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Study on a Ranging System Based on Dual Solenoid Assemblies, for Determining the Relative Position of Two Adjacent Wells

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Abstract: The measurement of the relative position of two adjacent wells is one of the key technologies in the directional drilling of twin parallel horizontal wells, and the downhole intersection of two adjacent wells. A new electromagnetic ranging system and a guidance method are introduced for determining the relative position of two adjacent wells. The system mainly consists of two solenoid assemblies, improved surveying instrument for measurement while drilling (MWD), and a computational procedure for guidance. Also, the distribution of the magnetic field of each energized solenoid assembly is discussed, by regarding the solenoid assembly as two independent oscillating magnetic dipoles. Through a case study, it is shown that the accuracy of computation of the ranging, and method of guidance of the system can meet the requirements of implementation in the field. It is shown that the solenoid assemblies should be placed near the target point for the two intersecting wells, or under the improved MWD survey instrument for the twin parallel horizontal wells. During the measurement while drilling, the solenoid assemblies can be motionless, and avoid absorbing too many iron filings. Therefore, the system has a higher precision and less operational time, during the measurement while drilling.

Keywords: Steam-assisted gravity drainage (SAGD), Coal-bed methane exploitation, Electromagnetic guiding, Directional drilling, Measurement while drilling (MWD)

1 Introduction

In order to increase the single well production of an oil and gas field, the precise control of the relative position between two adjacent wells is required from time to time. For example, the separation requirements between twin parallel horizontal

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SAGD wells vary from 4m to 10m, depending on the reservoir characteristics, with tolerances of no more than 2m [Kuckes et al (1996)]. If the wells are placed too close to each other, the steam can short circuit from the injector to the producer. If they are too far apart, the steam cannot heat enough bitumen to allow gravity drainage to occur [Grills (2002)]. In 2008, the technology of twin parallel horizontal SAGD wells was begun to be applied in the Xinjiang heavy oil field [Lin et al (2009); Yang et al (2009)]. Now, the technology is popularized in the Xinjiang heavy oil field. Another example is found in drilling a horizontal well, intersecting with an existing vertical well. The technology of adjacent well intersections is mainly utilized in coal-bed methane (CBM) development [Dong et al (2008); Gong and Duan (2006); Qiao et al (2007); Huang and Jiang (2009); Xian et al (2010)]. Meanwhile the technology of adjacent well intersections is also extended to exploit underground soluble minerals [Hu and Chen (2008); Song et al (2011); Wu et al (1999)]. But, the precise control of the relative position between two adjacent wells is very difficult while drilling, because a traditional survey instrument cannot directly detect the relative position between two adjacent wells.

Some magnetic ranging technologies are currently being researched, and the distance and direction from the well being drilled to a target well can be determined precisely with these technologies. However, each of these technologies possesses various advantages and disadvantages. For example, the Magnetic Guidance Tool (MGT) is the first method proposed for drilling twin parallel horizontal SAGD wells from the surface [Grills (2002)]. The MGT has been utilized to drill over 95% of the twin parallel horizontal SAGD wells in existence [Vandal et al (2004)]. However, the MGT is not adequate for guiding a horizontal well intersecting with an existing vertical well. Another example is the Rotating Magnet Ranging Service (RMRS) system. The RMRS can be utilized to guide a horizontal well to intersect an existing vertical well, and drill twin parallel horizontal SAGD wells. Also, the RMRS and the Single Wire Guidance (SWG) tool can be used to enable an efficient downhole intersection of two wells, for more information, one may consult SPE/IADC 119420 "*Rotating Magnetic Ranging Service and Single Wire Guidance Tool Facilitates in Efficient Downhole Well Connections*". However, acquiring a survey with the RMRS is more complex; the re-surveying procedure with RMRS can require 10-12 minutes; the temperature limitation of the RMRS is 85 degrees Celsius, so the RMRS is not adequate for the re-drills of SAGD well pairs; the magnetic field source of the RMRS will absorb many iron filings in the borehole being drilled, so the accuracy of measurement will be reduced. Of course, the MGT and the RMRS also have other disadvantages.

