

PAPER • OPEN ACCESS

Multi-Stage Fracgun SDP Perforation Technology for Deep Horizontal Wells

To cite this article: Xu Zhao 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **490** 052023

View the [article online](#) for updates and enhancements.



IOP | ebooks™

Bringing you innovative digital publishing with leading voices to create your essential collection of books in STEM research.

Start exploring the **collection** - download the first chapter of every title for free.

Multi-Stage Fracgun SDP Perforation Technology for Deep Horizontal Wells

Xu Zhao^{1,2,*}

¹Sinopec Research Institute of Petroleum Engineering, Beijing, 100101, China;

²State Key Laboratory of Shale Oil and Gas Enrichment Mechanisms and Effective Development, Beijing 100101, China;

*Corresponding author e-mail: zhaoxu.sripe@sinopec.com

Abstract: Multi-stage fracgun SDP perforation technology for deep horizontal wells developed in recent years is to form a plurality of radial hole in reservoir through deep penetrating perforation technology and gas fracturing technology, which could enlarge the drainage area and reduce production pressure drop. This paper analyzes the technical principles, and then proves the mechanism with well and layer selection of tests wells through technical applicability. On the basis of these, Deep Composite Directional perforation design plan of the test well was proposed, and the on-site operation situation was illuminated from the aspect of field test preparation and construction techniques. The testing results showed that both wells site construction had met the requirement of the design and made the yield increasing effect at some certain degree, however, there are also a large production change, it is thought that the key to the successful implementation of deep penetration composite directional perforation in horizontal well is the control of perforation depth and orientation, the application results are determined by well situation and reservoir layer, The design should be based on the technical adaptability of reservoir geological conditions and engineering conditions for a detailed demonstration.

1. Introduction

The multi-stage fracgun SDP perforation technology stems from the high-energy gas fracturing technology that has been invented in the 1980s. After years of development and improvement, currently, this technology has made great progress on fracturing propellant performance, detonation removal mode, directional fracturing and the composite deep penetration design, and it has gradually become one of the important auxiliary means for the secondary completion/stimulation and the deep development of tight reservoirs/shale reservoirs[1-3]. This technology adopts the deep penetration charge to perforate the production casing of the target layer. After the perforating charge is detonated, the broken shell cuts the sheet-like powder at a high speed and ignites the lower propellant column to generate high-energy gas, which realizes a fracturing on the basis of perforation, and forms an ultra-deep fracture system combined with holes and fractures to communicate the reservoir effectively. The whole set of technology uses the high-energy explosion gas to break down the rock and generate a



plurality of radial fractures at different depths and azimuths in the oil layer. The stimulation mechanism relies on the deep penetration of pollution zone and the nearby wellbore interlayer. By forming several radial channels within 2~4m around the wellbore, it is able to expand the drainage area and reduce the production pressure drop[4][5]. This technology will provide a cost-effective way for the development of low-permeability, side/bottom water reservoirs and mature/marginal oilfields.

2. Technical principle

The secondary oil-increasing completion technology based on multi-stage fracgun SDP perforation technology for deep horizontal wells uses two casing strings, and the technical principle is as follows[6][7].

(1) Convey the test tool by conventional tubing or drill pipe to test the condition of production layer and inner wellbore.

(2) Convey the fracgun to the completion section by tubing or drill pipe, measure the depth position with cable transmission magnetic locator and natural gamma depth gauge, and determine the perforation orientation with cable transmission gyroscope survey.

(3) Ground pressurizing method shall be used to detonate the deep penetration charge in the fracgun, and the jet penetration performed by the detonated charge causes channel and detonation shock. Directional Tunnels with the diameter of about 10 ~12mm and the penetrating depth of about 0.8~1.2m are created in the target reservoir.

(4) The explosion of perforating charge will detonate the fracturing propellant in the perforating gun, and ignite the lower propellant column simultaneously. The propellant explosive gas applies 1~3S fracturing work on the formation, so that 3~8 main fractures will be created along the perforation tunnels, which further extends the tunnels 2~4m into the formation, thus penetrating the low permeability zone and interlayer.

