Proceedings World Geothermal Congress 2020+1
Reykjavik, Iceland, April - October 2021

A New Approach to Prevent Lost Circulation While Drilling in Fracture-Cavity Type Carbonate Reservoirs: Theory, Numerical Assessment and Experimental Study

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Keywords: geothermal and hydrocarbon resources, lost circulation, plugging, carbonate reservoir, cavity

ABSTRACT

Lost circulation often occurs during drilling and completion processes of geothermal and hydrocarbon resources development. There have been mature plugging techniques for preventing drilling fluid loss in high-permeability and fractured formations. However, the plugging materials are so hard to reside that effective solutions of preventing serious karst cave-type leakage still need to be improved. This paper presents the application of a novel technique, known as energy-gathered bundle type nesting plugging and wall reinforcing device, in fracture-cavity type carbonate reservoirs using both numerical simulation and experiments. Firstly, the composition and function of this new technique are presented. The invented device comprises external slotted metal pipes and an internal nesting explosion tool. Either spiral slits or straight slits are cut on the slotted metal pipe. And the nesting explosion tool is a mandrel with several presetting grooves, in which explosives are placed. The plugging can be achieved by forming a crossed metal bridge-structure, which is to prepare small spaces for the refilling and better residing of lost circulation materials. Secondly, a coupled wellbore and cavity reservoir model was established to study the impact of the generated downhole explosion on wellbore stability. The explosion load was added at the fixed locations of limestone and dolomite formations. And the stress analysis was performed on both wellbore and cavity formation. Next, another coupled explosive-mechanical model was established. The deformation of this device induced by explosion was simulated in order to analyze the performance of different kinds of slotted metal pipes and to optimize the bridging material and the slotting structure. Finally, several explosion experiments were conducted in air, submerged water, and downhole environment respectively to verify the feasibility of this technique. This study indicates that explosion impacts on limestone and dolomite formations are close. Although the downhole explosion has effects on stress distribution of the borehole wall and the formation in both vertical and horizontal directions, the wellbore collapse would not be caused. The series 5 aluminum alloy pipe with straight slotting patterns, exhibits a suitable tensile deformation without failure under the loading explosion of detonating cord, and can be utilized as the plugging tool. In conclusion, the presented technique can solve the problem that the lost circulation material does not readily remain to form an artificial borehole wall, and can be an effective solution to improve the plugging results in fracture-cavity type carbonate reservoirs.

1. INTRODUCTION

Well leakage often occurs during the drilling and completion of the oil, gas and geothermal wells in the carbonate formations. The slight leakage will interrupt the drilling operation, and the serious leakage will waste a lot of production time and cost a plenty of manpower and material resources. If the well leakage is not treated in time, it will also cause many safety accidents, such as well collapse, blowout, and drilling tool jamming, which may lead to the scrapping of some well sections and even the whole well (Zeidouni, 2014; Fidan et al., 2004). A lot of research has been done in this area. Majidi et al. (2011) presented an analytical formulation describing mud losses in drilling induced fractures. Lavrov and Tronvoil (2003; 2004; 2005) established a drilling fluid leakage model and quantitatively analyzed the characteristics and rules of the leakage through the model. Currently, there are dozens of commonly used plugging technologies for the fracture-type leakage(Majidi et al., 2010; Lietard et al., 1999; Xia et al., 2015; Mehdi et al., 2010), mainly including the pressure-bearing plugging technology, the drilling while plugging technology, the plastic plugging technology, the expansion pipe plugging technology, the gas drilling technology and the cementing plugging technology. The first technology is suitable for plugging the deep wells and the vicious low-pressure absorption wells. The second technology is a method of actively causing a leakage and automatically stopping the leakage, which is suitable for formations with low pressure bearing capacities such as complex structural formation and fracture-development formation. The third technology causes plugging slurry to be “weightless” through the interaction between the preparations, and makes the driving force disappear, thereby solving the problem of well leakage, wherein the plugging slurry has the characteristics of plastic creep, adjustable density, durability, etc. The fourth technology is the expansion pipe plugging technology; the effect is obvious once the plugging is successful, and multiple complex layers of the same open hole section can be sealed for multiple times; but this technology requires reaming the drilled wellbore, and as known to the on-site construction personnel, the reaming is of high difficulty, low speed and high-risk, and the broken debris cannot be brought to the ground due to the leakage, which is also the reason why the expansion pipe plugging technology is not widely applied. The fifth technology is the gas drilling, which has can obviously prevent the leakage, while improving the rate of penetration and the wellbore quality and saving the drilling cost; however, the gas drilling cannot be carried out when the formation produces water or in an easily collapsed formation. The sixth technology is the cementing plugging.

