Study on Optimization of the Geometric Structure for Powder Liner in Shaped Charge

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Abstract. To obtain a shaped charge with greater penetration and better serve the perforating operation of oil and gas Wells, a geometric structure optimization method based on finite element simulation is proposed in this paper. Firstly, ANSYS/LS-DYNA was used to conduct a dynamic simulation of the process of shaped charge penetrating sandstone, and the influence of the geometry of the powder liner on the perforation depth was systematically analyzed. The geometric structure of the powder liner was optimized using the response surface method and multi-objective genetic algorithm combined with the actual process requirements. Finally, the numerical simulation of the perforation process is carried out based on the optimized geometry of the powder liner, and the simulation results are compared with those before optimization. The results show that the optimized perforation depth can be increased by 14.53% compared with that before optimization, indicating that the optimized perforation geometry can achieve better perforation depth.

Keywords: Perforation Numerical Simulation; Response Surface Method; Multiobjective Genetic Algorithm.

1. Introduction

Well-completion is the last important link before oil and gas exploitation, which plays a key "front foot" role. The quality of well completion directly determines the productivity and life of oil and gas Wells. At present, perforation completion technology is widely used in oil and gas fields at home and abroad [1], that is, a high-speed metal jet generated by a shaped charge in the detonation process is used to shoot through casing, cement ring, and formation rock in a very short time to establish oil and gas channel between reservoir and wellbore. Among them, the charge cover is the heart of the shaped charge and the core component forms a metal jet to complete the perforating operation, which has a decisive impact on the perforating effect [2].

With the turbulent international situation and increased national energy demand, oil and gas development has gradually expanded to deep-ultra-deep buried hill oil and gas fields and offshore oil and gas fields. Due to various factors such as high pressure and tight reservoirs in the wellbore, conventional perforating charges can not release oil and gas reservoirs as effectively as the medium and shallow reservoirs. Many oil and gas Wells have difficulties producing fluid after perforating, or even no fluid production, and it is difficult to determine whether the mud contamination zone is penetrated. Due to the very short operation time of the perforating process and the generation of high temperature and high pressure, the data collected by existing experimental observation methods are often scattered, and it is difficult to describe the whole physical process of perforating bullets in hard rock[3]. Therefore, it is challenging, expensive, and long to optimize the design of perforating charge based on experiment. The method of numerical simulation can effectively avoid such problems.

Therefore, this paper presents a method to optimize the geometry of the drug cover by combining numerical simulation, multi-objective optimization, and technological requirements. To improve the reliability and simplicity of the optimized perforating charge structure, it can better serve the related work of hard rock perforating.

2. Numerical Simulation of Perforation in the Downhole Environment

2.1 Numerical Calculation Model

Fig 1 (a) shows the complete downhole perforation model, with enlarged details in the black box line. The wellbore is filled with perforating fluid (represented by water in numerical simulations) and the cavity in the perforating gun is filled with air. The model is a 1/2 axisymmetric model, which is composed of a shell case, explosive, powder type cover, gun holster, water layer, casing, cement ring, hard rock target, and air. The shaped charge used in the simulation is the newly developed SDP-46 charge, and the geometric model of the charge cover is shown in Fig. 3. The air domain covers the entire model (blue dotted box section).

The arbitrary Lagrange-Euler algorithm (ALE) is used in numerical simulation [4], which combines the advantages of the Lagrangian algorithm and the Euler algorithm to calculate explosion shock problems faster and more accurately. However, it is worth noting that it is necessary to ensure that the explosive, powder type cover, air, and water layer adopts the Euler grid and common nodes. However, considering that the HJC constitutive model is used for hard rocks, the target is evenly divided into grids [5]. The model takes into account the downhole environment, so it is not only necessary to set axisymmetric calculation commands and flow-out boundary conditions for the Lagrange unit and the Euler unit respectively, but also to apply pressure to the water layer and the target to simulate wellbore pressures and confining pressures. The rock confining pressure is 30 MPa and the wellbore pressure is 25 MPa, the same as the actual underground environment. The confining pressure and wellbore pressure are added by applying them to the node.