(5) Tunnels can be opened in different azimuths at the same depth. Multiple fractures can be generated at different depths in the same azimuth, forming multi-branch radial oil and gas seepage channels. By means of combining perforating and fracturing, it is able to form the hole-fracture combination type ultra-deep fracture system in the nearby wellbore.

(6) In order to achieve the secondary stimulation/completion of old wells and prevent the impact of water breakthrough on the overall production of horizontal well, as for the horizontal wells in the side/bottom water reservoir, after the multi-stage fracgun SDP perforation is finished, the water breakthrough layer shall be blocked by tools such as packer or bridge plug.

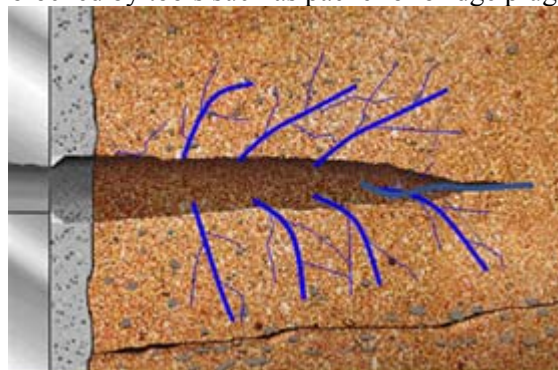


Figure 1. Multi-stage fracgun SDP perforation

3. Selection of candidate wells and layers

The vertical pilot hole of Well TH477H has the oil layer thickness of 11.5m in a composite rhythm reservoir. The thickness of oil layer is 12m and the water avoidance height is 11.3m. The single well control reserves are 9.42×10^4 t, and the accumulated oil production is 1.53×10^4 t. Before the measure, the daily production of liquid was 33.5t, and the daily production of oil was 0.1t; the water cut was high and the oil production was low for a long period, and the recovery degree was low, only 15.6%. The formation below 4835m in the horizontal section of the well is a low permeability argillaceous

interlayer. According to the well logging data, the content of mud shale in this section is relatively high, belonging to the interface between sandstone and interlayer. By combining the analysis of remaining oil numerical simulation in the area and the logging/mud logging data in the previous horizontal well drilling period as well as the electrical logging results, it was confirmed that the remaining oil was enriched in the low-permeability rear part of the horizontal section below the interlayer. The upper part of the horizontal well shall be plugged, and the multi-stage fracgun SDP perforation technology shall be applied in the low-permeability argillaceous interlayer below 4835m, in hope of penetrating the lower interlayer of the horizontal well, improving the seepage capacity of oil layer, enlarging the seepage area, and finally reaching the purpose of production and efficiency increasing.

4. Scheme design

4.1 Overall plan

In view of the tight layer at the toe of horizontal wells, the multi-stage fracgun SDP perforation is designed to penetrate the tight interlayer and communicate the high-permeability reservoir below the tight layer, in order to increase the liquid supply section and oil supply area. The overall plan of this design is:

- (1) Ensure that the interlayer can be penetrated to effectively communicate with the permeable sandstone;
- (2) The combination of hole and fracture can communicate the formation in a large area, and the liquid supply capacity of formation can be exerted to the maximum extent to increase the production capacity;
- (3) By properly controlling the perforating parameters and the explosive load, the depth of fracture can be optimized to achieve the purpose of water breakthrough control;
- (4) Tools such as packer or bridge plug can be used to block the water breakthrough layer.

4.2 Process design

In order to increase the penetration depth and create a wider fracture network around the tunnels simultaneously, the multi-stage fracgun SDP perforation technology for horizontal wells is used to communicate with the oil layer and release new oil reservoirs effectively. The wellbore trajectory indicates that the thickness of argillaceous sandstone interlayer continually thinning; on the premise of the identical bottom water level of the 60m horizontal section, in order to ensure the effective communication of reservoir while penetrating the thick argillaceous sandstone and ensure the consistent height of water breakthrough avoidance in the vertical direction after perforation, the following results are optimized and obtained (as shown in Table 1)[8-10].