However, the karst cave-type leakage is still difficult to be dealt with in practice. Only if filling large amounts of objects and long-fiber materials into the well can the conventional physical and chemical plugging technologies work. Even if the plugging is barely successful, the leakage can be easily caused again in subsequent drilling, and the plugging operations usually need to be repeated.

Based on the analyses of the downhole conditions and various tools, this paper provides an energy-gathered bundle type nesting plugging and wall reinforcing device and an application thereof in karst cave plugging, for a novel downhole explosion plugging tool and an application thereof for a karst cave-type leakage, thereby solving the difficulty that the plugging material cannot easily reside to form a bridge in the conventional plugging methods, and effectively improving the plugging success rate for the karst cave formation.

2. THEORY

This paper introduces an energy-gathered bundle type nesting plugging and wall reinforcing device, comprising an external slotted metal pipe and an internal nesting blasting tool, wherein the slotted metal pipe has spiral slits or straight slits cut on a pipe wall thereof; the nesting blasting tool is a mandrel (i.e., a shooting pole) having a surface provided with a plurality of explosive grooves in which explosives are placed; the slotted metal pipe is disposed to sleeve the mandrel and fixed, with a movable fit therebetween. The device and the cave shaped cement target are shown in Figure 1. Although the expansion pipe can also be exploded for plugging, there are three problems. First, the amount of explosives is large, about 2 kg of explosives per meter; second, the expansion pipe is made of a flexible alloy material with a high strength, so it is difficult for the drill bit to trim the part protruding from well wall; third, the expansion pipe has no drain passage, and in the process of explosion and deformation, a huge impact force is applied to the liquid in the annular space, which causes instability of the well wall and hinders the deformation of the expansion pipe.

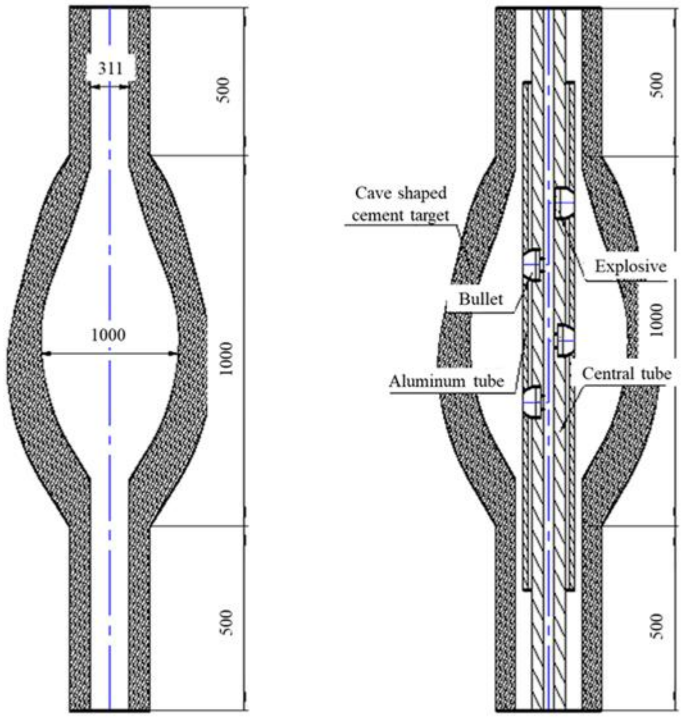


Figure 1: Schematic diagrams of the energy-gathered bundle type nesting plugging and wall reinforcing device (include artificial wellbore and cavity, which are made of cement)