This paper introduces the Solenoid Assembly Ranging System (SARS), which is a new electromagnetic ranging system. The system can directly detect the relative position of two adjacent wells, and eliminate the accumulated errors in survey, from the both wells.

2 Description and operation of the proposed SARS

The hardware of the proposed SARS includes primarily two parts: a solenoid assembly equipment, and an improved MWD survey instrument, as illustrated in Fig.1. The solenoid assembly equipment includes two solenoid assemblies, each of which includes two column solenoids, each column solenoid is placed in a plane, and the two planes are perpendicular to one another, as shown in Fig.2. For clarity of illustration, each solenoid assembly is shown as being constructed of only four solenoids, as illustrated in Fig.2, but it should be understood that numerous solenoids may be used. The solenoid assembly equipment is placed in a target well, and energized with alternating currents of two different frequencies, in such a way as to produce two rotating, elliptically polarized magnetic fields at the observation point in the borehole being drilled or surveyed. There are two current generators to produce alternating currents of two different frequencies, and each current generator produces two synchronized alternation currents, one for each of the two column solenoids, and these currents are in time quadrature with respect to each other, as illustrated in Fig.3. Preferably, the frequency of the alternating currents should generally lie in the range of 1Hz to 20Hz. The improved survey instrument of MWD includes a three-axis magnetometer, a three-axis inclinometer and a three-axis alternating magnetic field sensor, and it is utilized to sense the geomagnetic field, the gravitational field of the earth and the rotating magnetic fields generated by the solenoid assembly equipment, respectively. The computational procedure of the guidance system is used to process the data measured by the improved MWD survey instrument, and to determine the relative position from a well being drilled to a target well. At the same time, drillers can use the adjacent-well-distance-scanning [Gao and Han (1993)] to scan and plot the distances between the well being drilled and the target well.

3 Magnetic field distribution of the solenoid assembly equipment

The solenoid assembly equipment generates alternating magnetic fields, of two different frequencies, at the observation point. The distributions of the magnetic fields of the two solenoid assemblies are similar. Each energized solenoid assembly can be regarded as two independent oscillating magnetic dipoles m_1 and m_2, because the length of the solenoid assembly is less than 1m, and since we want to measure the magnetic field outside 5m from the magnetic field source. The magnitudes of the magnetic moments (m_1 and m_2) of the two magnetic dipoles can be described

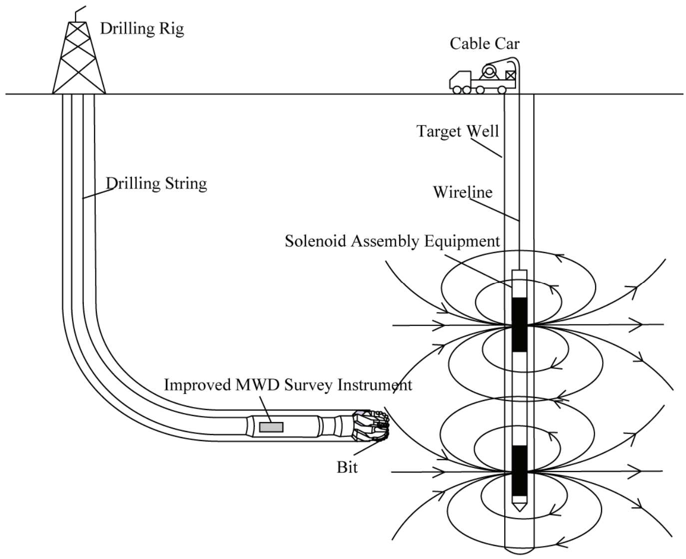

Figure 1: A Schematic diagram of the principle of SARS for a down-hole intersection of two wells