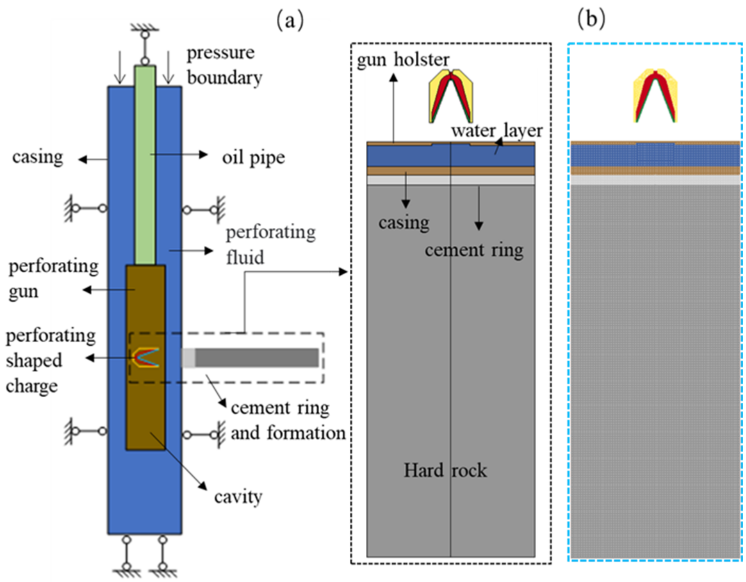

Fig 1. Numerical calculation model of perforation in the downhole environment: (a) Overall and local schematic diagram; (b) Finite element model

2.2 Material Model and Parameters

The model is mainly composed of a shell case, explosive, powder liner, gun holster, water layer, casing, cement ring, sandstone target, and air. These material models and parameters have been applied in the relevant perforation simulation field, so this section briefly introduces them. The steel target, shell, holster, and casing were $45^{\#}$ steel with a density of 7.83 g/cm^3, yield limit of 425 MPa, elastic modulus of 2.1×105 MPa, and Poisson's ratio of 0.3. Plasticv_Kinematic material model was adopted to characterize the steel target. The explosive type is RDX, with a density of 1.72 g/cm^3 and a detonation speed of 7980 m/s. It is described by the high explosive material model High_Explosive and JWL equation of state. Johnson-Cook (J-C) constitutive model and Grunensin equation of state are generally used to describe the mechanical behavior of the powder liner in the process of jet molding. The powder liner material used in this paper is a new type of powder with a density of 14.96

g /cm^3. The water layer and air domain are described by the Null material model and Grunensin equation of state. The cement ring and sandstone target are described by the HJC model, which well considers the accumulation of compressive damage, and also describes the strain rate effect, compressive strength, and confining pressure effect of the material, which can better reflect the dynamic damage of the material under large deformation and high strain rate.

2.3 Numerical Simulation Result

Based on the above model and parameters, the numerical simulation of the downhole environment through a sandstone target is carried out, and the results are shown in Fig 2. As can be seen from the Figure, the simulated perforation depth is 32.14 cm, and the perforation aperture is 1.13 cm. It can be seen that the perforation effect of this type of perforation charge in sandstone is good, and the perforation depth and aperture are close to the actual perforation results. Therefore, the results obtained by the simulation of downhole environment perforation based on this model and parameters are more reliable. Then, we can optimize the geometry design of the powder liner through the numerical simulation of the sandstone-penetrating target in the underground environment.

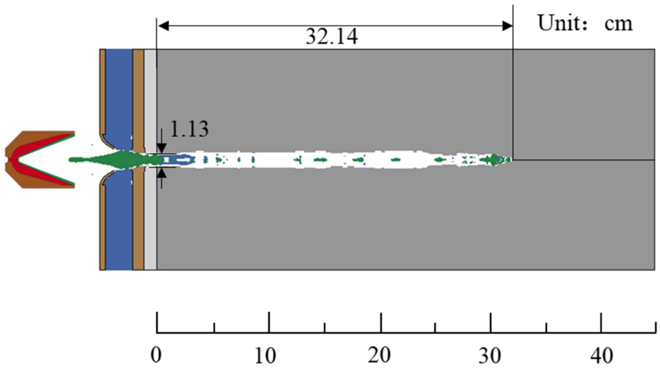

Fig 2. Numerical simulation results of sandstone target in the downhole environment