Table 1. Perforating parameters of perforation interval

Perforation interval	4870m—4892m	4892m—4913m	4913m-4930m
Hole density	13spm	13spm	13spm
Phase position	Vertically downward	Vertically downward $\pm 15^\circ$	Vertically downward

Since perforating operation has been conducted at the heel of horizontal section, the TCP conveyance mode is adopted, the multi-stage fracgun SDP perforation shall be delay-detonated by pressure perforating in pipe string, and the 60m section (interval of 4870m-4930m) will be perforated at one time.

4.3 Tool parameters

(1) Perforating gun: this well is a horizontal well completed with $\Phi 139.7$ mm casing. The perforating guns with diameter of 89mm, 96mm and 102mm can be used for multi-level composite perforation. The $\Phi 96$ multi-level fracgun has the optimal comprehensive performance, and it can meet the safety and effect requirements of perforation simultaneously, so this perforating gun is adopted in the operation.

(2) Perforating charge: the burial depth of oil layer in Well TK477H is deep, and the formation temperature is 106.87 °C. According to the relationship between the type of perforating charge and the downhole retention time, the maximum retention time of RDX perforating charge exceeds 80 hours at 114.38 °C, indicating that the performance and safety of perforating charge can be guaranteed in less than 80 hours from RIH to detonation. However, after taking the possible operation delaying into consideration, it is recommended to use the HMX perforating charge. By comparing the penetration depth of the commonly used HMX and RDX perforating charges, and combining the cost analysis, the SDP39HMX29-2 high-temperature perforating charge is recommended.

(3) The explosive load of fracturing propellant: the maximum vertical depth of the perforation interval is 4600m, formation fracture pressure is 78.5MPa and formation temperature is 112.77°C. By using multi-level composite perforation optimization software, the explosive load is analyzed in combination with the perforating gun, perforating charge, well data and geological parameters

Table 2. Basic parameters of well TH477H optimization design

Propellant parameters		Wellbore parameters		Rock mechanics parameters	
Order of staged ignition	2	Well depth	4600m	Rock elastic modulus	95.6Gpa
Propellant quality	3.4kg	Wellbore radius	107.25mm	Rock Poisson's ratio	0.25
Propellant column density	1600Kg/m ³	Casing radius	69.85mm	Permeability	0.1
Impetus	976KJ/Kg	Casing wall thickness	10.54mm	Reservoir thickness	11.5m
Propellant explosion temperature	2600K	Casing steel grade	P110	Effective top surface depth	4601.5m
Propellant volume	1.645L/Kg	Casing Poisson's ratio	0.3	Porosity	1.7-5.7
Specific heat capacity of combustion gas	1010J/(kg.K)	Maximum yield strength	965Mpa	Argillaceous rock content	28.4-49.9
Perforation depth	1107mm	Minimum yield strength	758Mpa	Formation pressure	49.17MPa
Tunnel diameter	11.1mm	horizontal well length	200m	Reservoir temperature	112.77
Perforation interval thickness	60m			Reservoir thickness	11.5m

The optimization results of explosive load: internal charge load is 390g/m and external charge load is 4.7Kg, the length of main fracture is 4.75m, fracture width is 3.5mm, peak pressure is 119MPa, and the fracture expansion pressure is 85MPa.

Table 3. The optimization results of explosive load

	4870m—4892m	4892m—4913m	4913m-4930m
Hole density	13spm	13spm	13spm
Internal charge load E3	5970g	5550g	4590g
External charge load E5	10200g	10200g	10200g
Total charge load	16.17Kg	15.75Kg	14.79Kg

4.4 Pipe string design

Delay-detonation by pressure perforating is adopted to conduct the perforation at interval of 4870m—4930m with a single trip. The structure of integral perforating string is as follows:

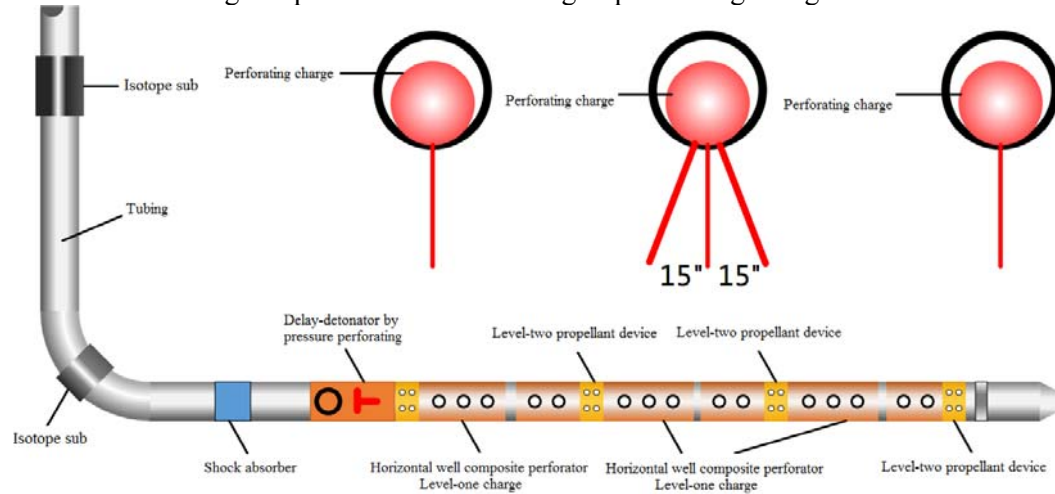


Figure 2. Schematic diagram of perforating string

4.5 Water plugging completion technical scheme

In view of the water breakthrough in the high-permeability heel of this well and the invalid chemical water plugging in the early stage, the hydraulic isolation packer + retrievable hanger are used to carry out water plugging at the heel and reduce the comprehensive water cut. The effective length of packer is 140mm (the axial distance of the original perforated wellbore is 62.5mm), which can effectively block the tunnels. After the well is drifted and the scraped, the tool can be RIH smoothly.

7" retrievable suspension packer+2⁷/₈" chamfering tubing+5¹/₂" hydraulic isolation packer+2⁷/₈" chamfering tubing+ pressurizing plug+ punched pipe+2⁷/₈" chamfering tubing +blind plug are used to conduct water plugging, and 3¹/₂" drill pipe is used to convey the water plugging string; the setting depth of isolation packer is 4850m-4859m, after the water plugging is finished, RIH the pump to the production interval of 4870m-4930m.

5. Field test

5.1 Test preparation

The preparation of field test is shown as follows:

(1) Oil well preparation

- ① Relocation, installation and commissioning of workover unit;
- ② Prepare 1.14g/cm³±killing fluid 240 m³± as required to meet the needs of well killing;
- ③ Perform inspection and maintenance to well control equipment, and all well control facilities must meet the requirements of oil and gas well control specifications;
- ④ The workover team cleans up the well site to ensure the smooth implementation of well completion;
- ⑤ Prepare a blowout prevention single (with anti-blowout plug valve) corresponding to the pipe string and anti-blowout sub;
- ⑥ Prepare the elevator and lifting ring corresponding to the pipe string;
- ⑦ Prepare the H₂S detection device and personal protection device as required.

(2) Preparation of operation tools

- ① Prepare the sucker rod elevator, small lifting ring, a set of Φ44mm tubular pump, a joint of Φ28mm polished rod and other auxiliary tools;

② By using the existing pumping unit and machine pumping wellhead, the integral pressure test shall be conducted according to the rated pressure: high pressure 34.5MPa for 30min, pressure drop shall be less than 0.5MPa; low pressure 2MPa for 30min, the pressure drop shall be less than 0.5MPa;

③ Relevant equipment shall be prepared while putting this well into production, such as machine pumping wellhead, sucker rod string, spiral gas sand anchor, oil well pump, pumping unit, sucker rod BOP, manual double ram BOP and polished rod sealer, etc.

④ Coordinate all the parties for the field operation.

(3) The preparation of perforating tools

The on-site personnel shall be familiar with the well conditions and pipe string. The downhole tools for perforating and water plugging shall be inspected in advance to verify the specifications and models of tools. The relevant tools shall be delivered in advance to ensure the smooth operation.

5.2 The process of field operation

(1) POOH the original production string, and conduct sand flushing, well washing, pipe scraping, and well drifting.