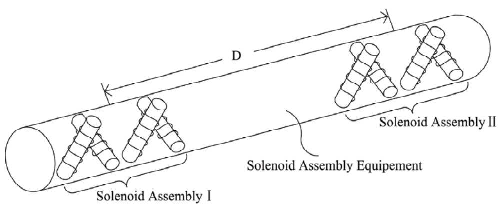

Figure 2: Schematic diagram of the solenoid assembly equipment

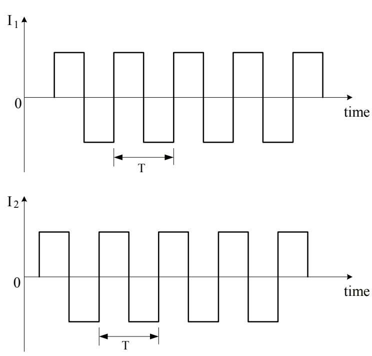

Figure 3: Currents in two orthogonal column-solenoids in each solenoid assembly

by the equations:

$$m_1 = m\sin(\omega t) \tag{1}$$

$$m_2 = m\cos(\omega t) \tag{2}$$

where, m is the maximum value of the magnetic moment of the solenoid assembly; ω is the frequency of the AC current.

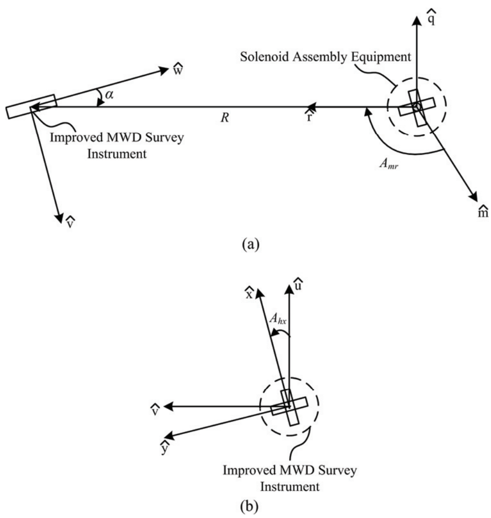

Figure 4: Geometrical relationship between the solenoid assembly equipment and the improved MWD survey instrument

As shown in Fig.4, the z axis is coincident with the along-hole axis of the solenoid assembly equipment, the r axis is coincident with the radius vector from the solenoid assembly to the improved MWD survey instrument, while the q axis is perpendicular to z and r axes. In the Cartesian coordinate system, the magnetic moment of the solenoid assembly can be described by:

$$\mathbf{m} = \hat{r}m\cos(A_{mr}) - \hat{q}m\sin(A_{mr}) \tag{3}$$

$$\mathbf{r} = \hat{r}R + \hat{z}Z \tag{4}$$

where, A_{mr} denotes the angle between the unit vector $\hat{m}$ and the unit vector $\hat{r}$. The magnetic field distribution of a magnetic dipole is described as [Liu et al (2006)]:

$$\mathbf{B} = \frac{\mu}{4\pi}\left(\frac{3(\mathbf{m}\cdot\mathbf{r})\mathbf{r}}{r^5} - \frac{\mathbf{m}}{r^3}\right) \tag{5}$$

Hence, the magnetic field distribution of the magnetic field source can be found from Eqs. (3), (4) and (5) as:

$$B_r = \frac{\mu m}{4\pi}\frac{3R^2 - r^2}{r^5}\cos(A_{mr}) \tag{6}$$

$$B_q = \frac{\mu m}{4\pi}\frac{\sin(A_{mr})}{r^3} \tag{7}$$

$$B_z = \frac{\mu m}{4\pi}\frac{3RZ}{r^5}\cos(A_{mr}) \tag{8}$$

and

$$B_{\min} = \frac{\mu m}{4\pi r^3} \tag{9}$$

where, μ is the magnetic permeability of the formation; B_r, B_q, B_z are the three-axial magnetic induction components in the Cartesian coordinate system; B_{min} is the minimum of the total magnetic induction.

