filter loss zone are, from up to down, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90%.)

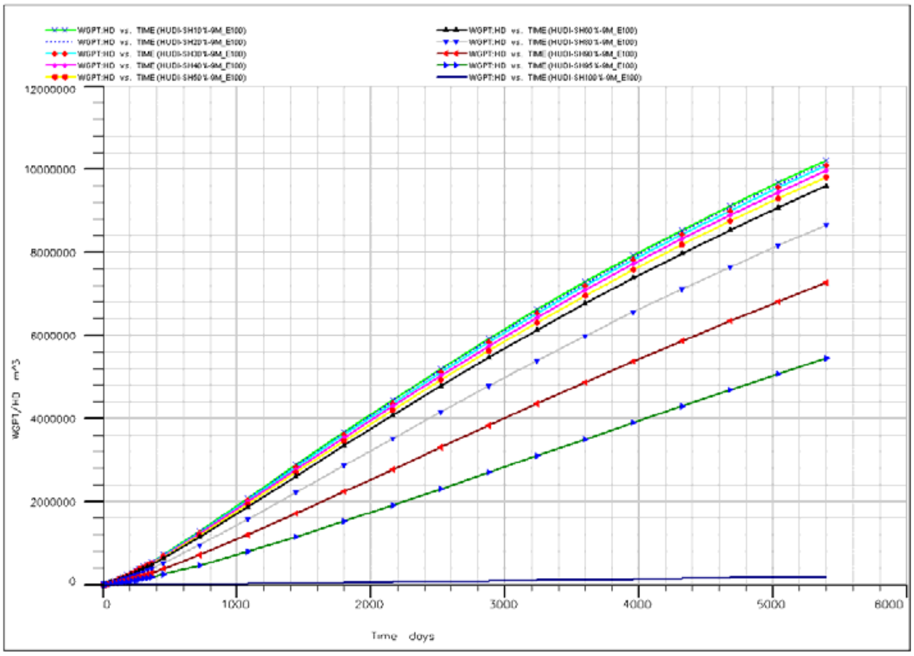

Fig. 9 Impact on cumulative gas yield as brought by permeability hazard in the filter loss zone.
(The corresponding hazard rates of permeability in the filter loss zone are, from up to down, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90%.)

by filter loss is big. According to the analysis on previous treatments, the efficiency of fracturing fluid for coal seams generally ranges between 15% ~ 30%; based on the differences in fracturing fluid system and the development of natural fractures, this paper, by taking into account the situations of coal seams in Qinshui Basin, estimates the filter loss depth (i.e., the vertical distance from the farthest end where filter loss of fracturing fluid occurs to the surface of fracture wall) at 5 m or so, provided 22.5% is taken for the average fracturing fluid efficiency and 80 m taken for the fracture half-length. For the filter loss zone, the impact on yield is simulated by assuming the hazard rate of coal-seam permeability to be 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80% and 90%, respectively, for the results of simulation, see Fig. 8 and Fig. 9.

Table 5 provides the cumulative yield and the yield loss rate, corresponding to various hazard rates of filter loss, resulted from the simulation in a time span of 15 years.

As reflected in the results of simulation, the eventual yield loss would be lower than 10% given a hazard rate of permeability lower than 60% in the filter loss zone; once the hazard rate exceeds 70%, a leap would be observed in the loss of yield; for instance, given a hazard rate of 90% (i.e., the typical hazard rate of coal-seam permeability in the case of conventional gel fracturing fluid [1]), the loss of yield would be as high as 47.6%.

2.5 Hazard Arising from Filter Cake

In the treatment with a gel system, the filter loss of fracturing fluid would deposit on the wall surface of fractures, which is called filter cake; no such hazard would exist in the case of treatment with activated water. Filter cake presents an extremely low permeability; here, the scenarios for simulation concern the permeability of 0, 0.1, 0.2, 0.3, 0.4 and 0.5 md in the filter cake zone; obviously, since filter cake is thin (generally 1 mm or so), in view of percolation, no impact would be brought against the yield except for the case where the permeability of filter cake decreases to 0; if the permeability is higher than 0 md, the resultant curves would basically coincide with each other; only when the filter cake is totally impermeable would lead to the decline of yield (with the eventual yield stepping down to 36.4%); nevertheless, it is rarely possible for the occurrence of such a situation, and thus the impact of filter cake could be disregarded. For the results of simulation, see in Fig. 10 and Fig. 11.

