

Application and Results of the New Generation of Plug and Perf Completions in the Changqing Area

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Abstract

With the development of domestic shale oil and gas development technology and the increasing difficulty of actual shale oil and gas well construction, in order to meet the perforation needs of unconventional oil and gas horizontal wells in China, such as uniform reservoir transformation, cluster perforation within the section, and efficient and safe construction, the bridge perforation joint process is improved and upgraded. At present, the proportion of domestic oil and gas horizontal wells is gradually increasing due to factors such as depth, wellbore temperature, wellbore pressure, and wellbore inclination. In order to overcome the problems and difficulties encountered in construction, achieve increased production and efficiency, further improve perforation performance, and enhance perforation operation efficiency, cluster perforation has become an obstacle that must be overcome in the development of shale gas horizontal wells. From a practical perspective, we have upgraded the process of bridge plug perforation joint construction from hardware to software and achieved certain results.

Keywords

Perforating Performance; Horizontal Well; Multi-Cluster Perforating; Updip Well; Modular Gun; Plug and Perf Completions.

1. Background of Plug and Perf Completions in the Changqing Region

With the development of shale oil and gas in the southern Changqing area in recent years, the difficulty of oil and gas horizontal well sub-cluster perforating construction has increased, and the workload of oil and gas horizontal well sub-cluster perforating construction has increased, and the 2.0 process in sub-cluster perforating has achieved a lot of results though. However, the actual construction difficulty of construction pressure, well slope, casing deformation, well temperature and other problems are becoming more and more acute, from the improvement of efficiency, high cost, construction difficulty, optimisation of the design software backward four aspects of the whole process process upgrading and optimization.

Focusing on the disposal of complex well conditions in horizontal wells, the company has developed a small OD ultra-deep penetrating cluster perforator to achieve perforating of cased wells and reduce the loss of perforating sections in casing changes of horizontal wells, developed a horizontal orientation detection and selection instrument to achieve perforating of fibre-optic outside the casing, and perfected Plug and completions upward tilting well construction technology, continuous tubing and crawler perforating technology to satisfy the first section of perforating, which reduces a large amount of costs; and popularized the application of the plug and completions type blowout preventer,

quick-loading bridge plug sitting sealing tool, modular cluster perforating gun and other quick-loading related equipment on the site, which reduces the time and number of personnel for perforating work and improves the work efficiency. The company popularly used plug-in blowout preventers, quick-loading bridge plug seating tools, modular perforating guns and other quick-loading equipment to reduce perforating operation time and the number of personnel, and improve operation efficiency; and developed software modules for automatic segmentation of shale gas horizontal wells into clusters and optimization of perforating parameters in clusters, and set up a perforating data centre that integrates data from multiple sources such as geology of horizontal wells, logging, perforators, fracturing and microseismic data, laying a foundation for analysis and assessment of perforating effects. It lays the foundation for analysing and evaluating the drilling effect. The integration of pumping operations further improves production efficiency and oil and gas output.

By upgrading the intra-segment cluster perforating process and equal aperture perforating equipment to meet the current domestic demand for Plug and perf completions. In terms of software, it strengthens the combination of perforating and geology, carries out rock targeting tests simulating the real formation environment, optimises the design of perforating based on the results of petrophysical experiments, researches a set of integrated perforating geo-engineering technology, introduces perforating big data and deep learning, and realises ‘one well, one strategy’, ‘one perforating for one cluster’, tailor-made perforating construction plans for horizontal wells in different blocks and reservoirs, and enhance the effectiveness of perforating operations.

2. Research and Application Results

2.1 Optimising Processes and Procedures to Increase Production and Efficiency

In order to achieve the goal of efficiency and speed up, optimisation and improvement are carried out in each step of the whole process of Plug and perf completions construction. The whole process mainly consists of the following six parts: ① disassembling and assembling the wellhead, ② disassembling and assembling the tool string, ③ lowering the straight section, ④ pumping the horizontal section, ⑤ multi-cluster firing, and ⑥ lifting up the tubing string. There are problems of complicated assembly and long time-consumption of cluster perforating tools in the ground operation process; problems of low time-consumption of manually changing the wellhead in the wellhead operation process; and problems of slow speed of straight well section up and down and slow speed of horizontal section pumping after perforator string entering the well. The above problems are solved by developing new equipment and improving the process system.

(1) Quick change process and plug-in wellheads

Plug-in quick wellhead device: The 140MPa plug-in quick wellhead device has been developed, featuring remote control of wellhead attachment and detachment, keeping away from high-altitude and high-pressure operation risks, and preventing pressurised/accidental disassembly of wellheads. It can reduce the changeover time of wellhead blowout prevention device to less than 30min, which meets the field construction requirements of fast switching between fracturing and perforating operations and maximising the efficiency of factory construction.