4 Working Principle of the SARS, for down-hole intersection of two wells

As shown in Fig.4, the u axis is coincident with the high side of the well being drilled, the w axis is coincident with the along-hole axis of the well being drilled, while the v axis is perpendicular to u and w axes. The angle α is the supplementary angle of the angle between the w axis and the radius vector $\hat{r}$, the x axis is the axis of sensitivity x magnetometer of the measuring tool; the y axis is the axis of sensitivity y magnetometer of the measuring tool; Noting Fig.4, the magnetic induction component B_w in the w-axis direction and the magnetic induction component B_v in the v-axis direction can be expressed by:

$$B_w = -B_r\cos(\alpha) - B_q\sin(\alpha) \tag{10}$$

$$B_v = -B_r\sin(\alpha) + B_q\cos(\alpha) \tag{11}$$

Inserting Eqs. (6), (7) and (8) into (10) and (11), the following is obtained:

$$B_w = \frac{\mu m}{4\pi r^3}\sqrt{\left(\frac{3R^2 - r^2}{r^2}\right)^2\cos^2(\alpha) + \sin^2(\alpha)}\cos(A_{mr} - P_x) \tag{12}$$

$$B_v = \frac{\mu m}{4\pi r^3}\sqrt{\left(\frac{3R^2 - r^2}{r^2}\right)^2\sin^2(\alpha) + \cos^2(\alpha)}\cos(A_{mr} - P_y) \tag{13}$$

and

$$\cos(P_x) = \frac{-\left(\frac{3R^2-r^2}{r^2}\right)\cos(\alpha)}{\sqrt{\left(\frac{3R^2-r^2}{r^2}\right)^2\cos^2(\alpha)+\sin^2(\alpha)}} \tag{14}$$

$$\sin(P_x) = \frac{-\sin(\alpha)}{\sqrt{\left(\frac{3R^2-r^2}{r^2}\right)^2\cos^2(\alpha)+\sin^2(\alpha)}} \tag{15}$$

$$\cos(P_y) = \frac{-\left(\frac{3R^2-r^2}{r^2}\right)\sin(\alpha)}{\sqrt{\left(\frac{3R^2-r^2}{r^2}\right)^2\sin^2(\alpha)+\cos^2(\alpha)}} \tag{16}$$

$$\sin(P_y) = \frac{\cos(\alpha)}{\sqrt{\left(\frac{3R^2-r^2}{r^2}\right)^2\sin^2(\alpha)+\cos^2(\alpha)}} \tag{17}$$

where P_x and P_y are defined by Eqs. (12) and (13). The cosine of 2α can be obtained from Eqs. (12) and (13):

$$\cos(2\alpha) = \frac{(2R^2-Z^2)^2+(R^2+Z^2)^2}{(2R^2-Z^2)^2-(R^2+Z^2)^2}\,\frac{|B_w|^2-|B_v|^2}{|B_w|^2+|B_v|^2} \tag{18}$$

where $|B_w|$ and $|B_v|$ denote the amplitudes of B_w and B_v. B_w and B_v can be obtained by measuring the three-axial magnetic induction components in the $\hat{x}$, $\hat{y}$ and $\hat{z}$ directions.

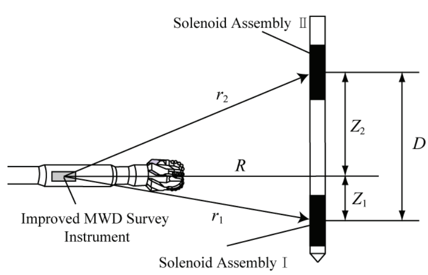

Figure 5: Side view of geometrical relationship between the solenoid assembly equipment and the MWD survey instrument

As shown in Fig.5, the minimum value of the magnetic induction activated by the solenoid assembly I at the improved MWD survey instrument can be expressed by:

$$B_{\min 1} = \frac{\mu m}{4\pi r_1^3} \tag{19}$$

where

$$r_1^2 = R^2 + Z_1^2 \tag{20}$$

The minimum value of the magnetic induction activated by the solenoid assembly II at the improved MWD survey instrument can be expressed by:

$$B_{\min 2} = \frac{\mu m}{4\pi r_2^3} \tag{21}$$

where

$$r_2^2 = R^2 + Z_2^2 \tag{22}$$

and

$$D = Z_1 + Z_2 \tag{23}$$

where, D is the axial distance between the two solenoid assemblies. So, the values of R,Z_1 andZ_2 can be obtained from Eqs. (19) to (23):

