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第二编

钻井、完井、增产改造与排采工程

Successful strategies for dewatering wells using ESP′s

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【Abstract】 Pumping water from a well is a straight forward effort that has been done for centuries. Pumping fluid from relatively shallow wells should be an easy task. Normally a pump is installed in a well, started and then forgotten. This premise does not hold true in CBM wells. In CBM wells, this pumping process can be complicated by many issues unless precautions are taken. This paper is designed to address the basic precautions that can be taken to improve dewatering of CBM wells and will focus on real experiences in producing CBM wells and the steps required to make them economical.

Even though every well is different, this paper will focus on the common areas that are key to getting acceptable performance using an ESP as the primary artificial lift method. As in most pumping situations, success is planned for and not just an accident.

1. Electric Submersible Pumps (ESP′s) best practices for a vertical well: This paper will address the key areas of importance for optimizing operations in a vertical well. The paper will address issues like proper motor cooling, successful operation in turbulent conditions and gas lock avoidance and solids control.

This paper will concentrate on these three items and show through real case histories how CBM can be successfully produced through proven dewatering techniques.

2. Electric Submersible Pumps (ESP′s) best practices for a horizontal well: A horizontal well is a place an ESP flexibility can really shine. This paper will identify the key areas that drastically improve the chances of success. The paper will identify the operational differences and the different options in running in a horizontal well compared to a vertical well. It will cover the preplanning required to avoid negative operational issues including gas locking, solids intrusion and optimized drawdown.

This paper will concentrate on these two items and highlight techniques that will increase the effectiveness of utilizing ESP equipment for dewatering.

【Keywords】 CBM; dewatering; pumps; electric submersible pumps; artificial lift; well bores; wells; solids control.

1 Introduction

The Electric Submersible Pump in one of the most under estimated artificial lift systems as a dewatering tool for CSM or CBM. In reality, with the proper precautions taken it can be the most flexible system with high reliability and extremely economical. This paper will identify specific areas to avoid and specific things to do to assure the best performance. Although it is true that every basin and even every well may be different, the information provided is based on years of experience in CBM basins around the world. Specifically, this paper is driven by the experience derived from the use of the ESP in the United States Powder River Basin where of the 45 000 producing wells, where ESP′s account for 75% of that number. Pumping water from a CBM well is a straight forward effort that has been done for centuries. Pumping fluid from relatively shallow wells, 500 to 5 000 feet, should be an easy task. Normally a pump is installed in a well, started and then forgotten. This premise does not hold true in

CBM wells. In CBM wells, this pumping process can be complicated by many issues unless precautions are taken. This paper is designed to address the basic precautions that can be taken to improve dewatering of CBM wells, primarily with an Electric Submersible Pump. These precautionary steps can save the operator money by reducing the month to month maintenance associated with CBM well dewatering while providing a higher degree of well control. Although we cannot cover every potential pitfall to dewatering operations, the basic steps discussed will identify potential problems and offer suggestions based upon actual experience in dewatering CBM wells using the electric submersible pump. The following information is compiled from 35 years of practical experience in product design, application engineering and years of solving problems in unconventional gas wells.

2 Initial planning using an ESP

Certain facts surround the use of an ESP. All ESP, as an example require proper cooling of the motor for optimal life. A submersible pump does not like coal fines or other solids and therefore steps must be taken to keep them from entering the pump and lastly, submersible pumps, like most pumps are designed to digest single phase liquid and do not like multiphase fluids, especially gas. Addressing these three items allows the operator a more likely success story from the very beginning.

It is also a well known fact that all electric submersible pumps are not created equal. As an example the domestic water well version is designed to produce fluid for short periods of time from relatively shallow depths. They are limited to small horse powers and small casing. These domestic versions are built for conditions that are very benign and are far less robust than the standard oil field style ESP. Although more expensive than the domestic version, the oil field style is designed for very rugged operation, designed for deeper operation and built to absorb more abuse for a longer period of time. These systems can generate much larger HP in smaller casing and at deeper settings, and offer higher voltages which will reduce the size of wire used to feed the motor with electricity.

The old rule of thumb was an ESP was selected when fluid rates exceeded 500 BPD or 15 GPM. With the developed technology of today, the pumps are now able to deliver 50 BPD which is a rate in which a standard rod pumping unit would be normally used. This new technology is especially significant when one evaluates the benefits of using an ESP in a horizontal well compared to any other surface driven lift systems. The flexibility and controllability of an ESP that eliminates the costly normal maintenance costs of surface driven devices moves the ESP from the category of optional system to the category of best choice overall. Five years ago, this could not be stated but today it can be stated with ease.