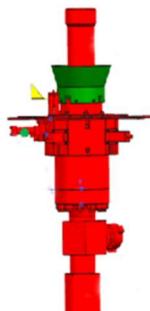


Fig. 1. Plug-in wellhead unit

The final result is the formation of 70/105/140MPa plug-in quick wellhead device, which realises the automated changeover of perforating wellheads, reduces the changeover time from 60min to 25min, and reduces the perforating personnel from 11 to 7, and ensures the rapid connection between fracturing and perforating of platform wells.



Fig. 2. Plug-in perforating wellhead unit applications



Fig. 3. On-site process flow

Optimisation of the process: The non-inverted blowout preventer changeover tool string process replaces the manual disassembly and installation of wellheads, inverted blowout preventers and manual dragging and pulling of tool strings, and realises automation, mechanisation and high efficiency in the changeover of wellheads and tool strings.

In comparison with the old process of lifting the blowout preventer and then manually installing it by the operator, it saves the time of repeated lifting, lifting and lowering of the blowout preventer, installation and dismantling at the wellhead, and reduces the time of manual work, as well as the risk of pressurisation of the operator working at the wellhead when the blowout preventer is connected to the perforator.

(2) Modular perforators and disposable quick-fit plug seating tools

Ground perforator assembly process, due to the old wire-type perforator there are many joints, wire multi-wrap complex, perforator assembly process is cumbersome, high complexity personnel assembly is prone to error, as well as too many joints parts and components caused by the perforator string is too long problem.

The development of modular perforating gun, no wire modular sub-cluster perforating gun, the development of the first set of wireless modular sub-cluster perforator, to solve the traditional connecting type sub-cluster perforating gun assembly time-consuming, high failure rate, perforating clusters of fewer but longer problems, the highest completion of the bridge plug - perforating joint work 16 clusters, reducing human assembly errors, saving assembly time-consuming 60%.

Formed a series of modular cluster perforators, with the number of types increased from 1 to 9, the ignition success rate increased from 97.13% to 99.95%, the perforating capacity of a single trip downhole broken through from 20 clusters to 100 clusters, and the maximum temperature resistance of 210°C and pressure resistance of 175MPa, which ensures the demand for reliable perforating of sub-clusters in the section of casing wells from 3-1/2" to 5-1/2".

Optimising the intra-segment cluster perforating process to ensure close cut fracturing, shortening the intra-segment cluster spacing from 15m to 4m and the inter-segment reform blind section from 25m to 6m, reducing the intra-segment reform blind section, optimising the distance between clusters, and reducing the intra-segment reform blind section, to support the implementation of the close cut and flow restriction fracturing reform in horizontal wells such as shale gas wells and to increase the rate of resource utilisation by more than 60%.

The same Baker bridge plug seating tool due to its many parts, assembly requires two people and each construction cleaning and maintenance work will take at least half an hour. Moreover, in the process of assembling the bridge plug tool, it is also easy to assemble wrongly, which leads to perforating gun string encountering stuck engineering accidents.

We have developed a compact, quick-assembling bridge plug tool that does not require oil injection and pressure relief, which solves the problems of large connection length and high risk of manual pressure relief of traditional bridge plug tools, reduces assembly time and connection length by more than 60%, and has a maximum pressure resistance of 175MPa, which ensures the reliable perforation of horizontal wells in the south of Sichuan Province in segments and in clusters.

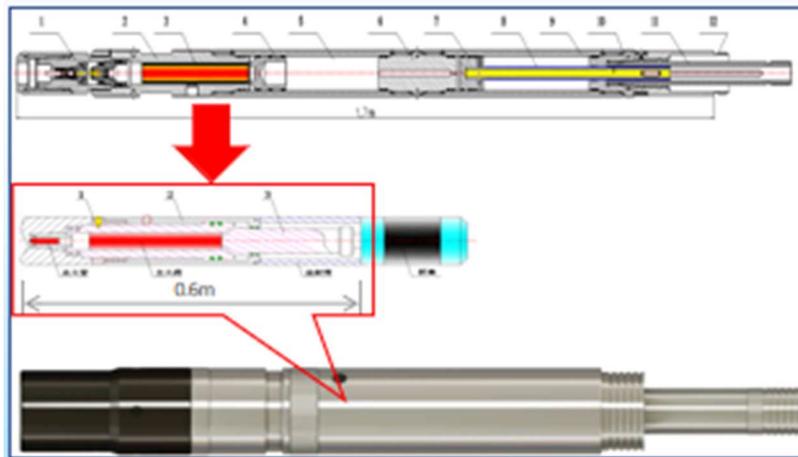


Fig. 4. Comparison of 20 gauge conventional (top) and speed loaded (bottom) seating tools

(3) Improvement of equal perforators to support uniform mobilisation of different reservoirs

Developing a perforator with equal aperture to reduce the friction of perforating holes and improve the strength of sanding.

