CHEMICAL ENGINEERING TRANSACTIONS
VOL. 59, 2017
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet
Guest Editors: Zhuo Yang, Junjie Ba, Jing Pan

ISBN 978-88-95608- 49-5; **ISSN** 2283-9216
DOI: 10.3303/CET1759016

Study on Recycling Technology of High Quality Perforating Liquid of Luodai Gas Field

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In Luodai gas field, people adopt positive electricity glue mud system and porous - throat temporary plugging agent that protects reservoirs, and corresponding technology to perform drilling, an accomplishment of drilling is with perforation method. After perforating, the perforation fluid is not completely discharged, and the salt crystal precipitation blocks the pipeline, leading damage to reservoir, and ecological environment will be damaged as well. To plan and implement the process of recycling and protecting the reservoir has become a problem to be solved. Based on the analysis of the composition of flowback fluid, combined with the re-use indicator of liquid waste back on the site, we decide to remove impurities with membrane at first, and then add processing agent of 0.4%DRS, 0.6%RT, 0.6%ZPJ-2, 1.0%FPJ-1, 0.6%HSJ-1 for performance tuning, so as to realize the recovery and reuse of perforating fluid and protect the oil and gas layer.

1. Introduction

Luodai gas field is the shallow gas reservoir found in the Jurassic shallow continental clastic zone in the middle of the western Sichuan Depression, with rich reserves.
The development of this gas field is of great significance to the economic development and the transformation of energy structure in Sichuan (Yao and Guo, 2012; Liu et al., 2015). The block is drilled with positive electricity glue mud system and porous - throat temporary plugging agent that protects reservoirs and corresponding technology (Wang et al., 2010). However, after perforating, the perforation fluid is not completely discharged, and the salt crystal precipitation blocks the pipeline, leading damage to reservoir, and ecological environment will be damaged as well. Therefore, to plan and implement the process of recycling, to protect the reservoir and improve natural gas production has become a problem to be solved (Nasri et al., 2017; Rahimi et al., 2017).

2. Analysis of potential damage factors of perforating fluid to reservoir

Through the collection of reservoir sensitivity test data, we conducted a comprehensive analysis, and the result is shown as Table 1.
Select the natural core of Penglai town group, Suining group reservoir of Luodai gas field to conduct core flow test, and then evaluate the damage of bentonite to the reservoir, the results as shown in Table 2.
The experimental results show, the damage rate of artificial sodium bentonite is up to 84.2%. That is because the size of the clay is often only a few microns, even less than 1 microns, so it is easy to enter the reservoir pore under positive pressure difference, and thus results in increased pore fluid flow resistance (Li et al., 2010). Therefore, in perforating operation, should try to avoid the invasion of small solid particles such as clay.
We investigated the effect of pressure and time on the degree of perforation damage, and the experimental data is shown in Table 3.

Please cite this article as: Hongjing Zhang, Chunyan Liu, Zhekui Zheng, Yingchao Chen, 2017, Study on recycling technology of high quality perforating liquid of luodai gas field, Chemical Engineering Transactions, 59, 91-96 DOI:10.3303/CET1759016

Table 1: Experimental results Sensitivity of different horizons in Luodai gas field

Name of sensitivity experiment		Experimental results (J3p)	Experimental results (J3sn)	Experimental results (J2s)
Speed sensitive experiment	Degree of gas sensitivity	Weak~medium	weak	weak
	Salt water sensitivity degree	Weak~medium	weak	Weak~medium
Water sensitivity test	Water sensitivity degree	Medium~strong	medium	medium
Salt sensitivity test	Reduced mineralization	Medium~strong	Strong	weak
	Increased mineralization	Weak~medium	- -	medium
	Critical mineralization	40930mg/l	30000mg/l	63400mg/l
Alkali sensitivity test	Alkali sensitivity degree	Weak~medium	Moderately weak	weak
	Critical pH value	11	8	11
Acid sensitivity test	Acid sensitivity degree	weak	Moderately weak	weak
Stress test	Stress test degree	medium	medium	Medium~strong

Table 2: Damage evaluation of solid particles under simulated downhole conditions

Solid type and content	Stratum	Kw_1 $10^{-3}um^2$	Kw_2 $10^{-3}um^2$	DR (%)	Simulation conditions
5% Bentonite	J_3p_1	4.782	1.063	77.8	Displacement pressure 3.5MPa, Shear rate $150s^{-1}$
	J_3sn	0.1128	0.0310	72.5	
	J_2s	2.0310	0.322	84.2	