(2) Using GR+CCL combination instrument to measure the short casing in the wellbore, once the logging depth is 60m larger than the designed depth of bottom boundary by perforation and depth calibration sub, POOH the logging tool string.

(3) Inspect the pipe string. According to the requirements on pipe string matching, the composite perforating string shall be RIH to the designed depth by Ø73 mm tubing. The structure of composite perforating string is: guider + Ø96 mm composite perforating string (including centralizer) + Ø96 mm × 73 mm crossover + directional sub + depth calibration sub + Ø73 mm tubing.

(4) Measure the azimuth of perforation with CCL+GR depth calibration gamma and perforation calibration sub, and rotate the tubing to adjust the azimuth until the designed azimuth is reached.

(5) Pressurize the string and detonate, connect the pressurizing pipeline, and close wellhead valve. Pressurize the tubing string, if pump pressure decline is observed while pressurizing the string, it means the detonator has been activated. Open the casing valve and observe the conditions of wellhead to determine whether it is detonated.

(6) Once the perforation is finished, pull the perforating gun out of the horizontal section immediately to observe the casing pressure for more than 5 hours to avoid the occurrence of casing deformation and sand filling.

(7) POOH the pipe string. When the wellbore is stable, pick up the string and record the pressure value while POOH. When the perforating gun is in the horizontal section, the tripping speed shall be 15 joints/hour. When the perforating gun is in the vertical section, the tripping speed shall be 40 joints/hour. During POOH, attention shall be paid to the liquid surface; if overflow is observed, kill the well timely.

(8) RIH the water plugging completion string: RIH the water plugging completion string in sequence, the tubing and drill pipe used in the hole shall be drifted and inspected carefully, no unqualified tubing and drill pipe shall be used; the structure of pipe string (from bottom to top) is: blind plug +27/8" EUE tubing (9m±)+27/8" punched pipe (2m)+pressurizing plug+27/8"EUE tubing (9m±)+51/2" hydraulic isolation packer +27/8" EUE tubing (604m±)+7" retrievable suspension packer +31/2" drill pipe (4250m±);

(9) Once RIH the string to the designed setting position, drop the ball, land the ball on seat and set the suspension packer. After the operation is finished, the sealing and suspension of packer shall be checked and the ball seat shall be blown off. Then the string is disconnected, and POOH the landing string.

(10) RIH production string, conduct well completion and production.

5.3 Implementation effect

5.3.1 Process evaluation

The operation was successfully carried out according to the operation steps, and the multi-level composite deep penetration completion string and the water plugging string was successfully

completed right the first time. By comparing the test results and design parameters, in combination with the inspection and record of perforating detonation, perforating gun punched, orienting and detonating, it is found that the azimuth error of each radial tunnel is controlled within $\pm 3^\circ$, the detonation rate is $> 95\%$, and both the level-one and level-two propellants took a fully combustion without obvious propellant residue; from the perspective of process, the test well has reached the scheme design requirements of multi-stage fracgun SDP perforation, and the compliance rate is 100%.

5.3.2 Analysis of test results

After the multi-level composite perforation and water plugging operation in Well TK477H was finished, the daily liquid production decreased from 33.4t/d (before the measure) to 7.8t/d; the daily oil production increased from 0.4t/d (before the measure) to 7.2 t/d; the comprehensive water cut decreased from 99.1% (before the measure) to 7.7%, decreased by more than 90%; in addition, the well has maintained a low water cut production after the measure, and the cumulative production increase is up to more than 5000t. Through the comparison on the liquid and oil production pre/post the measure, it is found that the field test of multi-stage fracgun SDP perforation has been conducted successfully, and the effect of water control and oil increase was realized to some extent, but this well also experienced a significant liquid production decline. The analysis suggested that this technology has the following characteristics and limitations:

(1) The multi-stage fracgun SDP perforation technology can play a role in communicating reservoirs, increasing oil drainage area, and improving oil well production, which realize the secondary production of remaining oil in old wells to a certain extent;

(2) During the operation, the optimal design on the technical influence factors such as perforating charge, perforating gun structure, explosive load, combustion mode and the form of explosive fracturing should be strengthened to increase the perforation fracturing depth, thus maintaining the stabilization of perforation tunnels and ensuring the wellbore integrity and operation safety;