This paper further presents the application of an energy-gathered bundle type nesting plugging and wall reinforcing device in karst cave plugging, comprising the steps of:

1) if an external slotted metal pipe is single-layered, requiring a length of the metal pipe to be 400 mm longer than a longitudinal length of a karst cave; if the external slotted metal pipe is double-layered, selecting two metal pipes of different sizes, a wall thickness of each of the metal pipes varying with different metal materials; an inner diameter of an outer layered metal pipe is equal to an outer diameter of an inner layered metal pipe, an outer diameter of the outer layered metal pipe is 5 mm to 10 mm smaller than a diameter of a drill bit for drilling a plugged well section, and the two metal pipes have a same length that is 400 mm longer than a longitudinal length of the karst cave;

2) for the single-layered slotted metal pipe, cutting a plurality of straight slits or spiral slits on a pipe wall of the metal pipe on the ground, and leaving an upper end and a lower end of the metal pipe for 30 mm to 200 mm without cutting, thereby obtaining the single-layered slotted metal pipe; for the double-layered slotted metal pipe, cutting spiral strips with different left and right turning directions on two metal pipes on the ground respectively, widths of the spiral strips being 10 mm to 50 mm; leaving an upper end and a lower end of each of the two metal pipes for 30 mm to 200 mm without cutting, thereby obtaining the double-layered slotted metal pipe; or, cutting a plurality of straight slits on a pipe wall of each of the two metal pipes, a straight slit spacing on the inner layered metal pipe is different from a straight slit spacing on the outer layered metal pipe; also, leaving an upper end and a lower end of each of the two metal pipes for 30 mm to 200 mm without cutting, thereby obtaining the double-layered slotted metal pipe;

3) connecting a mandrel having a plurality of explosive grooves below a downhole drilling tool, widths of the explosive grooves varying with amounts of explosives placed; if the straight slits are cut on the metal pipe, the explosive grooves of the mandrel are spiral grooves, and if the spiral slits are cut on the metal pipe, the explosive grooves of the mandrel are straight grooves; next, sleeving the mandrel with the slotted metal pipe and fixing the slotted metal pipe, with a movable fit therebetween, and placing explosives in the explosive grooves of the mandrel;

4) delivering the mandrel to the karst cave using the drilling tool to ignite the explosives; by using energy generated by an explosion of the explosives, causing the slotted metal pipe fixed on the mandrel to be plastically deformed and attached to a wall of the karst cave, the upper end and the lower end of the slotted metal pipe respectively abutting against an upper plate and a lower plate of the karst cave to complete a nesting operation; next, injecting a long fiber material or a plugging glue to form an artificial well wall, thereby ensuring that the drilling can pass through a plurality of meters of karst cave safely, efficiently and quickly.

In conclusion, with the energy-gathered bundle type nesting plugging and wall reinforcing device and the application thereof (new technique and new tool) of this paper, which are suitable for the downhole small-scale karst cave (the length of the section is not more than 8 m) leakage, a bridge can be formed after the explosion of the slotted metal pipe (the slotted metal pipe can be impacted into a bird nest shape after the detonation), which solves the difficulty that the plugging material cannot easily enter the formation in the conventional plugging method, and effectively improves the plugging success rate for the karst cave formation. Such a high-efficiency and low-cost plugging construction will help to increase the exploitation proportion of geothermal/natural gas in the carbonate formations in the North China Basin, Tarim Basin, and the Songliao Basin, and have great significances for China to successfully implement the green low-carbon strategy, optimize the energy structure, and maintain the sustainable economic and social development.

This device not only has important significances for plugging in the drilling of the karst cave formation, but also has certain reference values for the mine plugging and the tunneling plugging.