Table 3: Effect of pressure and time on the degree of perforation damage

Core number	Differential pressure	Time	Kw_1 ($10^{-3}\mu m^2$)	Kw_2($10^{-3}\mu m^2$)	Damage rate
Gragon 20 2 2/70 - 5	2	10	0.3237	0.06754	79.13%
Gragon 25 2 9/57 - 1	2	20	5.120	0.932	81.8%
Gragon 20 2 2/70 - 6	2	30	0.4419	0.06530	85.22%
Long Sui 15 1 106/111-2	1	20	0.1604	0.05892	63.27%
Long Sui 15 1 100/111-3	2	20	0.008901	0.002959	66.76%
Long Sui 15 1 100/111-2	3	20	0.02727	0.007825	71.31%

Note: the experimental fluid is $Cacl_2$ solution of ρ=1.20g/cm^3

We can seed from Table 3 that, for the same perforating liquid system, the larger pressure and longer soaking time will produce greater damage on reservoir.

3. Performance and composition analysis of perforating liquid backflow

3.1 Performance analysis

Take a certain amount of perforating liquid backflow on the site, and measure its performance at 45°C after stirring, and performance is shown as Table 4.

Table 4: Performance of perforating liquid backflow

Density (g/cm3)	PV (mPa•s)	YP (Pa)	FL (mL)	pH	n	Expansion rate (%)
1.19	2.5	0.5	＞120	6.5	0.778	37

We can see from Table 1, the performance of perforating liquid backflow has undergone great changes: its viscosity is very low; PV and YP are respectively only 2.5 and 0.5; water loss is more than 120mL; and n is also more than the design requirements. Since the performance of flowback fluid is not up to standard, it needs to be adjusted to two times for reuse.

3.2 Composition analysis

In order to make the perforating fluid and reservoir fluid compatible as much as possible, we considered to use the perforated liquid for backfilling liquid preparation, and realize reuse. Therefore, it is necessary to analyze the composition of the flowback fluid, and the analysis result is shown as Table 5.

Total mineralization degree of the flowback fluid is 187143.5mg/L, impurity content up to 83650mg/L. Due to the high content of impurities in the liquid, and cannot meet the requirements of the preparation of perforating fluid, so we need to filter the return fluid to remove impurities if need a secondary re-use of the perforating fluid.

Table 5: Composition analysis of the flowback fluid

Density (g/cm3)	Ca2 + (mg/L)	Mg2 +	Ca2 + (mg/L)	Mg2 +	Ca2 + (mg/L)	Total mineralization degree (mg/L)	Impurity content (mg/L)
1.19	16229	25603.5	128280	16420.1	610.9	187143.5	83650

4. Study on recycling of perforating liquid backflow

4.1 Removal of solid phase impurities in liquid return with membrane filtration

The pore throat radius of Penglai town in Luodai area is distributed within 1.0~18.75μm; Suining group pore throat radius is distributed within 1.04~22.77μm; Shaxi Temple group pore throat radius is distributed within 1.1719~120.4μm. Through the analysis of the laser particle size of perforation fluid, it can be found that Solid particle radius is in perforating liquid backflow is distributed within 0.1~36μm, and most solid particles radius is distributed within 1.0~32μm. Therefore, we need to use membrane separation technology to remove the solid particles with radius>1μm, in order to achieve the purpose of reservoir protection.

4.2 Performance tuning

(1) Adjustment of rheological properties
In order to make full use of the return liquid and save the costs, we used DRS as a tackifier, and carried out the optimization experiment separately adding 0.1%, 0.2%, 0.3%, 0.4%, 0.5% tackifier, and the performance of each addition is as Table 6. We can see from the table, when the addition is 0.4%, PV is 12, YP is 5, and water loss is 13.6mL; when the addition is 0.5%, PV is 14, YP is 8.5, and water loss is 8.0mL. When adding 0.4% or 0.5% tackifier, the performance is relatively good. Taking the costs into account, the addition of tackifier is determined to be 0.4%.