Therefore, planning to use an ESP for dewatering in an unconventional gas well requires the easy steps of selecting a rate required to dewater the seam, sufficient casing size to accommodate the motor cooling device which also can be built to positively keep solids out of the pump. Using fracturing methods that do not utilize abrasive materials to prop open the formation fractures and setting the pump below the producing zones starts the project off with the best chance of success. This planning should take place as part of the projects initial planning at the same time the completion methods and logging decisions are made. It is a little recognized fact that the largest expense an operator will see of the life of a well is the maintenance cost of dewatering. This is a larger expense than drilling or completing the well. A substantial amount of time is usually spent in preplanning for these two issues. Equal planning on using an ESP for dewatering the well will drastically reduce the lift cost over the life of the well.

2.1 Vertical well considerations

Today, the most common well to be drilled for CBM is the vertical well. This is by far the least costly method initially. Although less complicated to produce, specific precautions should be taken to assure the longest possible run life. Preparation for running an ESP in a vertical well must take the same steps as any well. The casing size must be large enough to accommodate a cooling shroud. This typically requires no less than a 5 ? cased well. Smaller 4 ? cased wells with multiple zones limits the operator to smaller equipment and eliminate the possibility of putting in solids control systems. If 4 ? is all that is available special applications can be supplied to meet most of the requirements of a successful installation.

The goal in all dewatering applications is to reduce the pressure holding back the gas to a bare minimum. This requires that the ESP pump the well down as close to the intake as possible. As the well continues to pump down several things begin to happen that can have a negative influence on the wells productivity. The first is the intake of the pump starts to see lower and lower intake pressures. The pressure seen at the intake is known as Net Positive Suction Head (NPSH), Sufficient pressure is required to keep the eye of the impeller "charged" sufficiently to allow subsequent stages in the pump to build the required pressure to push fluid all the way to surface. In a straight water well, with no gas present, the specific gravity of the fluid remains dense and less fluid over the pump is required to meet the stages NPSH requirement. Each stage design is unique and each stage type may require a different NPSH.

In CBM wells or other unconventional gas wells, the entrainment of gas bubbles change this density of the water to a lighter mix, requiring more and more feet of fluid over the pump to assure sufficient pressure at the eye of the first stage. Over saturation of gas in the liquid and lower pressure at the intake creates cavitations and or gas locking. Both conditions create a negative situation for the operator and steps need to be taken to minimize or avoid solids totally.

Finding the right spot to set the pump is not all that difficult to find, it can range from a few feet below the producing zone to over a hundred feet in the case of shot perforated casing. In the case of under reamed completions, the most effective setting is into a sump area or as low as possible in the open hole utilizing a motor shroud with provisions to keep out the wells solids.

Additionally, as the fluid level falls and the intake pressure drops, so does the velocity of the fluid through the pump and more importantly the velocity of the fluid up the tubing. It is a given that almost all wells will put up some form of solids. This might be in the form of coal fines, shale particle or even clay particles that weigh very little in the individual form. These particles at a give rate may become suspended in the fluid above the pump discharge somewhere in the tubing. These suspended solids, at a given rate, can not be totally purged from the tubing unless the velocity of the fluid is increased substantially. Failure to purge the tubing of these suspended solids in any form will lead to these particles dropping back into the pump during the shut down cycle and aggregate themselves from individual particles into a mass of particles that clump together. These clumps can act in the case of coal fines as blockages to the impeller or diffuser vanes or in the case of lighter materials become a clay based material that is as abrasive as jeweler's compound. Continual cycling will reach a point of buildup to where the ability of the pump to lift fluid is compromised or in the worst case, erode the rotating components to failure totally. It is absolutely critical and easy to accomplish to maintain a high velocity through the pump and up the tubing the entire pumping cycle to avoid the problems associated with this. In a vertical well, it is much easier as a minimal amount of factors come into play.

Plugging of pumps is usually a function of not generating sufficient velocity up the tubing of the produced fluids to move the suspended solids out of the tubing string. Coal fines especially have a tendency to suspend in the fluid stream if they are not carried all the way to surface. Every time the pump shuts down due to low fluid or gas locking, those suspended solids fall back into the pump and will eventually plug the pump. This can be avoided by maintaining high discharge velocity sufficient to expel the solids from the tubing string. The conditions described, low NPSH and fluid velocity are easier to accomplish if the pump setting is below the lowest producing zone

Likewise, solids entering the well bore can be reduced by assuring low inflow velocities as well. Keeping inflow velocities below $1/10^{th}$ of a foot per second will minimize the amount of solids the fluid can carry into the well bore. Standard practices of perforating the casing using oil field methods can have a detrimental affect on solids production.