2.6 Comparative Analysis on the Extent to Which Various Hazard Factors Having Impact on Yield

Fig. 12 shows the impacts on yield as brought by different hazard rates of four factors, i.e., fracture length, flow conductivity, residual gel and filter loss (barring the extremity of hazard, e.g., 100%). Based on the analysis conducted to the figure, it is evident that the factors have non-identical impacts on the yield: fracture length presents the largest impact, which is followed, in sequence, by hazard in filter loss zone, hazard of flow conductivity and hazard of residual gel. The hazard of filter loss zone is unique in that, once a certain value is exceeded, the impact would rise abruptly (e.g., when the hazard rate exceeds 60%, the curve of yield loss would become sharper). The yield loss resulted from the hazards of fracture length and permeability in filter loss zone would be, in unfavor-

Table 4 Impact of residual gel hazard on post-frac flow.

Hazard rate of residual gel on flow conductivity of fractures (%)	Cumulative gas yield (10^4 m^3)	Yield loss rate resulted from residual gel hazard (%)
0	1 038.9	0.0
17	1 030.1	0.9
33	1 024.5	1.4
50	1 015.7	2.2
67	999.3	3.8
83	881.6	15.1
100	553.0	46.8

Table 5 Impact of filter loss hazard on post-frac flow.

Hazard rate in filter loss zone (%)	Cumulative gas yield (10^4 m^3)	Yield loss rate resulted from hazard in filter loss zone (%)
0	1 038.9	0.0
10	1 020.2	1.8
20	1 014.8	2.3
30	1 008.3	3.0
40	996.8	4.1
50	981.4	5.5
60	959.6	7.6
70	865.9	16.7
80	726.6	30.1
90	544.9	47.6

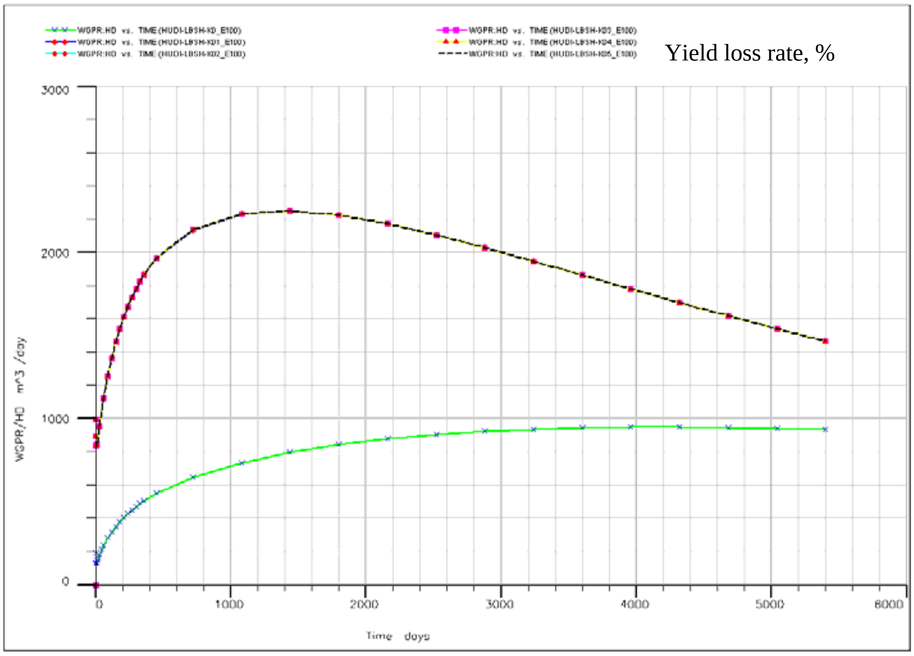

Fig. 10 Impact of filter cake on gas yield.

(The lower curve assumes the filter cake presents no permeability, while the upper one assumes a permeability ranging 0.1 ~ 0.5 md.)