Table 6: Optimization of Tackifier

Formula	Density (g/cm3)	PV (mPa•s)	YP (Pa)	FL (mL)	n	G_1/G_2
Flowback fliud + 0.1%DRS	1.19	7	2.5	28	0.663	0.5/0
Flowback fliud + 0.2%DRS	1.19	8	2	22	1.000	0.5/0.5
Flowback fliud + 0.3%DRS	1.19	9.5	3.5	20	0.656	0.5/1
Flowback fliud + 0.4%DRS	1.19	12	5	13.60	0.628	1.25/2
Flowback fliud + 0.5%DRS	1.19	14	8.5	8.0	0.538	2.5/4

(2) Optimization of filtration performance
We took RT as fluid loss additives, and carried out the mutual experiment by RT addition of 0.6%, 0.8%, 1.0% and DRS addition of 0.2%, 0.3%, 0.4%, at 45°C, and the experimental results are shown in Table 7. We can seed from the table, in the mutual experienment, the PV and YP of formula (1)-(5) cannot meet the requirements; n value of formula (6) is quite large; formula (7) and (8) have good interaction effect, which PV, YP, n value all accord with the requirements of perforating fluid preparation, and the filtration loss is only 11mL, but taking the costs into account, formula (7) is better.

Table 7: Optimization and interaction of filtrate reducer

Formula	Density (g/cm3)	PV (mPa•s)	YP (Pa)	FL (mL)	n	G_1/G_2
(1) Flowback fliud + 0.2%DRS + 0.6%RT	1.19	9.5	2.25	20	0.747	0.25/1
(2) Flowback fliud + 0.2%DRS + 0.8%RT	1.19	10	2	12.4	1.30	0.5/1
(3) Flowback fliud + 0.2%DRS + 1.0%RT	1.19	13	2.5	11.8	0.784	0.7/1
(4) Flowback fliud + 0.3%DRS + 0.6%RT	1.19	11	3.5	14	0.632	0.5/1.5
(5) Flowback fliud + 0.3%DRS + 0.8%RT	1.19	13	5.5	11.8	0.625	1/1.5
(6) Flowback fliud + 0.3%DRS + 1.0%RT	1.19	16	4.5	11	0.714	1/2
(7) Flowback fliud + 0.4%DRS + 0.6%RT	1.19	17.5	6.5	11	0.654	2/2
(8) Flowback fliud + 0.4%DRS + 0.8%RT	1.19	20	7.5	11	0.652	1.5/2

(3) Optimization of the auxiliary drainage performance
Considering the preparation condition of the return fluid of perforation fluid into the well, we took ZPJ-2 as the added surfactant. We measured the surface tension after adding 0.2%, 0.4%, 0.6% and 0.8% ZPJ-2 in the perforating liquid back-discharging solution, respectively, and the experimental results are shown as Table 8.

When the addition of ZPJ-2 changes within 0.2~0.8%, The surface tension was gradually reduced; when the addition is 0.6%, 0.8%, the surface tension was 27 mN/m and 25.9 mN/m, respectively. Perforation liquid surface tension generally requires less than 28mN/m, and taking the costs into account, the addition of ZPJ-2 is determined as 0.6%.

Table 8: The surface tension when different concentrations ZPJ-2 were added to the effluent

Medium	Surface tension (mN/m)			Average value (mN/m)
Flowback fliud	32.5	32.3	32.7	32.5
Flowback fliud + 0.2%ZPJ-2	30.6	30.4	30.7	30.6
Flowback fliud + 0.4%ZPJ-2	28.3	28.7	28.5	28.5
Flowback fliud + 0.6%ZPJ-2	27.1	26.8	27.2	27.0
Flowback fliud + 0.8%ZPJ-2	25.8	25.7	26.1	25.9

(4) Optimization of corrosion resistance performance
The recovery and reuse of the return liquid must consider the corrosion problem of the flowback fluid to the field equipment. We selected the CaCl2 solution with a density of 1.20g/cm3 as base fluid, and measured the corrosion inhibition performance after adding different amounts of HSJ-1 into the flowback fluid, and the experimental results are shown as Table 9. The corrosion inhibition rate of perforating liquid was only 17.02%. When the addition amount of HSJ-1 changed within 0.2%~0.8%, the corrosion rate was gradually increased; while the addition amount of HSJ-1 changed within 0.6%~0.8%, the corrosion inhibition rate did not change much; when the HSJ-1 concentration is 0.6%, the corrosion inhibition rate will be up to 91.45%, so the addition amount of HSJ-1 in perforating liquid backflow should be 0.6%.