In the case of shot perforated seams and especially in wells with multiple producing seams, it is advantageous to get below the lowest producing zone to avoid the worst of the turbulent flow where the gas enters the fluid column. Depending upon the amount of gas produced this turbulent flow will increase dramatically as the wells pressure is decreased due to fluid drawdown. The rolling or turbulence of the gas in the water can extend in both directions above and below the producing zones sufficient to cause gas interference in the pump. Getting the intake of the pump below this turbulence even 50 feet will be the difference between pump operation and gas locking. The positive results are startling and the subsequent increase in gas production very profitable.

In summary, getting a successful result from an ESP in a vertical well is not all that complicated. If the normal requirements for long life are met in the form or proper motor cooling, keeping solids to a minimum, avoiding turbulent flow and planning for sufficient fluid velocity over the life of the well problems are drastically reduced.

2.2 Horizontal well considerations

The horizontal well brings another level of challenges for the ESP, however it is in this application its flexibility and versatility really shines. Again it is extremely important that the ESP vendor is part of the planning stages as some very critical steps must be taken to assure success.

One of the most important areas of attention is the build radius. An ESP is a very flexible mechanical machine that is built to tight tolerances. The decision on the build radius would need to be determined as it pertains to the size of the casing. As an absolute maximum is the build radius of any size casing can be no more than 20 degrees per 100 feet in 7 inch casing. As a norm, the build radius for 5 ? casing would be no more than 12 degree per 100 feet unless special precautions are taken. It is recommended that the pumping system not be set in the bend itself.

The same criteria are required in a horizontal well as in a vertical well. The motor will require cooling, the system will need to protected from solids and as much as possible must be done to avoid turbulent flow conditions and avoid gas locking. One of the key methods of providing all of these options is to run the equipment inside a motor shroud with built in solids protection. The most successful completion alternative is to build a sump that extends below the producing coal at some 60 degree from vertical and set the pump with shroud into the sump. This configuration reduces gas interference at the intake and subsequent gas locking and cavitation issues. A second approach that is successful is to the land the pump in the bottom 90 degree and attach perforated and screened tail pipe onto the shroud system. Extending this tailpipe back into the lateral 500 to 1 000 feet can also lead to good run times and reduce gas interference. It is important however to run centralizers on the tailpipe to assure the pipe is a centered as possible. Lastly consideration should be given to two more areas. It is important to "index" the cable so it rides on the top of the tubing as it goes into the hole to avoid as much rubbing as possible. The other consideration is to preload the thrust bearing in the ESP seal section to assure the load is equally applied with the pumping system lying on its side. Laying the pumping system in a horizontal well is absolutely not detrimental to the life of the equipment as long as the application is planned for. New technologies, like tapered compression pumps and more efficient gas separators have been developed in the past five years to address all of these special needs and have been implemented in hundreds of applications. The key issues to avoid are running equipment not designed for horizontal applications. Following these basic key points will assure a successful installation.

In both the vertical and horizontal well, the use of a Variable Speed Drive (VSD) would be the preferred motor controller. The use of a VSD in conjunction with an ESP gives the operator the best of all worlds in well optimization. By varying the frequency and thus the rotational speed of the pump one also varies the rate and head of the pump. This allows an almost infinite control over the pumping system that can lead to optimal production rates that match the inflow of the fluid. It allows the well to be stabilized at optimum gas production without having to pull the well and resizing the pump. In cases where gas interference becomes an issue, the VSD operating in automatic control can speed up and slow down without operator inputs to keep the pump free from gas locking. Operating the VSD in conjunction with an accurate down hole pressure transducer can increase the ease in which a well can be controlled.

3 CBM electric submersible pump

Over the past few years advances in Unconventional Gas specific Electric Submersible Pumps (ESP′s) has addressed many of the problems Unconventional Gas applications present. A standard ESP NPSH required is about 64 psig. With the CBM specific Electric Submersible Pump available today, this NPSH required is now about 16psig, depending upon the pump selected. The addition of CBM specific patented products this NPSH requirement can be cut further as the technology builds artificial internal pressure. Additionally, an ESP can operate in a horizontal CBM well and automatically regulate its speed through a variable speed drive to optimize a wells production and speed up to clear gas interference. ESP technology has been developed that addresses solids handling, low flow conditions and automatic operations. Of all the current lift systems, the specially designed CBM ESP may be the least understood and yet most flexible system available for unconventional gas operations.