The development of equal aperture perforator solves the problem of inconsistency of perforating holes due to the gap of gun sleeve of conventional perforator, which leads to large friction of perforating holes, uneven fracturing fluid feed, and is not conducive to the improvement of fracturing displacement and sanding strength.

The average hole diameter of 89-type perforator is $\Phi 11.7\text{mm}$, and the standard deviation of hole diameter is 4.96%, which is 23.16% and 15.46% higher than that of 89-type deep perforating perforator, respectively.

Development of directional and fixed-face perforators: adopting a special replenishment method, inducing fracturing cracks to be generated in the stress concentration zone of the perforating holes, which can control the fracture expansion along the radial direction of the wellbore. The directional cluster perforator adopts gravity internal directional bullet deployment to induce fracturing cracks to extend towards the target reservoir through directional perforating in the well section where the trajectory of the borehole deviates from the high-quality reservoir, so as to target the fracturing modification of the reservoir.

To ensure the demand for perforating in 4-1/2" and 5" small boreholes in Changqing and Xinjiang regions and Chuannan suite of variable wells, the company has newly researched and developed 73-type and 80-type small OD perforators, and the types of perforators have been upgraded from one to four, with the deviation of perforation controlled within 6%, which can strongly guarantee the uniform utilisation of different reservoirs.

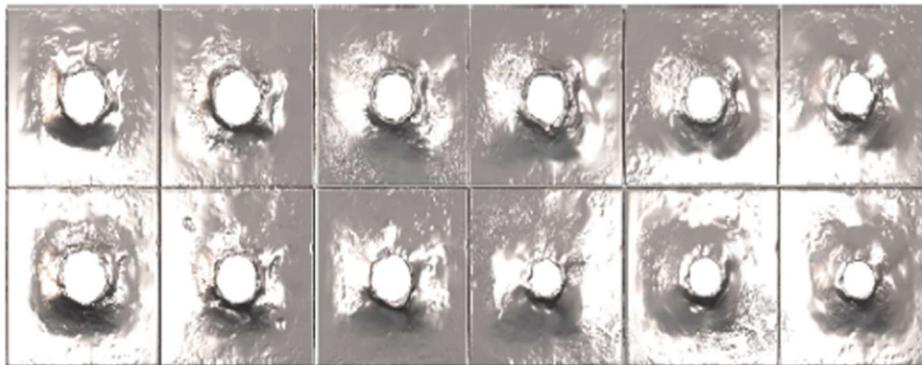


Fig. 5. Comparison of Conventional (Top) and Equal Bore (Bottom) Perforating Eyelets

2.2 Software Development and Applications

Aiming at the lack of understanding of the mechanical behaviour characteristics of the cluster perforating string and the lack of scientific basis for starting and lowering control, the company has constructed a multi-scenario perforating string mechanics model for rapid starting and lowering of the straight well section, high-efficiency pumping of the horizontal section, and static starting of the upturned well section, laying a solid foundation for the development of high-efficiency and safe starting and lowering of the perforating string and the development of the perforating software.

Developed China's first integrated software platform for pumping operations, which integrates pumping displacement design, passability analysis and 'visualisation' support, and realised the transformation from empirical to informative and refined operation of the whole wellbore delivery and all processes of the perforating string in clusters, with the design accuracy of $\geq 95\%$ and the analytical error of $< 8\%$, which has continuously lowered the complexity rate of the pumping accidents by more than 30%.

The specific split-cluster perforating string structure consists of several tools of different lengths and different outer and inner diameters, which makes the pass-through calculations too cumbersome, and therefore, some simplification of the specific string structure must be made. The part of the string with the same outer diameter is regarded as a section of beam, and the whole cluster perforating string is connected by several sections of beams with different outer diameters, as shown in Fig.6.