Table 9: Optimization of corrosion resistance performance

Medium	Quality before corrosion m_1 (g)	Quality after corrosion m_1 (g)	Quality difference (g)	Experiment time (d)	Corrosion inhibition rate (%)
Base liquid (1.20g/cm3CaCl2 solution)	8.9095	8.9048	0.0047	7	/
Perforating liquid backflow	8.6851	8.6812	0.0039	7	17.02
Flowback fliud + 0.2%ZPJ-1	8.7165	8.7131	0.0034	7	27.66
Flowback fliud + 0.4%ZPJ-1	8.3518	8.3505	0.0013	7	72.34
Flowback fliud + 0.6%ZPJ-1	8.4837	8.4833	0.0004	7	91.45
Flowback fliud + 0.8%ZPJ-1	8.7806	8.7803	0.0003	7	93.62

(5) Optimization of suppression performance
Considering the condition of perforation fluid entering well, w1e added 0.5%, 0.8%, 1%, 1.5% FPJ-1 to the perforation fluid, respectively, and the experimental results are shown as Table 10. With the increase of FPJ-1 dosage, shale swelling ratio constantly decreased. When 1.0% FPJ-1 was added into the perforation fluid, the shale swelling ratio is only 14.28%, with good clay stability.

Table 10: Optimization of suppression performance

No.	1	2	3	4	5
Soaking medium	perforating liquid backflow	Flowback fliud + 0.5%FPJ	Flowback fliud + 0.8%FPJ	Flowback fliud + 1.0%FPJ	Flowback fliud + 1.5%FPJ
Expansion rate	37%	17.45	15.19	14.28	9.06

4.3 Recycling process

(1) Perforated liquid return fluid is processed by natural sedimentation, and then remove the sedimentation.
(2) Remove the solid phase impurities in the sedimented liquid flowback liquid by filtration through a membrane filter.
(3) Adjust the pH value of the perforating liquid backflow, and take a certain amount of perforating fluid back to the liquid filtrate to do a small experiment, and determine the adjustment scheme of the re-use of the perforating liquid back-discharging liquid.
(4) Add 0.4%DRS, 0.6%RT, 0.6%ZPJ-2, 1.0%FPJ-1, 0.6%HSJ-1 into perforating liquid backflow, respectively, and remake the perforating liquid backflow the perforating fluid with excellent reservoir protection effect as required.

(5) Prepare the perforating fluid according to site requirements, and take 1000ml perforating fluid to measure its performance. If the performance indicators are beyond the design scope, should adjust the amount of treatment agent.