In a horizontal or deviated well, the flexibility of the ESP system is able to snake its way into the well and operate successfully. Other lift systems that are run from the surface connected by rotating rods create maintenance problems due to friction wear on tubing or knuckle joints. A CBM ESP can operate from totally horizontal to vertical and all positions in between. New technology has been developed that allows the ESP to operate in these real low NPSH environments, and protect themselves from solids plugging. In these applications an ESP can be designed to operate over a wide range of rates with the same pump.

New technologies have been developed, like tapered compression stages, higher efficient gas separators and VSD algorithms designed to automatically fine tune a well without operator input. The older systems were required to operate within a recommended operating range to avoid excessive wear in up thrust or down thrust. The new CBM-ESP technology eliminates the wear in the extreme low operating range and allows the pump to over produce without up thrust wear.

During the initial well evaluation of drilling a horizontal or deviated well, consideration must be taken keep the bend radius to less than 20 degree per 100 feet. Installing larger casing along with slim line ESP equipment allows easy installation with the appropriate protection devices installed. Communication with the ESP provider in the early stages of development can lead to a much better installation and a successful and economical end result.

4 Conclusions

Experience in the Powder River Basin and in other producing basins has proven that the use of an ESP to dewater unconventional gas wells has made the ESP the lift system of choice. With well over 33 000 ESP′s operating in the PRB a substantial amount has been learned and needs to be shared with the rest of the industry. The lessons that have been learned are simply if the ESP is applied within the parameters of an ESP long run times can be realized. The key points to keep in mind are; use robust products that are designed for unconventional gas applications. Assure that the motor is properly cooled and solids protection systems are used in every case. One thing we have learned for sure is that at some point in the life of the well solids will become an issue. Prepare for and use the available technologies and tactics learned to avoid cavitation and or gas locking. In horizontal wells, following the key points will reduce complications and increase success.

Last but not least is elevate the preplanning of selecting artificial lift for dewatering to the same level of preparation as is done for well drilling and well completions. Evaluating all three at the same time will equate to a more successful operation with the least amount of trouble and by far the least costly application. Eliminating potential problems from the beginning instead of addressing the problems after the fact will drastically reduce the maintenance cost of the well over the life of the well. It is impossible to cover every issue in the confines of these papers however following the basic facts as presented above will elevate the use of ESP's to the level these flexible and durable mechanical systems have proven to be.

Microbially enhanced coalbed methane production in laboratory

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【Abstract】 Microbial methane is a very important unconventional natural gas, and natural gas at least 20% is biogenic origin in worldwide. Which study has important academic significance and practical value. Paper based on the theory of microbial methane generation, the lignite and gangue from Yima mine area, Western Henan province, were investigated in different ratios for their ability to support microbially enhanced coalbed methane production in laboratory. The results show that the organic matters in coal and gangue can be used to produce miciobical methane by microorganisms, and gas production are range from 2. 35 mL/g to 3. 50 mL/g and methane content is range from 66. 56% to 78. 34%, which methane carbon isotope is −6. 54% to −5. 87%. And the results also show that under the miciobes actions, higher coal content in samples have much gases production in amount, but the fixed carbon be used to generate methane is lower; and higher gangue content in samples have fewer gases production in amount, but the fixed carbon be used to generate methane is higher. This recognization provide a scientific foundation for microbially enhanced coalbed methane production.

【Keywords】 coalbed methane; lignite and gangue; miciobial methane; production

1 Introduction

Coalbed methane is a very important unconventional natural gas, which have a good developing prospect. However, the gas content is very low in some coalbearing basin in China, this brought a considerable degree difficulty for its exploration and development, and how to enhance coalbed methane production is essential for coalbed methane development to this kind of coalbed methane geology.