3. Geometrical Structure Optimization of Powder Liner

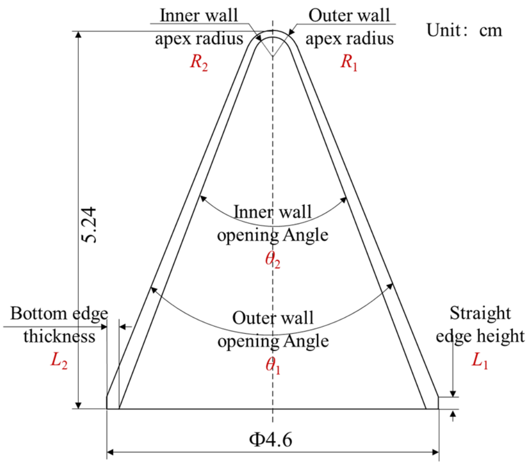

Fig 3. Geometric model and size of powder liner

There is a certain correlation between the geometrical parameters of the powder liner and the perforating results. The geometric parameters of the powder liner include caliber, height, opening Angle, top cone Angle radius, etc. The change of these geometric parameters will affect the explosive explosion and jet energy distribution, thus affecting the perforation depth and perforation aperture. The geometric model of the powder liner is shown in Fig 3. There are six parameters that can be changed under the condition that the height and caliber of the powder liner remain unchanged, four of which are key parameters that are independent of each other. They are respectively the outer wall apex radius R_1, inner wall apex radius R_2, outer wall opening Angle θ_1, and inner wall opening Angle θ_2. Process range: outer wall top Angle radius 0.35 cm ~ 0.5 cm, inner wall top Angle radius 0.25 cm ~ 0.4 cm, outer wall opening Angle 40°~ 45°, inner wall opening Angle 40°~ 43°. In the initial state, they are 0.4 cm,0.3 cm,45°, and 43° respectively.

3.1 Numerical Calculation Model

Based on the above model and parameters, the values of parameters R_1, R_2,θ_1, and θ_2 are changed to simulate the perforation depth of the perforation projectile penetrating the sandstone target under different parameter values. Then find out several parameters that have the greatest impact on the perforation effect, and then carry out targeted optimization. To avoid local contingencies in the results, the four parameters were extended appropriately based on the allowable range of the process.

Fig. 4 shows the law of the influence of perforation depth on the geometrical parameters of the cartridge casing. It can be seen from the Figure that with the increase of parameters R_1 and θ_1, the perforation depth decreases significantly. With the increase of parameter R_2, the perforation depth increases first and then decreases, and the overall change range is also large. However, with the increase of θ_2, the perforation depth changes smoothly, and there is no obvious trend of increasing or decreasing. According to the research in this section, the following conclusions can be drawn: the outer wall opening Angle θ_1, the outer wall apex Angle radius R_1, and the inner wall apex Angle radius R_2 have more significant effects on the perforation depth. Therefore, to improve the optimization efficiency, the influence of the inner wall opening Angle θ_2 is no longer considered during the optimization process, and it is fixed at the initial state of 43°.