4.4 Field perforation liquid recycling process

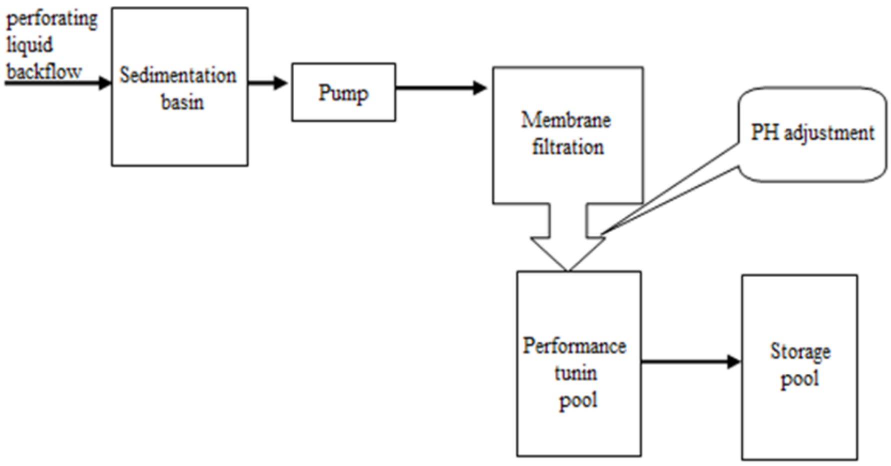

Figure 1: A typical exhaust gas analyser appearance schematic

5. Feasibility analysis of recycling

5.1 Basic formula for perforating liquid

(1) Formula of perforating fluid in reservoir of Penglai group: brine (density as 1.15~1.25g/cm^3) + 0.4~0.5% DRS + 1.0~ 1.5% RT + 2.5~3.0% FPJ-1 + 0.8~1.0% ZPJ-2 + 0.8~0.9% HSJ-1.
The composition of brine is: 28~46.5% $CaCl_2$ or 18~34% KBr.
(2) Formula of perforating fluid in reservoir of Suining group: brine (density as 1.25~1.30 g/cm3) + 0.3~0.4%DRS + 1.0~1.2%RT + 2.5~3.0%FPJ-1 + 0.9~1.0% ZPJ-2 + 0.9~1.0%HSJ-1.
The composition of brine is: 46.5~56%$CaCl_2$ or 34~42%KBr.
(3) Formula of perforating fluid in reservoir of Shaximiao group: brine (density as 1.30~1.40g/cm^3) + 0.3~0.4% DRS + 1.0~1.2% RT + 2.5~3.0% FPJ-1 + 0.9~1.0% ZPJ-2 + 0.9~1.0% HSJ-1.
The composition of brine is: 18% KBr + 35~45% HCOOK.

5.2 Additional drug cost required for recycling

Here the cost of the return fluid of the perforating fluid is estimated, assume that 100m^3 perforating liquid backflow is recycled. According to the formula above, the material budget for well test of perforating liquid backflow is shown as Table 11.

Table 11: Material budget for well test recycling 100m^3 perforating liquid backflow

Material name		Quantity (T)	Unit price (thousand/T)	Total (thousand yuan)
Perforating fluid material	RT(Salt water reducing agent)	0.6	23	13.8
	DRS(Tackifier)	0.4	35	14.0
	FPJ-1(Clay stabilizer)	1.0	23	23.0
	ZPJ-2(Auxiliary agent)	0.6	29	17.4
	HSJ-1(Corrosion inhibitor)	0.6	21.5	12.9
Total (Thousand yuan)		81.1		

Here the cost of 1.20g/cm^3 perforating fluid is estimated, designed as 100m^3 perforating fluid. According to the previous experimental formula, the material budget for well test of perforating liquid backflow is shown as Table 12. We can see from Table 8 and Table 9 that, from the perspective of pharmaceutical cost, to prepare a 100m^3 density of 1.20g/cm^3 perforating fluid and recycle 100m^3 perforating liquid backflow of 1.20g/cm^3, recycling costs 67% less than reconfiguring perforating fluid.

Table 12: Material budget to prepare 100m^3 perforating liquid backflow of 1.20g/cm^3

Material name		Quantity (T)	Unit price (thousand/T)	Total (thousand yuan)
Perforating fluid material	$CaCl_2$	40	2	80
	RZ-5(Salt water reducing agent)	1.5	23	34.5
	DRS(Tackifier)	0.5	35	17.5
	FPJ-1(Clay stabilizer))	3	23	69
	ZPJ-2(Auxiliary agent)	1	29	29
	HSJ-1(Corrosion inhibitor)	0.9	21.5	19.35
Total: 249.35 thousand yuan				

5.3 Input device required for recycling

Types and prices of equipment needed for recycling is shown as Table 13.

Table 13: Types and prices of equipment needed for recycling

Device type and model	Unit price (yuan)	Manufactor
JYWQ-type Automatic submersible pump	5250.00	Shanghai Pacific Pump Co., Ltd.
Grundfos water pump CR3-29-type	11610.00	Denmark
Membrane filtration device	14000.00	Chengdu Huayi filtration equipment Co. Ltd.
Stirrer	10000	
Pipeline	5000.00	
Total costs	45860.00	

The cost analysis above is only the pharmaceutical costs and equipment investment for recycle of perforating fluid. If take the station mode, then it would also involve land acquisition, housing, the investment costs would be quite high, so constructing recovery station is not recommended. Considering the factors of the total cost of the perforating liquid backflow, we could take use of the existing equipment on Well site, and then purchase the membrane filter and pump, to achieve the recycle of perforating liquid backflow. This can not only prevent the pollution because of direct discharge of perforating liquid backflow on the environment, but also save the pharmaceutical costs to prepare the perforating fluid. But meanwhile the storage and transportation problems after the recovery and reuse of perforating fluid should be considered.

6. Conclusions and recommendations

(1) The perforating liquid backflow is removed the impurities through sedimentation and membrane filtration device. Adding 0.4%DRS, 0.6%RT, 0.6%ZPJ-2, 1.0%FPJ-1, 0.6 %HSJ-1 into the filtrate can the recovery and re-use of the perforating liquid back-discharging liquid, so as to protect the oil and gas layer.
(2) We had better take use of the well site conditions to recycle and reuse the perforating fluid, rather than building recycling station.

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