The studies on microbial gas show that organic matters can be used to produce miciobical methane by microorganisms at suitible geological conditions(Schoell, 1980; Woltemate, etc. , 1984; Whiticar, etc. , 1986; Whiticar, 1999). It can effectively improve coalbed methane content in coal seam, and make coalbed methane content to the level of development. From the National 7th to 9th Five-Year Key Technologies R&D Program, diffient types organic matters from different mines were degradated by microorganisms to get the production rate of microbial gas(Li, etc. , 1997; Guan, 1997; Huan & Xiao, 2002). However, the samples were demineralized or only coals in those experiments, and it did not calculate the influences of minerals and/or wall rock of coal seams. In order to preferable simulation the process of microbial gas generation in geological conditions, coal, gangue and groundwater from Yima mine with different ratio were degradated by microorganisms in laboratory.

2 Materials and methods

2.1 Sample preparation

Coal and gangue were collected from II1 coal seam of Yima mine field, Henan province, which fixed carbon and carbon isotopic values listed in Table 1. In order to simulate the process and the environment of coalbed microbial gas production preferably, the water used in the experiments is also collected from II1 coal seam of Yima mine field, Henan province. The inoculation microorganisms is collected from II1 coal seam and were domesticated in labortory. In order to let organic matters in coal and gangue were full degradated by microorganisms, the samples were crushed into 2 mm, sterilized and degassed.

Table 1 **Samples' fixed crabon content and carbon isotope value**

Samples	Fixed carbon/%	Carbon isotopic value/%
coal	51.45	−2.48
gangue	27.62	−2.37

2.2 Experimental procedure

① Preparation the culture mediumm, and cultivate the microorganisms collected from II1 coal seam of Yima mine field, Henan province.

② Proportion of coal and gangue by 2 : 8, 5 : 5 and 8 : 2 ratio, and named with I, II, III, then weight 100 g each sample for experiment.

③ The samples were inoculated for 60 days under constant temperature 35 ℃ and anaerobic conditions. And the pH of solution was measured by pH detector

④ The gas compositions and methane carbon isotope values were determination by HP6890 gas chromatograph (GC) and HP6980/5973 MS (GC / MS).

3 Results and discussion

3.1 Production law and characteristic of the gas

The results show that the lignite and gangue were degradated by microogisms to produce gas with production ranges from 235.4 mL to 349.6 mL (Table 2 & Figure 1). The analytical results of three gases shows the the similarities in compositional features as follows: The content of methane ranges from 66.56% to 78.34%; the content of carbon dioxide ranges from 15.99% to 28.99%; and the contents of heavy-hydrocarbons and nitrogen are very low. From Table 2, we can see that carbon isotopic composition of methane ranges from −65.4‰ to −58.7‰. The features of gases composition and methane carbon isotopic values have microbial gas features.

Table 2 **Gases production from samples degradation**

编号	Gas production/mL	CH_4/%	CO_2/%	Other gases/%	CH_4 carbon value/‰
I	235.4	78.34	15.99	5.67	−58.7
II	286.3	73.76	21.21	5.03	−62.5
III	349.6	66.56	28.99	4.45	−65.4

From Figure 1, we conclude that the amount of gas production by microganisms with coal and gangue change with the time changes, and it has three stages.

First stage, from the beginning to 20 days, the gas production of organic matters degradation by microganisms is very slowness. Thus because that the organic matters are mainly exist in the form of macro-molecular in coal, and the small molecule organic matters, such as acetic acid, CO_2 and H_2, can be degradation directly by microogisms are relatively few, so the gas production is few.

Second stage, from 20 days to 40 days, the gas production of organic matters degradation by microganisms is faster than first stage, and the most of the gas is production in this stage. The macro-

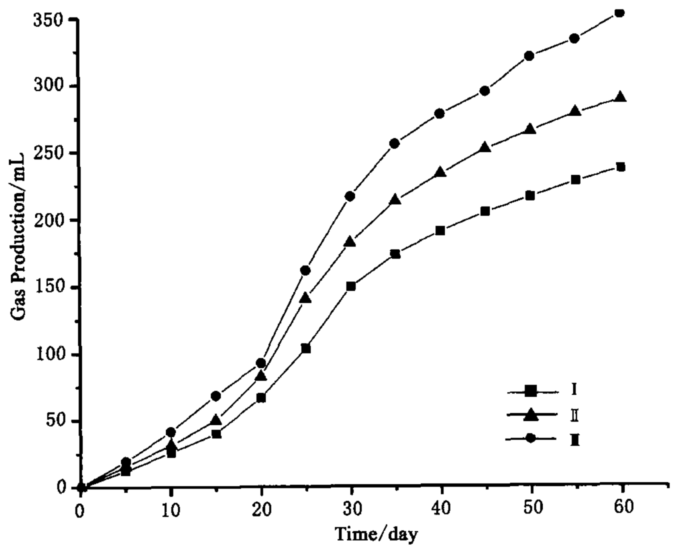

Figure 1 Relationship between gases production and time

organic matters in coal and gangue were degradated into small molecule organic matters, which could be used by methanogens to produce gas. And at the same time, the existence of hydrogen-producing bacteria and metal reduction can provide the necessary hydrogen source for CO_2 reduction to generate microbial methane.