$$Z_1 = \frac{D^2 - \lambda + k}{2D} \tag{24}$$

$$Z_2 = \frac{D^2 + \lambda - k}{2D} \tag{25}$$

$$R = \sqrt{k - \left(\frac{D^2 - \lambda + k}{2D}\right)^2} \tag{26}$$

where

$$k = \left(\frac{\mu m}{4\pi B_{\min 1}}\right)^{2/3} \tag{27}$$

$$\lambda = \left(\frac{\mu m}{4\pi B_{\min 2}}\right)^{2/3} \tag{28}$$

If the angles α_1 and α_2 are the supplementary angles of the angle between the w axis and the radius vector $\hat{r}$ at the two ends of solenoid assembly equipment, then, the value of α_1 can be obtained by inserting Eqs. (24), (26) into (18), and the value of α_2 can be obtained by inserting Eqs. (25), (26) into (18). So the angle α can be obtained from the average value between the values of α_1 and α_2.

The fact that the angle α given by Eq. (18) leaves a 180 degree ambiguity in that angle is usually not a problem. Hence, the relative positions of the solenoid assembly equipment, and the improved MWD survey instrument, can be determined by the radial distance R and the angle α. Then, the distance and direction from the well being drilled to the target point can be determined by the radial distance R, the angle α and well survey data (measured depth, inclination and azimuth).

5 Working Principle of the SARS in Two Horizontal SAGD Wells

Fig.6 is a schematic diagram of the SARS as used in drilling a SAGD well pair. As illustrated in Fig.4 and Fig.7, the x axis can be regarded as the w axis, and the angle A_{xr} is regarded as the angle α. So the radial distance R and the angle A_{xr} can be obtained, and the method is similar to the method introduced in the above section. This makes it possible to determine the relative direction of the solenoid assembly equipment with respect to the improved MWD survey instrument. Then the orientation of the magnetometers in space, which is placed in improved MWD survey instrument, is needed. One way to orient the magnetometers is determine the direction of the high side (Hs) of the borehole in which the magnetometers are located, and then to determine the angle A_{hx}, which is the angle between the x axis of the magnetometer and the direction of the vertical projection of the Hs onto the plane of measurement, as shown in Fig.7. Once the angle A_{xr} is determined, as discussed above, thereafter, the relative position between the solenoid assembly equipment and the improved MWD survey instrument can be determined by the radial distance R, the angle A_{xr} and the angle A_{hx}.

6 Example analysis

In the following example, the two solenoid assemblies are separated by a distance D=8m and the magnetic equipment has a magnetic moment of m=400A·m^2. The exciting current of the solenoid assembly I has a frequency of 2Hz, and the exciting current of the solenoid assembly II has a frequency of 4Hz. The radial distance from the solenoid assembly equipment to the improved MWD survey instrument is 20m. It is assumed that the midpoint of the solenoid assembly equipment is origin of coordinates, and the improved MWD survey instrument is located at (q, r, z)=(0m, 20m, 0m). If various quantities are plotted as a function of time, the magnetic field components measured at the improved MWD survey instrument (B_u, B_v and B_w) are shown in Fig. 8.

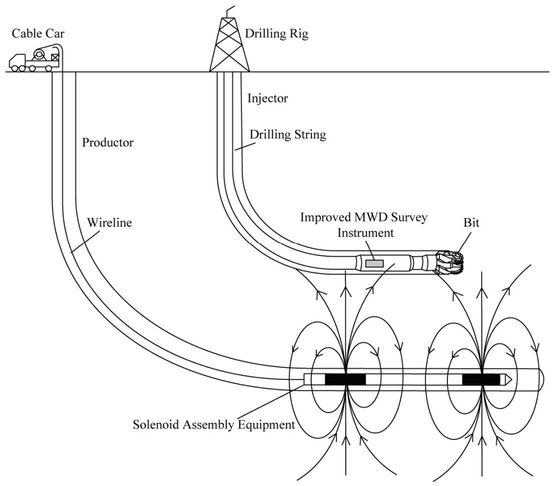

Figure 6: Schematic diagram of SARS working for twin horizontal SAGD wells

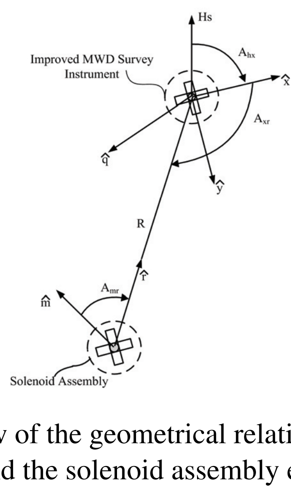

Figure 7: Axonometric view of the geometrical relationship between the improved MWD survey instrument and the solenoid assembly equipment