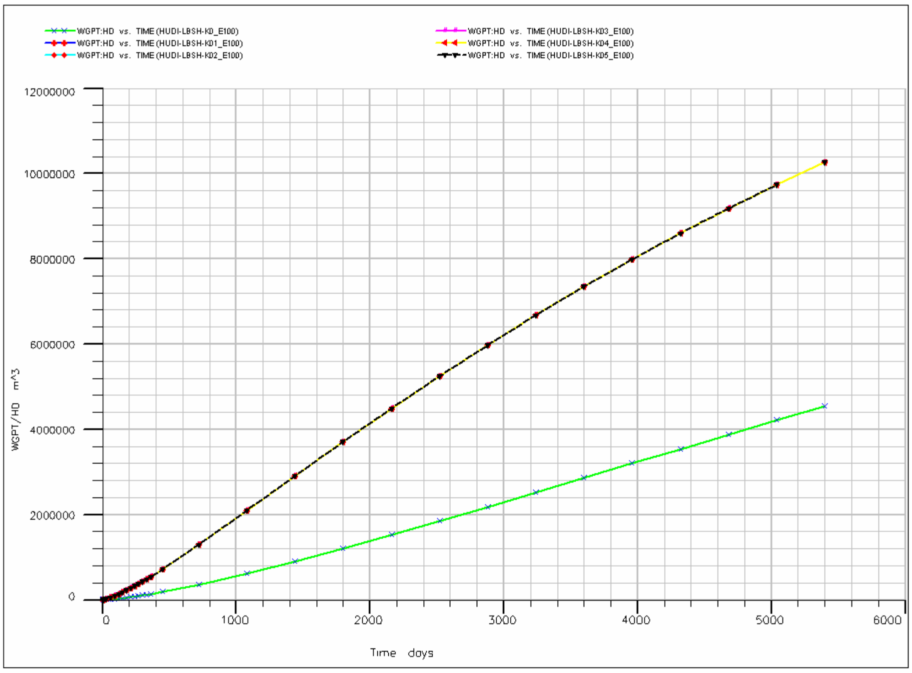

Fig. 11 Impact of filter cake on cumulative gas yield.

(The lower curve assumes the filter cake presents no permeability, while the upper one assumes a permeability ranging 0.1 ~ 0.5 m.)

able cases, up to 35% ~ 50%; obviously, how to reduce such hazard factors would be the main research orientation in the future for effectively improving the post-frac flow of CBM holes.

3. Main Technical Solutions for Reducing Hazards in Coal-Seam Fracturing while Improving the Post-Frac Flow

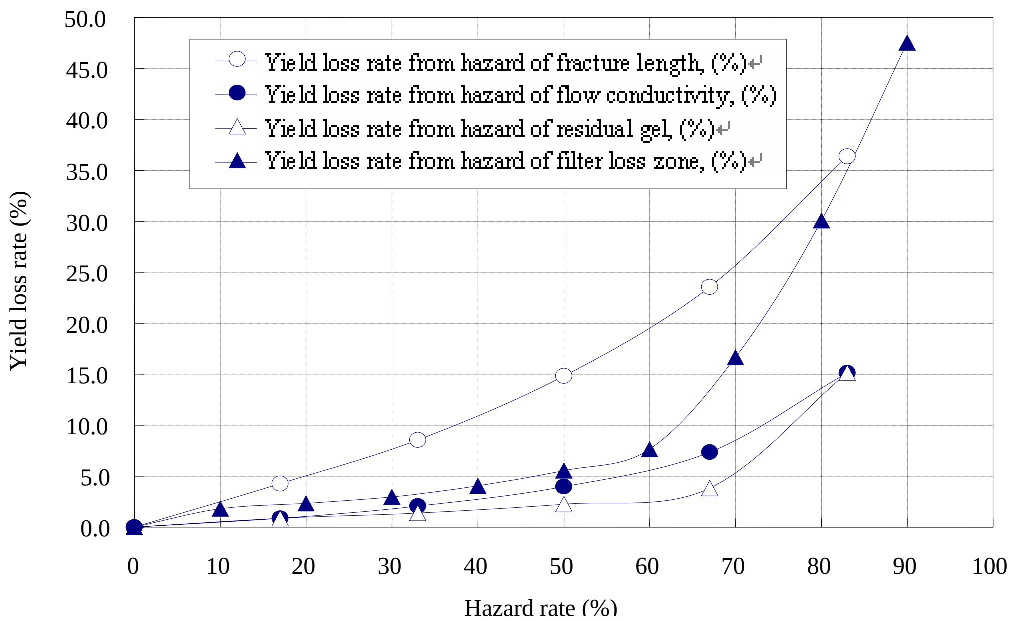

Fig. 12 Synthetic impact on yield as brought by various hazard factors.

It is signalled from the researches above that fracture length represents the most pivotal factor having impact on tight or super-tight coal seams; that is, the fracturing of low-permeability coal seams would focus on the pursuit of a certain length of fracture propagation (or the propagation length of the principal fracture). Though, in the fracturing treatment for coal seams, a complicated fracture network (involving the propagation of multiple fractures) would be formed as driven by the natural fracture system, it is necessary to prolong, as much as possible, the length of the principal fracture by making adjustments to techniques. To this end, the reasonable measures comprise the minimization of the development degree of near-wellbore multiple fractures, and the enlargement of extension of the principal fracture. The effective technical solutions are: the proppant slugging technique in the preflush stage, and a prolonged period of flushing & grinding technique at a low proppant ratio in the sand carrier stage (favourable for the joint propagation of multiple fractures adjacent to the wellbore). Moreover, it is necessary to, in the sand carrier stage, rationally control the flow rate based on the real-time variation of net pressure, thus precluding the possibility of the open-up of much more fractures (resulted from additional pressure), and the premature occurrence of sand plug or the presence of much more fracture branches.