Third stage, from 40 days to 60 days, the gas production of organic matters degradation by microganisms become slow down. And that maybe because that the macro-molecule organic matters, which could be degraded by microganisms, is few in coal, and the small molecule organic matters is exhausted by methanogens.

3.2 The influence of samples

In the simulate experiments, the most of gas production is group III in amount, followed by group II, and less gas production is group I. We conclude that the more carbon content in samples, more gas production. However, the gas production can't be a measure of organic matters uesd by microganisms, that because the ratios of samples are different. At here, based on the data of the simulate experiments, calculated the methane production capacity and carbon dioxide capacity of per gram organic matters (Figure 2). The results show that the gangue content more in samples, the amount of methane production of per gram organic matters degraded by microganisms more; and on the other hand, the amount of carbon dioxide is more. According to the results of previous studies (Dong, etc., 2002; Xu & He, 2003), we consider that those are attributed to the high iron element content present in gangue and low valence metal altered. That is to say, on the one hand, high iron element content present in gangue increased the activity of methanogens on methane production because that iron element is essential for methanogens survive, thus high iron element content in gangue have an active role on microogisms degradation organic matters. And on the other hand, low valence metal alteration to generate a mount of hydrogen, which will be used through CO_2 reduction by methanogens.

In addition, Methane carbon isotopes change in law. It maybe because that a limited number of carbon dioxide, which light carbon isotope of carbon dioxide limited, can be selected to produciton methane by methanogens. And it also maybe result is coincidence because that the data is limited, the further study should be taken.

3.3 pH values

Previous studies show that most methanogens growth in the pH ranges of 5.9 to 8.8 and when the pH is ranges from 6.8 to 7.8, the methanogens activity is strongest (Guo, 2006). In our simulate experiments, the solution inoculated with pH value is 8. 6, and after the experiment the pH value is 7. 9, 8. 1 and 8. 0, respectively. the experimental pH value of the initial solution is not very suitable for the survival of methanogens; and after experiments, the pH is still not suitable for the survival of methanogens, however, it get some improve. Due to lack the data of pH values change with time postpone of methane production, the study did not involve the relationship between changes in pH values and methane production.

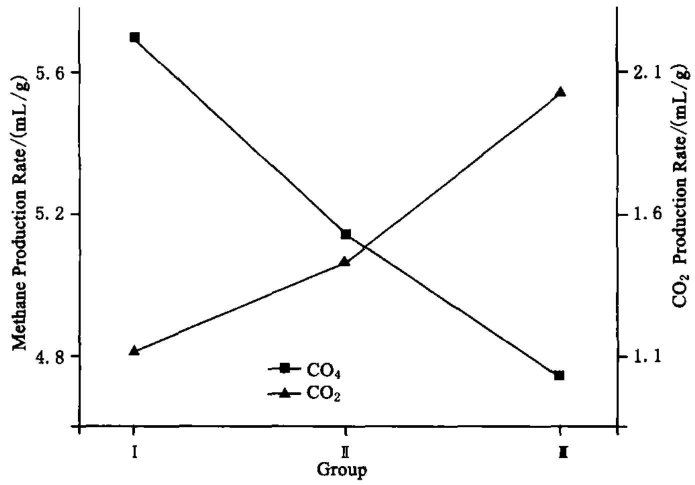

Figure 2 The relationship between fixed carbon and CH_4, CO_2 production rate

4 Conclusion

We can get the following conclusions through the study on methane production during the degradation of coal and gangue with different ratio by microorganisms in laboratory:

① The organic matters in coal and gangue can be degradation by microorganisms to produce microbial gas, and the gas production capacities are range from 235. 4 mL to 349. 6 mL. Methane content is range from 66. 56% to 78. 34%, and its carbon isotopic value is range from −6. 54% to −5. 87%. It has three stages between gas production and time.

② Under the action of microorganisms, organic matters content higher in samples, the gas production more in amount; and minerals content higher in samples, the methane production more in mount per gram organic matters.