(3) Whether the multi-stage fracgun SDP perforation technology can penetrate the interlayer and open a new oil flow communication channel is the key to the successful application of this technology in the secondary completion/stimulation, and the thickness of interlayer in horizontal well and the accurate positioning of such interlayer determine the application effect of this technology to a certain extent;

(4) There was a significant change on the liquid production before and after this measure, indicating the fact of production layer shifting in horizontal well. The high water cut section in original production layer was completely sealed by the packer, the production capacity of oil well after the measure is basically supplied by the horizontal section perforated by the multi-stage fracgun SDP perforation technology, and the water plugging performance for horizontal wells also has a significant impact on the implementation of this technology;

(5) Compared with the conventional mechanical water shutoff operation, this technology has the characteristics of simple operation, safety and reliability, and it is suitable for producing the remaining oil by means of the secondary completion in deep wells and ultra-deep wells;

6. Conclusions and recommendations

(1) The multi-stage fracgun SDP perforation technology for deep horizontal wells provides a cost-effective way for the recovery of remaining oil in old oilfields, and has an extensive application prospect.

(2) The successful implementation of multi-stage fracgun SDP perforation for deep horizontal wells relies on the effective control on the depth and azimuth of perforation fracturing, and the application effect depends on the proper selection of wells and layers. The design should be discussed in details based on technical adaptability from the aspects of reservoir geological and engineering conditions.

(3) During the operation, the optimal design on the technical influence factors such as the perforating charge, perforating gun structure, explosive load, combustion mode and the form of explosive fracturing should be strengthened to increase the perforation fracturing depth, thus

maintaining the stabilization of perforation tunnels and ensuring the wellbore integrity and operation safety;

(4) It is recommended to carry out the R&D of deep penetration multi-level composite directional perforation technology for large tunnels and supporting tools/equipments to increase the formation communication capability of multi-level composite perforation, thus fundamentally solving the problem of limited penetration depth in multi-level composite perforating operation.

References

- [1] Yuan Jinping, Qi Fengzhong. Status Quo And Research Direction Of Well Completion Technology In China[J]. Drilling & Production Technology, 2007, 30(03): 03-06.
- [2] Diao Gangtian, liu Zhihua, Etc. The Application of Compound Perforation Technology [J]. Drilling & Production Technology, 2003, 26(6): 39-42.
- [3] Xiong Youming, Liu Liming, Zhang Lin, et al. Present Status and Development Comments on Horizontal Well Completion Techniques in China[J], Petroleum Drilling Techniques, 2012, 40(01): 02-06.
- [4] Li Hai-tao, Luo Wei, Jiang Yu-sheng, Etc. Initiation and extension of gas-driven fracture during compound perforation[J]. Explosion and Shock Waves, 2014, (03): 307-314.
- [5] Li Dongchuan, Jin Chengfu, Liu Quanmin, Etc. Status And Trend of Compound Perforation Test Technology[J]. Well Logging Technology, 2011, (02): 164-166.
- [6] Zhao Xu, Ding Shidong, Zhou Shiming, Etc. Experimental Study On Gas Movement Mechanism In Wellbore After Compound Perforation [J]. Well Logging Technology, 2011, (02): 167-170.
- [7] Li Keming. High Power, Multiplex Perforation Techniques and Its Prospect[J]. Petroleum Drilling Techniques, 2002, 30(3): 72-74.
- [8] CHEN Dong-bo; XU Gang; SU Peng; LI Wei-liang; Application of Composite Perforating Technique in Tahe Oilfield[J]. Journal of Yangtze University(Natural Science Edition), 2014, (14): 50-52.
- [9] Wang Haidong, Sun Xinbo. A Summary of Perforating Technology Development inside and outside of China[J]. Explosive Materials, 2005, 35(3): 33-36.
- [10] ZHAO Xu1 LIU Gonghui 1,2 ZHANG Tao, Movement mechanism of control fluid in propellant perforation under the action of downhole high-pressure gas[J]. Acta Petrolei Sinica, 2009, 31(02): 295-300.