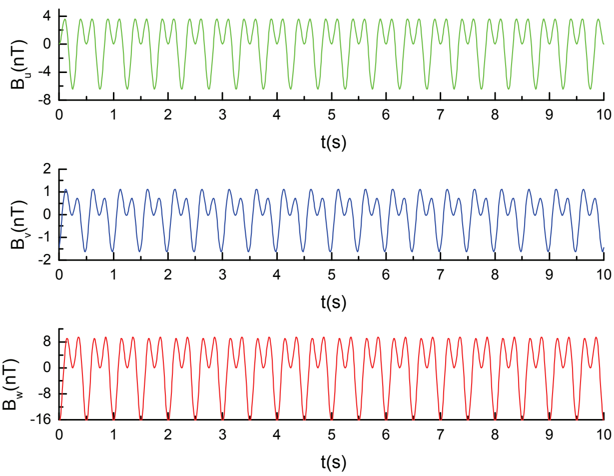

Figure 8: The graph of the magnetic induction components measured

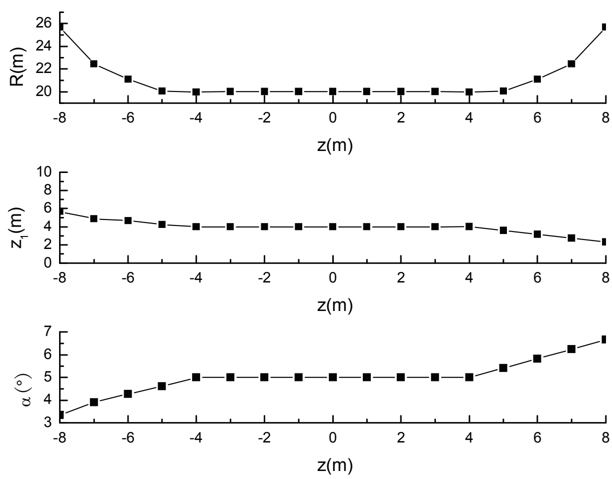

Figure 9: The variation of the calculating R, z_1, and α versus z

In Figure 9, the z-axis position of the improved MWD survey instrument is increased from -8m to 8m while inverting for R, z_1 and α, respectively. As shown in Figure 9, the results are best when –D/2$\leq z \leq$D/2. So the midpoint of the solenoid assembly equipment should be placed near the intersection point, when the system is utilized to guide a horizontal well to intersect a vertical well; and the solenoid assembly equipment should be placed under the improved MWD survey instrument, when the system is utilized to drill twin parallel horizontal SAGD wells.

7 Conclusions

(1) The SARS can be utilized to probe the relative positions of two parallel horizontal wells, as well as to make a downhole intersection between a horizontal well and an existing vertical well.

(2) The midpoint of the solenoid assembly equipment should be placed near the intersection point when the system is utilized to make a downhole intersection between a horizontal well and an existing vertical well. The solenoid assembly equipment should be placed under the improved MWD survey instrument, when the system is utilized to probe the relative positions of twin parallel horizontal SAGD wells.

(3) The magnetic source of SARS is the solenoid assembly equipment, whose magnetic density can be controlled by changing the exciting currents. Thus, the SARS has a wider measurement range.

(4) The SARS has higher precision and less operational time during the measurement while drilling.

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References

Dong, J.H.; Wang, X.G.; Qiao, L.; Shen, R.C.; Wang, K.L. (2008): Application of CBM multi-branch horizontal well for drilling technology in Fanzhuang Block. *Coal Geology & Exploration*, vol. 36, pp. 21-24.