③ After the degradation of coal and gangue by microorganisms, the pH value of solution decrease.

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Detecting of coal bed fractures using P-wave data

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【Abstract】 Because coal bed fractures are the main storage space and migration channels, CBM detecting is reasonable transformed into the exploration of coal bed fractures. By introducing a physical modeling results, compared P-wave detecting methods of travel-time anisotropy, interval velocity anisotropy and azimuthal AVO. By that comparison, found the detecting results of above methods affected by structures except the predicting of azimuthal AVO. By set up several numerical models, discussed theoretical responses of azimuthal AVO reflected on coal roof. To a given coal roof, with the crack density increasing the AVO gradient and intercept of special azimuth linear increases and decreases respectively, and with the crack density increasing the gradient differences between special azimuth increases linearly. On the other hand, the AVO gradient of sandstone roof is almost the double of mudstone roof. That is to say, it is theoretic possibility to detect coal bed fractures and its roof's lithology.

【Keywords】 coal bed methane; coal bed fractures; P-wave anisotropy; azimuthal AVO

1 Introduction

For the resource of CBM (Coal Bed Methane), it does not mainly appear with gas phase but adsorption phase[1]. At all CBM resource with adsorption phase, most of them are absorbed in coal bed and its roof/floor fractures. That is to say, the fractures of coal bed and its roof/floor are the main storage space and migration channel of CBM. On the other hand, permeability of CBM resource is the key factor, which determines the success or failure of CBM resources' development; and the permeability of coal seam is principally decided by the connectivity among coal bed fractures. In a way, the detecting of CBM is the exploration of coal bed fractures.

Among all present prospecting methods, 3-D seismic survey has become a main method to resolve the issues of coal bed's fine structures and lithology by its characters of high efficiency and high precision[2]. Regarding 3-D seismic survey, P-wave anisotropic technique is the most efficient method to resolve the fractures of coal reservoir. At present, P-wave anisotropy method includes travel-time anisotropy, interval velocity anisotropy and azimuthal AVO (Amplitude variation with offset)[3].

2 Comparison among detecting methods of strata fractures using P-wave data

Since there are three kinds of P-wave methods mentioned as above could use to detect fractures of interested strata. Which one is the best? In order to analyze this issue, introduces a physical modeling result to make comparison.

Figure 1 is a 3-D physical model built to analyze the validity of different P-wave methods(Shangxu Wang, 2003). In this model, the middle stratum is fractured with vertical cracks and contains an anticline and a fault, its up and blow strata are the same isotropy media. In this model, the fracture density of the middle stratum is a constant. By using wide azimuthal layout to this model, thousands of raw gathers achieved. To all those raw gathers, the forecasted fractures as Figure 2 were obtained after seismic process and anisotropic interpretation. In Figure 2, Figure 2(a) is the predicted result of travel-time anisotropy, Figure 2(b) is the predicted result of interval velocity anisotropy, Figure 2(c) is the predicted result of azimuthal AVO and the solid white line given in this figure is the location of geological section mentioned in Figure 1.

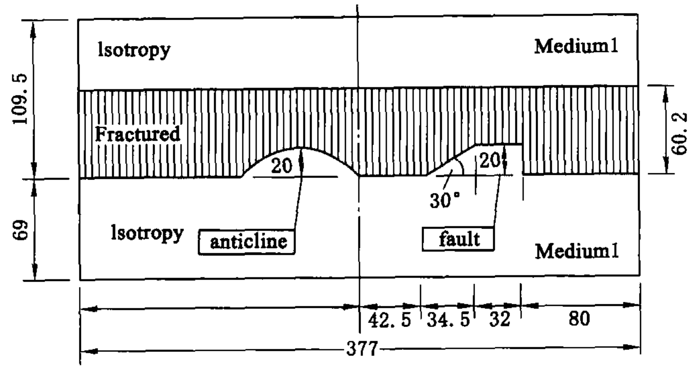


Figure 1 Geological section of a 3-D physical model containing fractured stratum (Shangxu Wang, 2003)

By comparing among the predicted results as Figure 2, it is easy to find the phenomena as below: ① The predicted densities and normal directions of fractures by travel-time anisotropy badly affected by the structures of anticline and fault. ② The predicted densities and normal directions of fractures by interval velocity are affected by the structures of anticline and fault in some limitation. ③ The predicted densities and normal directions of fractures by azimuthal AVO are independent to the structures of anticline and fault. That is to say, the azimuthal AVO technique is the best way to detect coal bed fractures.