3. NUMERICAL ASSESSMENT

Two numerical models were established to study the stability of the borehole wall and the formation (Case 1), and the slotted pipe after explosion (Case 2). For Case 1, limestone and dolomite formation were selected as research objects, and commercial finite element numerical simulation software COMSOL was used for research. A wellbore-cavity-formation coupled model was established. The blast load was added at a fixed location to numerically simulate a downhole explosion, and stress analysis was performed on the effect of the blast generated by this technique on the wellbore wall and the cavern. For Case 2, slotted pipe is selected as research object, and commercial finite element numerical simulation software LS-DYNA was utilized. The effects of explosion on different materials and slotting types of the pipes were analyzed.

3.1 CASE STUDY 1

A wellbore-cavity-formation coupled model was established to study the stability of the borehole wall (Figure 2). The mechanical properties of the limestone and dolomite are illustrated in Table 1. In this case, the explosive loading is described by the following equation (Li, 1994):

$$P(t) = P_b f(t) \tag{1}$$

Where P_b is the peak value of pulse and $f(t)$ is a time delay function. The function $f(t)$ is defined as:

$$f(t) = P_0(e^{-n\omega t\sqrt{2}} - e^{-m\omega t\sqrt{2}}) \tag{2}$$

Where n and m are damping parameters, t_R is the initiation time of explosion pulse and ω is a function of medium longitudinal wave velocity c_p and hole diameter a. And ω and t_R can be defined as:

$$\omega = \frac{2\sqrt{2c_p}}{3a} \tag{3}$$

$$t_R = \frac{\sqrt{2}\ln(n/m)}{(n-m)\omega} \tag{4}$$

In this case, the Equation 1 can be simplified to Equation 5, which is defined as:

$$P(t) = P_b e^{-\gamma t/t_R} \sin\frac{4\pi}{1+t/t_R} \tag{5}$$

Table 1 Mechanical properties of limestone and dolomite

Mechanical property name	**Limestone**	**Dolomite**
Density (kg/m^3)	2600	2700
Tensile strength (MPa)	18	20
Compressive strength (MPa)	120	150
Elastic modulus (GPa)	75	70
Poisson's ratio	0.3	0.25

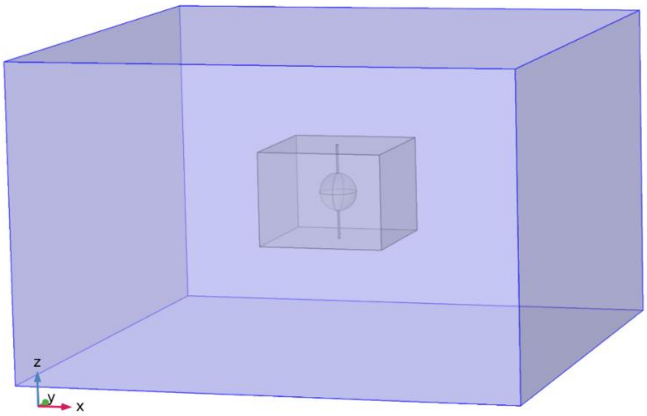


Figure 2: A well-cavity-formation coupled model

The stress distribution at the moment when stress reaches maximum and the stress distribution at the final moment are shown in Figure 3 and Figure 4, respectively. Taking limestone as an example, the explosion time is set to 0.15 ms, and the maximum stress is found to occur at 0.1 ms. The simulation result shows the stress on the borehole wall at the explosion site reaches 95 MPa, which does not exceed the compressive strength of limestone so that the rock is regarded as undamaged.

The maximum pressure along the axial direction of the well wall is 9.6 MPa. It is shown that the pressure wave generated by the explosion is transmitted on the well wall with a range of more than 3.5 m. The radial stress peak of the borehole wall is 5.8 MPa, and the sweep range is about 0.7 m. The maximum stress of the cave is 100 MPa, which does not exceed the compressive strength of the rock. Similar to the borehole wall, the peak stress is 5.8 MPa with a sweep range of about 0.7 m.