Another efficient way for improving fracturing results is to reduce the hazard against coal-seam permeability within the filter loss zone. On one hand, it may utilize the working fluid system featuring low hazard or low filter loss, e.g., activated-water fracturing fluid or foamed fracturing fluid. On the other hand, whereas gel is highly capable in carrying proppant, it would not be acceptable for us to reject the use of gel fracturing fluid in coal seams. Presently, the innovative gel system could largely cut down the hazard against coal seams (for instance, the innovative gel system developed by the Fracturing & Acidizing Service Center of China National Petroleum Corporation Research Institute of Petroleum Exploration and Development-Langfang could lower the hazard from the conventional 80% ~ 90% to 7% ~ 36%). In addition, the rational design of pad fluid per cent, proppant/fluid ratio, as well as the compound (gel plus activated water) fracturing technique would be effective in cutting off the hazard rate of filter loss.

For the purposes of reducing the hazard on fracture flow conductivity (including the hazard of residual gel), it is to, on one hand, (e.g., in view of such hazard as fracture length) control the development extent of multiple fractures so that the open-up fracture system could be efficiently supported to the maximum practicable degree, and, on the other hand, adopt high-efficiency breaking technique (e.g., low-temperature enzyme) in the course of gel fracturing treatment so as to actualize the complete breaking.

4. Conclusions

Rooted in numerical simulation, this paper conducts researches and comparisons to the post-frac yield loss as resulted from five hazard factors, namely, fracture length, flow conductivity of fracture, filter cake, residual gel and permeability of filter loss zone. According to the results of simulation, there would be nearly no impact at all on yield so long a certain permeability exists within the filter cake zone; the other 4 factors have impacts on the yield in an order (from high to low) as below: fracture length, hazard in filter loss zone, hazard of flow conductivity and hazard of residual gel. The yield loss resulted from the hazards of fracture length and permeability in filter loss zone would be, in unfavorable cases, up to 35% ~ 50%. Based on the researches of hazard factors, efforts are made to the major technical solutions for reducing hazards while improving yield in the course of coal-seam fracturing.

According to the researches described in this paper, it is pivotal, in the course of fracturing treatment for CBM holes, to, on one hand, control the effective propagation and efficient supporting of hydraulic fracture network system, and, on the other hand, reduce the hazards of fracturing fluid against the coal seams. After all, there is no other way to improve the fracturing performance.

Acknowledgments

The authors would like to thank fracturing and acidizing technology service center, Langfang Branch of research Institute of Petroleum Exploration & Development, to allow this article to be published.

References

[1] Q.B. Zhao, Chinese Coal-Bed Methane Exploration Results and the Knowledge, Theory and Practice of Coal-Bed Methane Exploration and Development, Petroleum Industry Press, Beijing, China, 2007, pp. 3-11 (In Chinese).

[2] X. Wang, Low Damage High Technology Research and Application of Coal Seam Fracturing, Theory and Practice of Coal-Bed Methane Exploration and Development, Petroleum Industry Press, Beijing, China, 2007, pp. 249-253 (In Chinese).

[3] G.A. Petzd, Devon pressing fruitland coal seam program, OGJ Special Issue, Nov. 5 (1990) 28-30.

[4] W.P. Diamond, D.C. Oyler, Effects of stimulation treatments on coalbeds and surrounding strata, evidence from undergroud observations, U.S. Dept. of Inferior, Bureau of Mines Report of Investigations (Rl), Number 9083, 1987.

[5] B.W. McDaniel, Hydraulic fracturing techniques used for stimulation of coalbed methane wells, SPE 21292-MS, 1990.

[6] I.D. Palmer, Review of coalbed methane well stimulation, SPE 22395-MS, 1992.

[7] S.J. Sha, S.H. Zhang, Analysis of fracturing propagation law of coalbed methane well, Natural Gas Industry 25 (1) (2005)130-132.

[8] Y.L. Hao, Q.H. Wang, Fracturing pressure and fracture morphology analysis of coalbed methane well, Coal Geology and Exploration 29 (3) (2001) 20-22.

[9] X.M. Wu, The reasearch od occurrence and morphology of hydraulic fractur of coal-bed methane wells, Exploration Engineering 6 (1995) 19-21.

[10] Y.L. Wang, Technology research of fracturing fluid using in coal-bed methane wells, Coal Geology and Exploration 12 (1) (2002) 27-30.

[11] Z.J. Luo, X.L. Yang, Numerical simulation of coal-bed methane gas reservoir, Coal Geology and Exploration 4 (1997) 28-30.
X.R. Wei, G.X. Wang, D.P. Massarotto, A review on recent advances in the numerical simulation for coalbed methane recovery process, SPE 93101-MS, SPE Asia Pacific Oil and Gas Conference and Exhibition, Apr. 5-7, Jakarta, Indonesia, 2005.

[12] Y.H. Wang, X. Wang, D. Jiang, Research of the impact of hydraulic fracture on dynamics of secondary oil recovery, Oil Drilling Technology 6 (1996) 13-15.