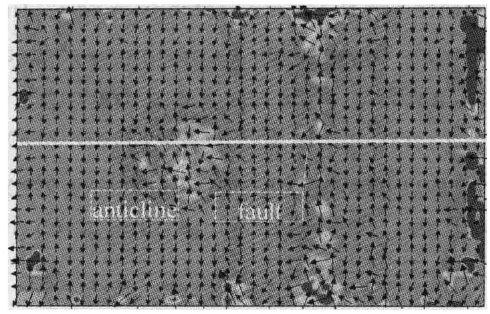
3 Azimuthal AVO characters of coal beds

3.1 Principles of azimuthal AVO

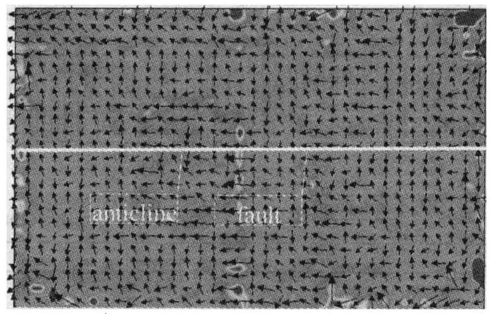
AVO technology uses the principle that the P-wave reflection coefficient varies with incidence angles (or offsets)[2,4-11]. By analyzing the relationship between reflected amplitudes and offsets in pre-stacked seismic gathers, the parameters of rock elasticity estimated. The primary factor that affects the relationship between amplitudes and offsets is the Poisson ratio; a secondary factor is velocity[4]. Therefore, the abnormal AVO response is the Poisson ratio that indicates an anomaly in the strata. When divides any macro bin into several sub-bins according to azimuthal angles and carries out AVO analysis in all azimuthal sub-bins, it is called azimuthal AVO analysis[5,11]. Its sketch map shows as Figure 3. In this figure, the Figure 3(a) is the division of macro bin and the Figure 3(b) is the azimuthal AVO curves corresponding to special sub-bins.

3.2 Models of fractured coal beds

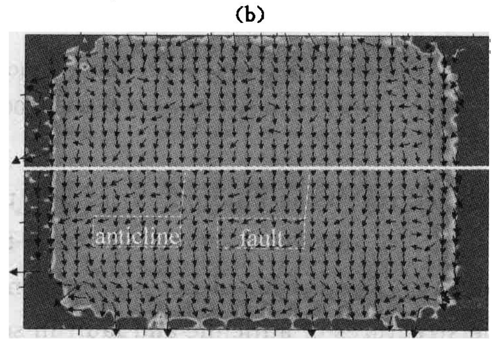
In order to analyze the detecting method of coal bed fractures by azimuthal AVO technique, some models of coal bed containing fractures given as Table 1. In those models, all fractures are vertical aligned and have the same crack density, and their normal directions are along to ox1 axis of cartesian coordinate system. In this Table, the crack density increases along with the increasing of model' s number.



(a)



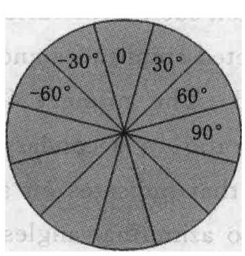
(b)



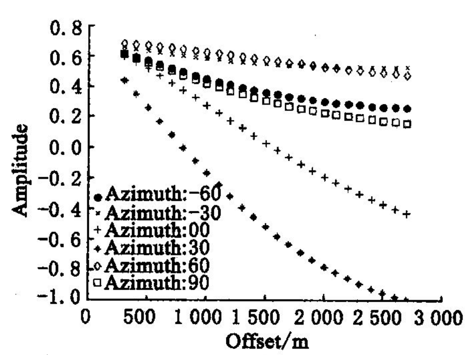
(c)

Figure 2 Predicted fractures of interested stratum by P-wave anisotropy (Shangxu Wang, 2003)

(a) result of travel-time anisotropy; (b) result of interval velocity; (d) result of azimuth AVO



(a)



(b)

Figure 3 Sketch map of azimuthal AVO analysis

(a) six sub-bins of every macro bin; (b) AVO response curves of every sub-bins

Because the reflected amplitude on interested coal bed are not only affected by coal bed elasticity but also controlled by the elasticity contrast between coal bed and its roof. In coalfield, the most possibility roof of coal bed is sandstone or mudstone. Therefore, use sandstone and mudstone as coal roof and their parameters as Table 2 shown.