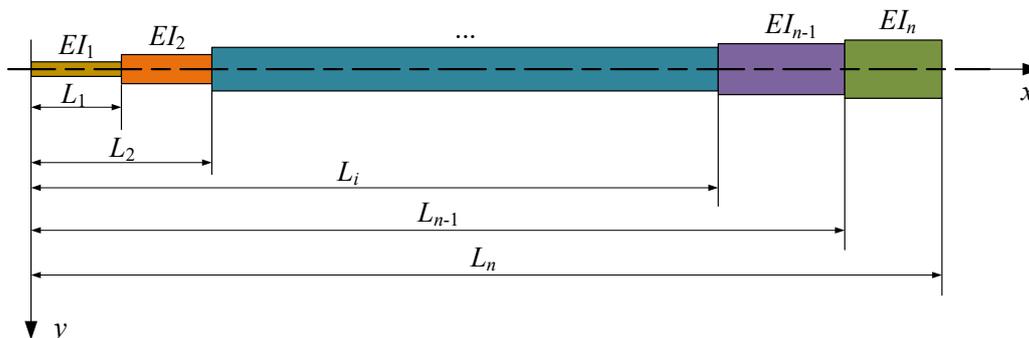


Fig.6. Schematic diagram of the structure of a cluster perforating tube string

In the process of lowering by its own gravity, the pipe string is lifted by the cable and lowered at a relatively stable speed, at this time, the pipe string is subject to the net weight, cable tension, well wall friction and fluid resistance, the pipe string is equivalent to the axial tension and the distribution of loads by the role of the variable cross-section of the simply-supported beam, as shown in Fig.7.

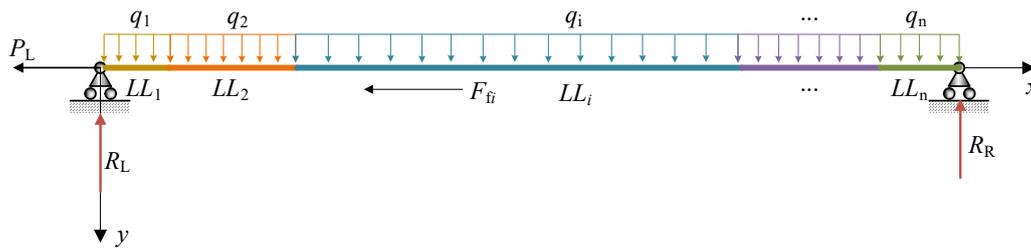


Fig.7. Schematic diagram of the force analysis of cable-conveyed sub-cluster perforating pipe strings

$$\begin{cases} F_p = WL \cos \alpha \\ F_n = WL \sin \alpha \\ F_f = WL \sin \alpha \cdot u_1 + \frac{1}{2} C_d \rho_m v_r^2 A \\ F_d = W'L' \sin \alpha \cdot u_2 \\ F_b = WL \sin \alpha \cdot u_1 - WL \cos \alpha + W'L' \sin \alpha \cdot u_2 \end{cases} \quad (1)$$

Where: W, W' is the weight per unit length of the tubing string and cable in the well fluid, N/m; L' is the length of the cable in the inclined and horizontal sections, m; C_d is the coefficient of fluid resistance; v_r is the relative velocity between the tubing string and the well fluid, m/s; ρ_m is the density of the well fluid, kg/m³; and A is the maximum cross-sectional area of the tubing string, m². Compared with the cluster pumping software 1.0, 2.0 solves the problems of unknown downhole perforator status and low interaction of construction information during the construction process, and focuses on solving the needs of increasing the number of clusters in a single section of perforating, more complex trajectories of borehole penetration, and difficult engineering conditions, and adds the functions of infinite level of positioning and tracking of perforators, real-time simulation of pumping simulation displacement, and real-time analysis of pumping force, which effectively enhance the data visualisation degree of cluster perforating, make horizontal well pumping and drilling operations safer, more reliable and more efficient, and improve the safety, reliability and efficiency of horizontal well pumping and drilling operations. This function effectively improves the degree of data visualisation of cluster perforating construction and makes horizontal well pumping and perforating operations safer, more reliable and more efficient.

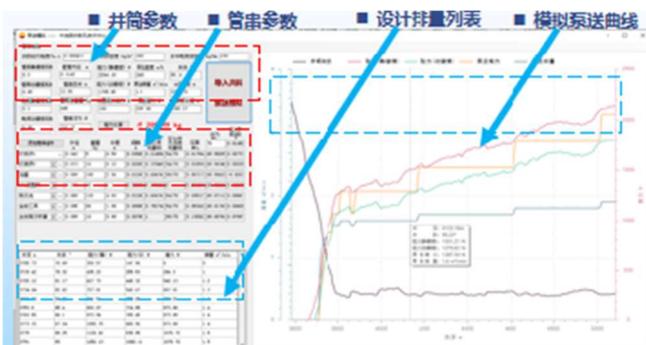


Fig. 8. Pumping Displacement Design Software Module



Fig. 9. 'Visual' pumping support software module

2.3 Software Development and Applications

The software module of automatic segmented cluster and cluster perforating parameter optimisation design for shale gas horizontal wells was developed, and a perforating big data centre integrating multi-source data of horizontal well geology, logging, perforating, fracturing and microseismic was built, which lays the foundation of analysis and evaluation of perforating effect.