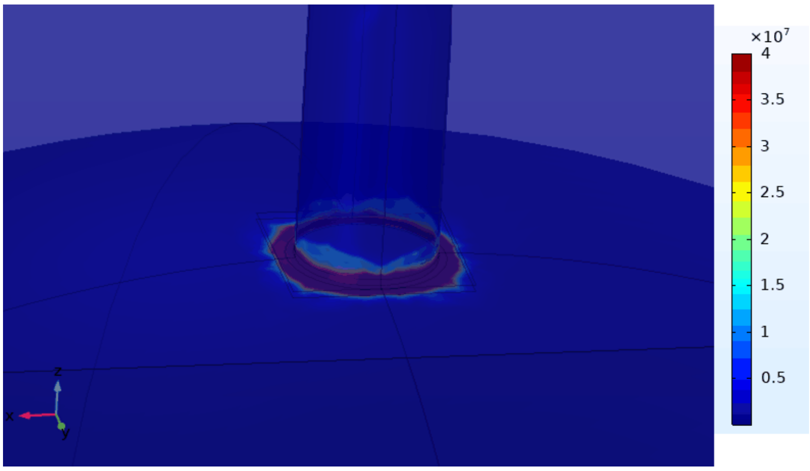


Figure 3: Stress distribution at the moment of maximum explosive load (unit of color bar: Pa)

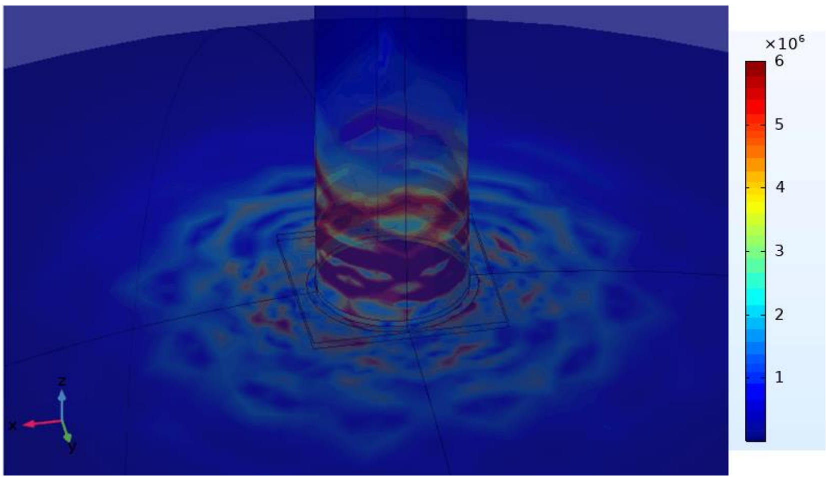


Figure 4: Stress distribution at the end of the explosion (unit of color bar: Pa)

The simulation result of dolomite is similar to limestone, and the simulation results are summarized in Table 2. We can conclude that the explosion will not lead to instability of the borehole wall, and it is feasible to build energy-gathered bundle type nesting plugging technique. The results of the study indicate that the impact of the explosion on dolomite and limestone formations is similar. The effect of the explosion has a greater effect on the wellbore wall in the vertical direction and a greater influence on the cavern in the horizontal direction.