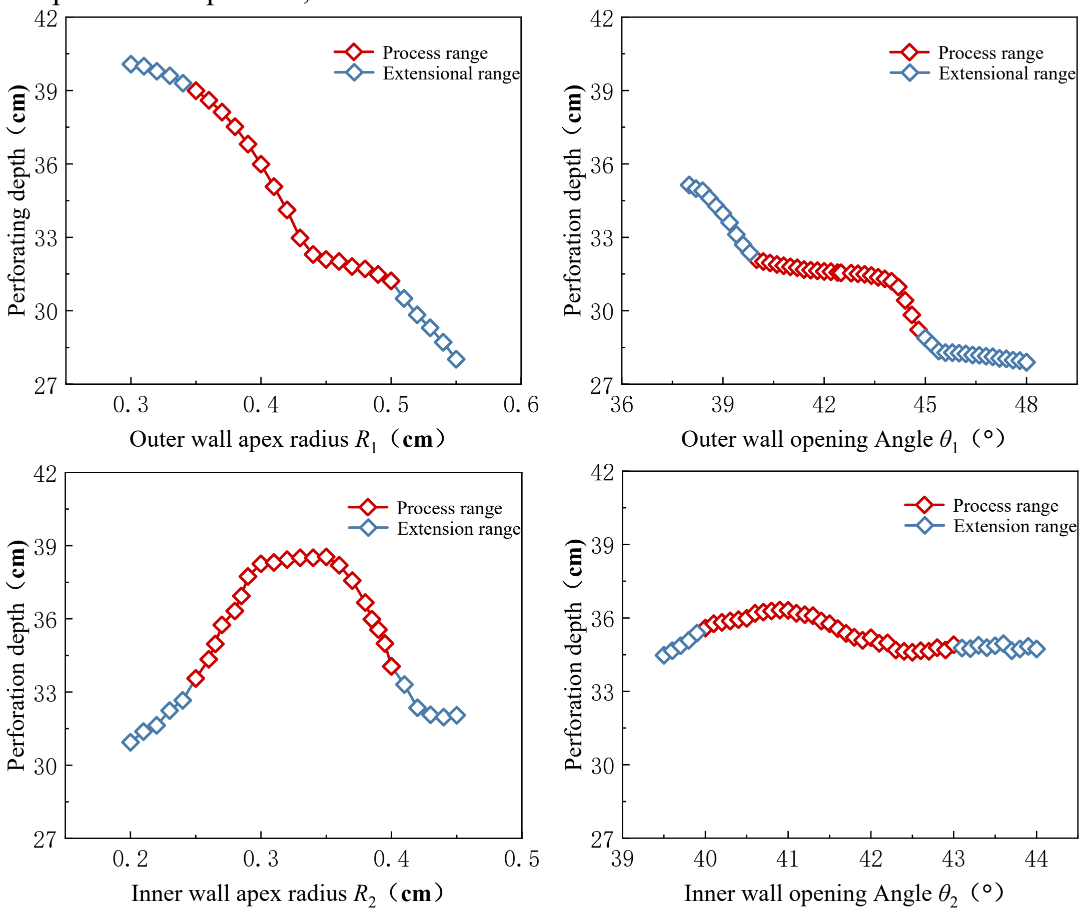

Fig 4. Influence of the geometry size of the powder liner on the perforation depth

3.2 Multi-objective Optimization

Based on the results of sensitivity analysis of the geometric parameters of the powder liner in the above section, the parameters R_1 (set as *a*), R_2 (set as *b*), and θ_1 (set as *c*) of the inner wall top Angle were taken as the inversion design variables, and the perforation depth L and perforation aperture D were taken as the inversion target variables. On this basis, the fitting surface of the target variables (L, D) and the design variables (a, b, c) can be obtained by using the central composite design to simulate the combination of different parameters [6]. Taking b and c as examples, Fig. 5 shows the fitting surface of perforation depth and perforation aperture under the interaction of two parameters. It can be seen from the Figure that the response surface fits these data points well, and the local fluctuation of the surface is small, which can provide a reliable fitting surface for the subsequent extraction of display expressions.

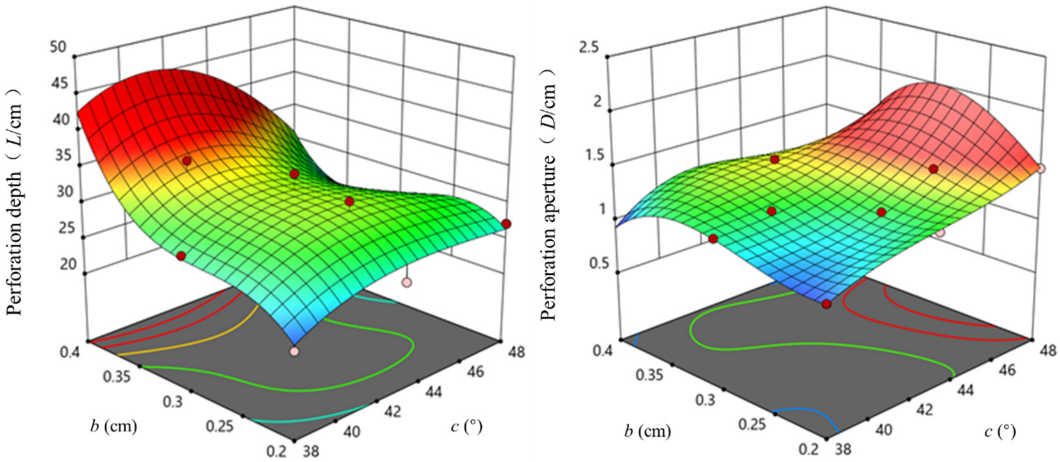

Fig 5. Fitting surface of perforation depth and perforation aperture under parameters b and c