The perforating geo-engineering integration technology combines engineering desserts and geological desserts, using artificial intelligence algorithms, optimising the calculation of the test layer, segmented clustering, two artificial intelligence perforating effect evaluation algorithms, GCNN+LSTM and SR-CNN, and neural network model learning for segmented clustering methods, so as to form a segmented clustering method assisting the personnel in the segmented clustering of horizontal wells.

It forms a closed-loop perforating software platform with perforating field operation assistance software as the data source, perforating optimisation design software as the optimisation core, and perforating data analysis software as the analysis centre, and initially realises the ‘trinity’ function of perforating geo-engineering analysis, calculation, and decision-making, which fills the gaps in this field in China.

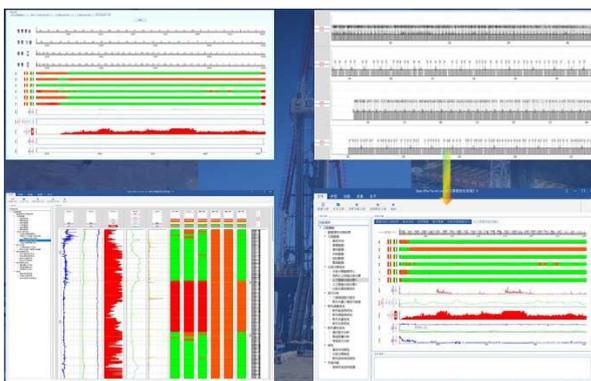


Fig. 10. Horizontal Well Segmented Cluster Optimisation Design Interface



Fig. 11. A big data centre for perforating that fuses data from multiple sources

3. Conclusion and Recommendations

(1) The combination of most perforating parameters with geological desserts and fracturing parameters is not strong, cluster perforating involves a wide range of regions, and the perforating geological and engineering conditions of major unconventional oil and gas blocks such as Daqing, Changqing, Xinjiang, and Southwest China are very different, and at present, although the preliminary construction of an integrated software platform for perforating and geological engineering has been carried out, it has not yet been formed to ‘customise’ a complete set of solutions combining specific reservoir conditions and fracturing parameters. ‘Cluster perforating programme’ has yet to be formed in conjunction with specific reservoir conditions and fracturing parameters.

(2) Obtaining perforating performance curves under different temperature and pressure conditions to further improve the isopore perforating technology, and suggesting to increase the popularisation and application in unconventional oil and gas blocks such as Daqing, Changqing and Xinjiang. Meanwhile, using the international advanced high-temperature and high-pressure perforating test device (200°C/200MPa) and charge explosion impact test system, the company will carry out perforating tests under different well temperatures and pressures, obtain the performance curves of iso-hole diameter perforating under different temperatures and pressures, and further optimise the structure to improve the perforating performance.

(3) R&D of special perforators and supporting technologies to ensure efficient perforating of complex wells in clusters and safe and efficient fracturing, relying on the perforating ‘whole industry chain’ technology integrating ‘perforating technology research and development, perforator manufacturing, perforating optimisation design and perforating construction service’. Focusing on new perforating challenges such as fibre-optic tubing and reconstructed horizontal wells, the company will research and develop special cluster perforators and ancillary construction technologies, so as to ensure the demand for efficient perforating in clusters and safe and efficient fracturing of complex horizontal wells.

(4) Deepen the research on integrated perforating geo-engineering technology and ‘tailor-made’ perforating solutions for oil and gas reservoirs. Strengthen the combination of perforating and geology, carry out rock targeting tests under simulated real formation environment, and optimise the design of perforating on the basis of the results of petrophysical experiments. Introducing perforating big data and deep learning to realise ‘one strategy for one well’ and ‘one shot for one cluster’, providing ‘customised’ perforating solutions for different blocks and reservoirs. ‘perforating solutions for different blocks and reservoirs.

(5) Plug and perf completions 2.0 is a combination of ‘software and hardware’, which improves and upgrades the Plug and perf completions process from software to hardware and equipment, and upgrades and improves the Plug and perf completions process with scientific theories and scientific methods.

(6) High efficiency, low cost and environmental friendliness are the fundamental requirements for the development of shale gas perforating technology. Innovative operation modes, research and development of new technology, upgrading tools and equipment, and enriching the means of handling engineering complexities are all necessary to achieve the quality, speed and efficiency of shale gas perforating operations.

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