Table 2 Simulation results of stress distribution

Parameters	**Well wall**		**Cavern**	
	Limestone	**Dolomite**	**Limestone**	**Dolomite**
Maximum stress (MPa)	95	95	100	110
Axial sweep range (m)	0.5	0.5	0.05	0.05
Axial stress peak (MPa)	9.6	9.6	3	2.75
Radial sweep range (m)	0.6	0.62	0.7	0.75
Radial stress peak (MPa)	5.8	5.8	3	3.4

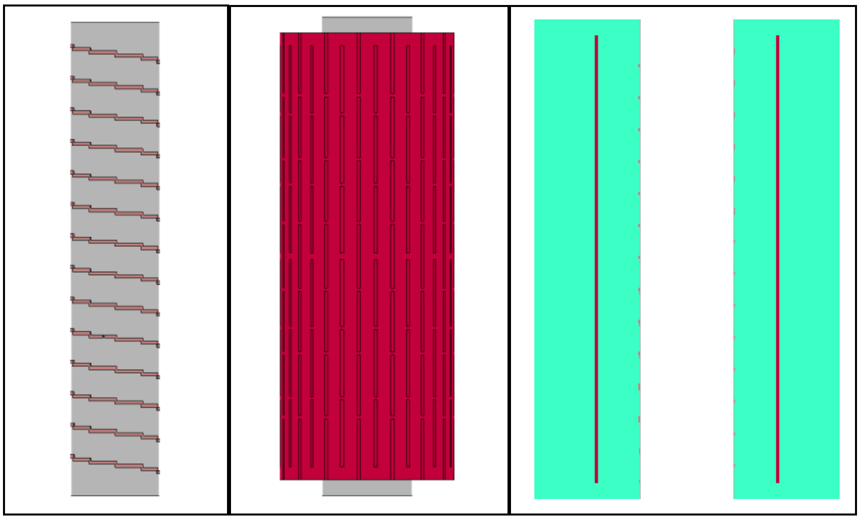
3.2 CASE STUDY 2

In order to verify the feasibility of the modified method, LS-DYNA is used for numerical simulation to observe the process of changing the slotted pipe under explosive conditions. Two different types of aluminum alloy materials (AL 2024 and AL 5182) are used in the slotted pipe model to select parameters that meet the experimental requirements. The model consists of an inner rod, a detonating cord, a slotted pipe, and the submerged environment. The outer diameter of the inner rod wrapped around 14 laps of detonating cord is 14 cm, and the length is 150 cm. The slotted pipe's parameters are as follows: wall thickness of 1cm, outer diameter of 27.2 cm, length of 140 cm, and 32 slits with the depth of 0.75 cm per turn, which are discontinuous in the vertical direction. The model is shown as Figure 5, and each part is in the submerged environment (the green part in Figure 5(c)).

In this case, Lee (JWL) equation of state (Esmaeili and Tavakoli, 2019) was adopted to model the explosives, which is usually defined with Equation 6.

$$P = A\left(1-\frac{\omega}{R_1 V}\right)e^{-R_1 V} + B\left(1-\frac{\omega}{R_2 V}\right)e^{-R_2 V} + \frac{\omega E}{V} \tag{6}$$

where *A*, *B*, R_1, R_2, and ω are constants determined by the properties of the explosive material, *V* is the relative volume, and *E* is the initial internal energy per unit volume of explosive.



(a) (b) (c)

(a) Distribution of detonating cord on the inner rod (b) Slotted pipe (c) Longitudinal section of the model

Figure 5: Geometric model of the energy-gathered bundle type nesting plugging and wall reinforcing device

The ALE method applied to the explosion simulation can better deal with the problem of mesh distortion under large deformation conditions. The Johnson–Cook constitutive equation is one of the Semi-empirical models, which is useful for modelling different machining processes, due to their simplicity and capability to adequately describe flow curves in a wide variation range of the basic parameters (Johnson and Cook, 1983). The material model of Johnson Cook and equations of state (EOS) Gruneisen together describe the process of destruction of slotted pipe, and the parameters of Al 5182 Material are shown in Table 3.

Table 3 Parameters of Al-5182 Material

Density (g/cm^3)	Shear Modulus (GPa)	A	B	N	C	M	Melt Temperature(K)
2.661	70.6	0.0025	0.00236	0.34	0.001	1.25	893
Room Temperature (K)	Specific Heat	Failure Stress (GPa)	D1	D_2	D_3	D_4	D_5
300	0.91	-4.281	0.8	0.62	1.15	0.016	1.16
C(cm/μs)	S_1	γ	a	V_0			
5200	1.4	1.97	0.48	1			

The detonating cord material is Cyclotrimethylenetrinitramine (RDX), whose quality is calculated to be 142.16g in this model. The material model of HIGH EXPLOSIVE BURN and EOS JWL together describe the process of explosion, and the parameters of RDX are shown in Table 4.