Hu, H.Y.; Chen, Q.S. (2008): RMRS application on target-hitting of horizontal drilling. *Geology and Prospecting*, vol. 44, pp. 89-92.

Huang, Y.; Jiang, J. (2009): Adaptability analysis of U shaped horizontal connected wells in CBM exploitation in Liulin area, Hedong coalfield. *Coal Geology of China*, vol. 21, pp. 32-36.

Gao D.L.; Han Z.D. (1993): Adjacent Well Distance Scanning Calculation and Plotting Mechanism. *Oil Drilling & Production Technology*, vol. 15, pp. 21-29

Gills, T.L. (2002): Magnetic Ranging Technologies for Drilling Steam Assisted Gravity Drainage Well Pairs and Unique Well Geometries – A Comparison of Technologies. Paper No. SPE 79005, *International Thermal Operations and Heavy Oil Symposium*, Calgary, Alberta, November 2002.

Gong, Z.M.; Duan, N.Z. (2006): Technology of drilling mixed with gas for Lan M1-1 coalbed gas multi-branch horizontal well. *Oil Drilling & Production Technology*, vol. 28, pp. 15-18.

Kuckes, A.F.; Hay, R.T.; McMahon, J.; Nerd A.G.; Schilling D.A. (1996): New Electromagnetic Surveying/Ranging Method for Drilling Parallel Horizontal Twin Wells. *SPE Drilling & Conference*, vol. 11, pp. 85-90. Paper No. SPE-27466-PA DOI: 10.2118/ 27466-PA.

Lin, J.; Song, Z.H.; Luo, Y.H.; Liu, L. (2009): SAGD horizontal drilling technology. *Xinjiang Oil & Gas*, vol. 5, pp. 56-60.

Liu, Z.H.; Yan, G.H.; Yu, H.; Jiang, D.G. (2006): The far magnetic field of magnetic dipole. *Physics and Engineering*, vol. 16, pp. 24-25.

Oskarsen R.T.; Wright J.W.; Fitterer D.; Winter D.; Nekut A.; Scheckler J. (2009): Rotating Magnetic Ranging Service and Single Wire Guidance Tool Facilitates in Efficient Downhole Well Connections. Paper No. SPE/IADC 119420, *SPE/IADC Drilling Conference and Exhibition*, Marth 2009.

Qiao, L.; Shen, R.C.; Huang, H.C.; Tang, C.J.; Zhuang, X.Q.; Xian, B.A.; Bao, Q.Y. (2007): A Preliminary Study on Drilling Technique of Wu M1-1CBM Multi-Branched Horizontal Well. *Coal Geology & Exploration*, vol. 35, pp. 34-36.

Song, Q.; Chen, X.; Tang, F.B.; Liu, B. (2011): Application of RMRS Precise Positioning Technology in Rock Salt Ming, *China Well and Rock Salt*, vol. 42, pp. 21-23.

Vandal, B.; Grills, T.; Wilson, G. (2004): A Comprehensive Comparison Between the Magnetic Guidance Tool and the Rotating Magnet Ranging Service. *Petroleum Society's 5th Canadian International Petroleum Conference (55th Annual Technical Meeting)*, Calgary, Alberta, June 2004.

Wu, J.T.; Yang, Y.M.; Zhou, J.K.; Cui, H.X.; Wang, H.X. (1999): Application of Interconnected Horizontal Well Drilling Technology in Mirabilite, *Petroleum Drilling Trchniques*, vol. 27, pp. 7-9.

Xian, B.A.; Xia, B.R.; Zhang, Y.; Bao, Q.Y.; Wang, H.J.; Liu, J.W. (2010): Study on drilling and extraction technologies for U-shape CBM wells. *Oil Drilling & Production Technology*, vol. 32, pp. 92-95.

Yang, R.; Guan, Z.G.; Jiang, G.; Guo, J.J.; Zhai, Y.F. (2009): SAGD parallel horizontal drilling technology in Xinjiang Fengcheng oil field. *China Petroleum Machinery*, vol. 37, pp. 79-82.