Based on the fitting surface, the explicit expression of the target variable about the design variable is further obtained, as shown in equations (1) and (2). The highest order term in the formula has reached 4 times, which indicates that the simultaneous change of the three parameters of the drug type mask has required a huge amount of computation, and it is the optimal number of decision variables that can be achieved under the existing computing power. Meanwhile, the multiple determination coefficients of the explicit expressions of the objective function (equations (1) and (2)) are $R^2_L = 0.9802$ and $R^2_D = 0.9974$, respectively, both of which are very close to 1. This means that the fitted explicit expression can reasonably characterize the relationship between the objective function and the three powder liner shape parameters.

$$\begin{aligned}
L=\,&46.42-4.307\times10^{-3}a+28.06b-20.86c-0.0869ab+0.0388ac+33.88bc-4.18\times10^{-4}a^2\\
&-80.95b^2+31.83c^2+0.0187abc-8.58\times10^{-4}a^2b+1.317\times10^{-3}a^2c-0.0557ab^2\\
&+0.0778ac^2+90.68b^2c-84.6bc^2-2.18\times10^{-6}a^3-31.05b^3+10.78c^3\\
&+1.216\times10^{-3}a^2b^2+6.31\times10^{-4}a^2bc+1.831\times10^{-3}a^2c^2-0.0578ab^2c-0.0764abc^2\\
&-78.42b^2c^2+1.766\times10^{-5}a^3b-134.51b^3c+80.24b^4-47.02c^4
\end{aligned} \tag{1}$$

$$\begin{aligned}
D=\,&1.39-7.711\times10^{-3}a-4.08b+4.72c-0.023ab+0.0126ac-4.71bc-1.79\times10^{-4}a^2+9.01b^2\\
&-6.94c^2+0.0313abc-3.13\times10^{-6}a^2b+2\times10^{-4}a^2c-9.24\times10^{-4}ab^2-0.0307ac^2\\
&-8.97b^2c+11.83bc^2-6.203\times10^{-7}a^3+4.01b^3-9.53c^3+7.278\times10^{-5}a^2bc\\
&+2.06\times10^{-4}a^2c^2-1.094\times10^{-3}ab^2c+0.0313abc^2-9.04b^2c^2+2.25\times10^{-6}a^3b\\
&-4.21\times10^{-6}a^3c+17.23b^3c+1.57\times10^{-6}a^4-8.94b^4+2.04c^4
\end{aligned} \tag{2}$$

3.3 Optimization Results and Evaluation

A multi-objective optimization algorithm program is written in Matlab based on explicit expression to obtain Pareto optimal solution distribution [7]. Fig 6 shows the distribution of Pareto solutions for target variables, and each Pareto solution corresponds to a set of powder liner structures. Pareto solutions do not consider the actual process means, so not all Pareto solutions meet the requirements. Depending on the range of parameters allowed by the process, the Pareto solution that meets the requirements is replaced with a red circle. When the perforation depth is selected as the main measurement standard, the optimal solution is marked in green, and its corresponding outer wall opening Angle is 44.3°, outer wall top Angle radius is 0.3837 cm, and inner wall top Angle radius is 0.2813 cm. Other parameters corresponding to the optimal solution are inner wall opening Angle of 43°, diameter of 4.6 cm, bottom edge thickness of 0.15 cm, and straight edge height of 0.174 cm.