Table 4 Parameters of RDX (Equation 6)

Density (g/cm3)	Detonation velocity (cm/μs)	Chapman Jouget pressure (GPa)	A	B
1.63	0.863	33.79	5.24	0.7678
R_1	R_2	OMEG	E_0	V_0
4.12	1.1	0.34	0.17	1

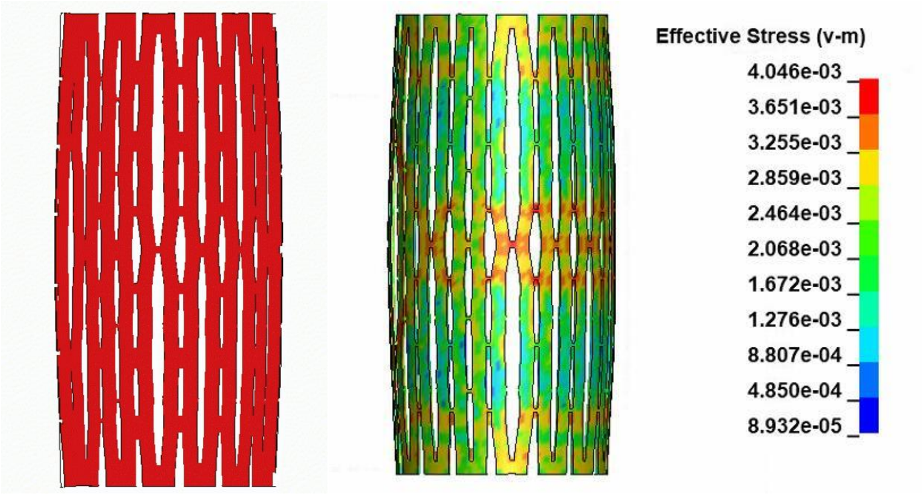
The 2024 and 5182 aluminum pipes were selected as the material of the slotted pipe, and they were used for a preliminary comparison on a simpler model only have one slit in the vertically direction. It was found through simulation that the slotted pipe made of AL 5182 expands under the action of explosion and has regular crack generation. However, the pipe made of AL 2024 expands under the action of the explosion but no crack is generated, and the part without the slit is cut off. The simulation results are shown in Figure 6, and the results show that AL 5182 is more in line with the experimental needs.

(a) **(b)** **(c)**

(a) Slotted pipe (b) Explosion results of AL 5182 (c) Explosion results of AL 2024

Figure 6: Explosion results of slitted pipes of different materials

Put the data of material 5182 into the model for numerical simulation, and the results is shown in Figure 7. When the explosion occurs, the material at the slits reaches the failure condition, and the mesh of the failed portion is deleted to form slits, resulting in an increase in the diameter of the slit pipe, however, some joints of the slits are also destroyed by the explosion, resulting in larger cracks. The numerical simulation results show that the method is feasible to achieve the aim of bridging and then leakage plugging.



(a) (b)

(a) Slotted pipe after 20ms of explosion (b) Stress distribution

Figure 7: Explosion results of a slotted pipe using AL 5182 material (unit of color bar: 100 GPa)

4. EXPERIMENTAL STUDY

In order to verify the feasibility of the slotted pipe in the underground explosion, and to determine the type of detonation, optimize the form of the slotted seam, and improve the explosive nesting and plugging device, eight field experiments were carried out in Luzhou, Sichuan. Figure 8 show the experiment site and the results of eight experiments are summarized in the Table 5.

Figure 8: Experiment setup and experiment site

Table 5 Results of eight experiments

Order number	Slotted pipe size L(m)×D(mm)×δ(mm)	Aluminum pipe type	Number of Slotting	Detonating cord size L(m)×D(mm)×g/m	Environ ment	Inner rod/ mandrel size
1	1.5×180×10	Series 6 (6063)	30	5×5.2×17	Air	Φ127
2	1.5×180×10	Series 6 (6063)	14	5×5.2×17	Water	Φ127
3	3.0×180×10	Series 6 (6063)	16	11×5.2×17	Water	Φ127
4	1.8×185×10	Series 6 (6061)	30	7×5.2×17	Water	Φ127
	1.8×165×10		14		Water	
5	1.4×180×10	Series 5 (5182)	14	3×5.2×17	Water	Φ114
6	1.4×180×10	Series 5 (5083)	14	5×5.2×17	Water	Φ114
7	1.4×273×10	Series 5 (5182)	32	10×5.2×17	Water	Φ140
8	**1.4×273×10**	**Series 5** (5083)	**30**	**8×5.2×17**	**Water**	**Φ140**

Among them, the eighth experiment is the most successful. The structure of the slotted pipe is shown in Figure 9. The pipe made of series 5 Aluminium, which is a kind of Al-Mg alloy. The experiment was carried out underwater at the depth of 1.5 meters. After the explosion, the outer diameter of the upper end of the pipe is 384mm, and the outer diameter of the lower end is 380mm, which basically coincide with the simulation results and meet the original design requirements (Figure 10).

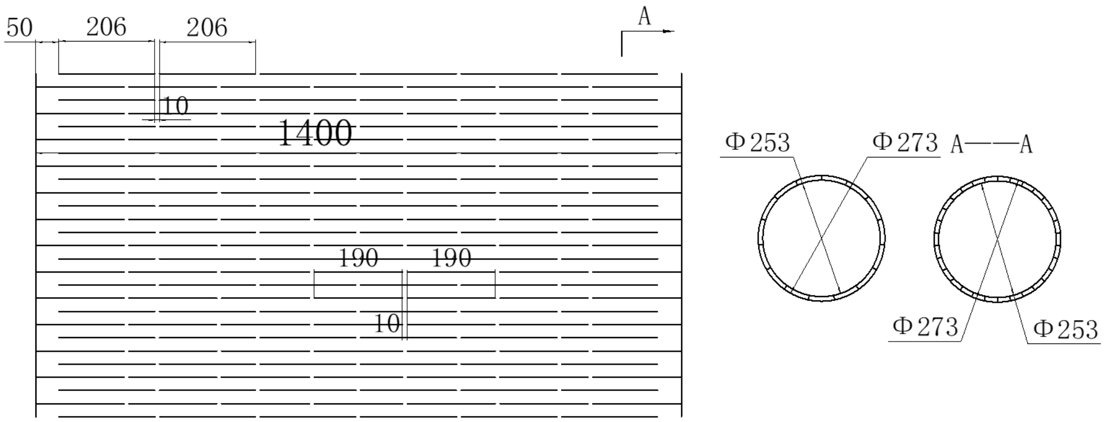


Figure 9: Structure of the slotted pipe used for 8th experiment

Figure 10: Slotted pipe after the explosion

5. CONCLUSION

This paper presents the application of a novel technique, known as energy-gathered bundle type nesting plugging and wall reinforcing device, in fracture-cavity type carbonate reservoirs using both numerical simulation and experiments. The simulation results indicate that explosion impacts on limestone and dolomite formations would not cause the wellbore collapse. Moreover, the series 5 Aluminium has low density, high tensile strength and good ductility, which is regarded as a suitable bridging material. Several explosion experiments also verify the feasibility of this technique. The energy-gathered bundle type nesting plugging and wall reinforcing device has great prospects, it can solve the problem that the lost circulation material does not readily remain to form an artificial borehole wall, and can be an effective solution to improve the plugging results in fracture-cavity type carbonate reservoirs.

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