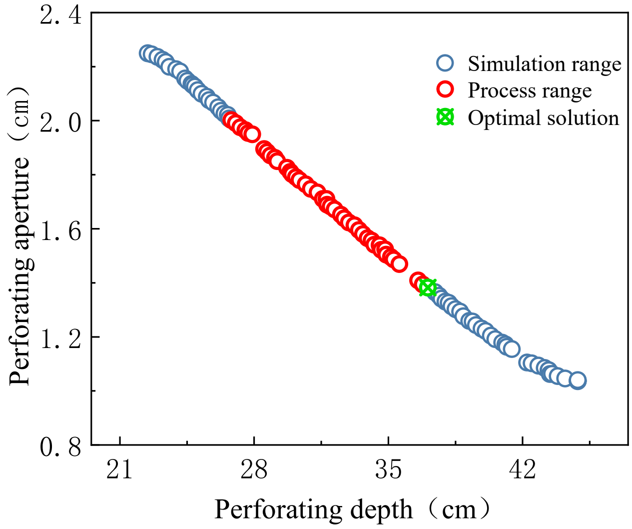

Fig 6. Pareto solution distribution of target variables

The geometric parameters of the optimized liner were re-modeled, and the target perforation simulation of sandstone in the downhole environment was re-performed according to the above method. The results are shown in Fig. 7 (a). Based on the optimized geometry parameters of the powder liner, the perforation depth is 36.81 cm, which is 14.53% higher than the 32.14 cm before the optimization. This shows that the optimization effect of the geometric parameters of the powder liner is remarkable.

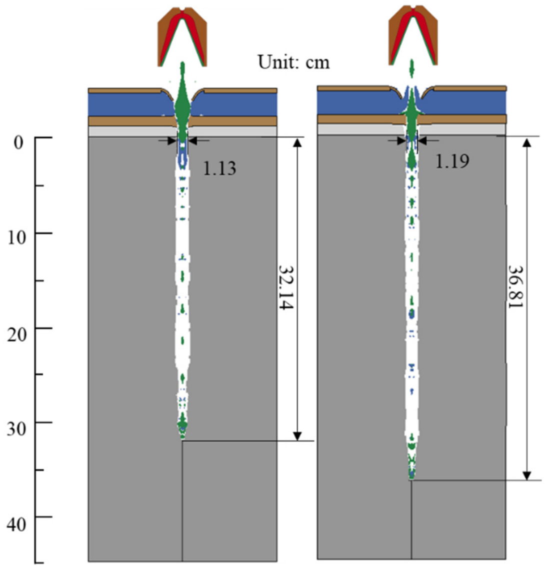

Fig 7. Perforation simulation results: (a) before geometric parameter optimization; (b) after geometric parameter optimization;

4. Summary

Based on numerical simulation, this paper optimizes the geometric structure of the powder liner by using a multi-objective optimization method and finally finds the geometric structure parameter with maximum penetration within the permissible range of the process. Then, the optimal structure of the powder liner is used for numerical simulation and compared with the simulation results of the initial structure. The results show that the optimized powder liner structure has a better perforation effect, which can improve by 14.53% compared with the initial structure. At the same time, this method also provides a new idea for similar optimization problems in engineering.

Acknowledgments

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References

[1] Cheng Dengfeng, Yang Dengbo, Tang Kai, et al. Current status and development analysis of perforating technology in oil and gas well. Well Logging Technology, 2021, 45(01): 1-7.

[2] Feng Kehua, Du Ning, Zhang Ruochen, et al. Discussion on penetration influence coefficient of shaped charge liner from titanium alloy in powder metallurgy technique. Journal of Ordnance Equipment Engineering, 2022, 43(08): 112-116.

[3] Tang Jianbo. Dynamics simulation of jet penetration under down-hole environment. China University of Petroleum (East China),2016.

[4] Yang Zhenyu, Yuan Ye, Liu Xin, et al. Numerical simulation on the effects of initiation methods on the initial movement of fuel dispersal in a frustum-shaped FAE device. Acta Armamentarii, 1-12.

[5] Lu Shan. Finite element simulation of single tooth impact sandstone experiment. Hefei University of Technology, 2021.

[6] G.E.P. Box, N.R. Draper, R.H. Myers, D.C. Montgomery, A.I. Khuri, J.A. Cornell, Empirical model building and response surface, Journal of the American Statistical Association, 93 (1998) 401-402.

[7] Zheng Qiang. Research and application of non-dominated sorting genetic algorithm with elite strategy. Zhejiang University,2006.