Feasibility study of swash plate plunger pump system in drainage gas recovery process

Wei Xiong¹, Shengli Zhang¹, Lina Wang¹, Xu Zhang¹, Jixiang Ma¹, Kang Zeng², Jianchao Tian¹, Meng Wang², Ran Li¹, Zhiqiang Jing², Quansheng Wang², Tong Zhu¹, Liya Wang³, Jingzhi Liu¹, Li Hao¹, Shuanglong Xu⁴ and Ran Duan⁵

¹ Engineering Technology Research Institute of Huabei Oilfield Co., Ltd., PetroChina, Renqiu, Hebei Province, China
² Sulige Exploration and Development Branch of Huabei Petroleum Administration Co., Ltd., PetroChina, Ordos, Inner Mongolia, China
³ No. 1 Oil Production Plant of Huabei Oilfield Co., Ltd., PetroChina, Renqiu, Hebei Province, China
⁴ No. 3 Oil Production Plant of Huabei Oilfield Co., Ltd., PetroChina, Hejian, Hebei Province, China
⁵ Underground Gas Shore Management Agency of Huabei Oilfield Co., Ltd., PetroChina, Langfang, Hebei Province, China
⁶ E-mail: cyy_wln@petrochina.com.cn

Abstract. With the continuous development of Sulige gas field, the formation pressure has gradually dropped, problems that liquid loading and water flooding affects the normal production of gas wells have gradually appeared. Drainage gas recovery delays the decline of gas field production to some extent, but the stable production of gas wells with large water production has become a field problem. Therefore, the pneumatic swash plate plunger pump system that does not need external power equipment but has large displacement and is easy to manage is studied. It has become another weapon to prolong the blowout period of gas wells.

1. Introduction
The Sulige gas field is a lithologic gas reservoir with the characteristics of low pressure, low permeability, low abundance, poor connectivity, strong heterogeneity, low production, and short stable production period. Its single well controlled reserves are low, the formation gas supply is insufficient, the formation pressure drops quickly, and the shut-in pressure of high liquid-gas ratio well recovers slowly. At present, water breakthrough wells account for more than 50%, and wellbore liquid loading has seriously affected the productivity and recovery efficiency of gas wells. Although the drainage gas recovery technology has basically covered most gas wells in recent years, but the application effect of conventional drainage technology for gas wells with high liquid gas ratio is very poor.

Drainage gas recovery technology for gas wells with large water production on-site mainly includes organic drainage gas recovery technology, electric submersible pump drainage gas recovery technology, jet pump drainage gas recovery technology and etc. The principle and technical characteristics of some drainage gas recovery technology are shown in Table 1. These technologies are suitable for strong drainage or reproduction of water flooded gas well. They are all mature drainage
gas recovery techniques. However, these technologies are not applicable to Sulige gas field for three reasons: ① The application of these technologies requires an external stable power source. As Sulige gas field is located in Maowusu sandy land, data transmission of single well depends on solar power supply, and there is no industrial power supply to provide stable power. ② These process technologies require well killing operations when implemented on site. The "three low" characteristics of Sulige gas field determine that the gas well will lose productivity if it is killed. ③ The operation cost of single gas well with these technologies is high. Sulige gas field follows the "low cost, sustainable" development strategy, and the high cost is not in line with the long-term development concept of the gas field. In order to solve the above problems, the author independently developed the swash plate plunger pump drainage gas recovery technology.

Table 1. Working principle and technical characteristics of some drainage gas recovery technology.

| Process name                  | Process principle                                                                 | Technical features                                                                 | Adaptive conditions                                           |
|-------------------------------|-----------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|--------------------------------------------------------------|
| Organic drainage gas recovery technology | The pumping unit drives the plunger under the sucker rod in the tubing to do reciprocating movement continuously. Through the opening and closing of the valve installed in the plunger and pump barrel, the liquid in the wellbore is discharged from the tubing to the ground. | 1. The wellhead is sealed and the working pressure is high. 2. Integral pump barrel and efficient downhole gas-water separator are adopted to reduce pump leakage and gas interference and improve pump efficiency. 3. Use sand control string for sand producing wells. | Setting depth of pump ≤ 2400 m Maximum displacement ≤ 70 m³/d Suitable for reproduction of flooded wells, drainage of intermittent blowout wells and gas wells with low pressure small water production. |
| Electric submersible pump drainage gas recovery technology | A multistage centrifugal pump device is used to run down the well with the tubing to discharge the liquid in the water-flooded gas well rapidly from the oil pipe. | 1. With suitable pressure and temperature resistance, and strong corrosion resistance. 2. Used high efficiency gas processor. 3. Improved the cables: choose cables with high temperature resistance, pole-insulated cables or lead-sealed cables. | Maximum pump depth ≤ 2700 m Maximum displacement ≤ 500 m³/d Suitable for reproduction of flooded wells or strong drainage of gas reservoirs. |
| Jet pump drainage gas recovery technology | The high-pressure power liquid provided by the surface pump passes through the nozzle to draw the well fluid into the throat. After mixing, it enters the diffusion tube. The pressure is obtained by reducing the flow rate, and then the well fluid is discharged from the surface. | 1. The nozzle and throat are made of anti-wear materials, which can work under complex conditions such as high temperature, high gas-liquid ratio, sanding and corrosion. 2. The flow rate can be adjusted by changing different nozzle throat combinations. | Maximum pump depth ≤ 2800 m Maximum displacement ≤ 300 m³/d Suitable for reproduction of flooded wells. |

2. Working principle of swash plate plunger pump drainage gas recovery

2.1. Working principle
Swash plate plunger pump [1-3] drainage gas recovery technology is a new type of drainage technology, which relies on the energy of gas well itself. It uses the characteristics of high casing pressure of single well in normal production, introduces swash plate plunger pump drainage tools, uses gas in the casing or from the well beside. Its main working principle is to run a pneumatic motor and a swash plate plunger pump in the wellbore. The mixture of gas and water enters the pneumatic motor.
Through this motor, the natural gas is discharged from the oil casing annulus, the produced liquid enters the swash plate piston pump [4-6], making it discharged to the ground through the oil pipe. Its design sketch is shown in Figure 1. Compared with traditional plunger drainage gas recovery technology, this process mainly increases the power and makes it better to discharge a large amount of liquid. The comparison between swash plate plunger pump drainage gas recovery technology and traditional plunger drainage gas recovery technology is shown in Table 2.

Figure 1. Schematic design of swash plate plunger pump system.

Table 2. The comparison between swash plate plunger pump drainage gas recovery technology and traditional plunger drainage gas recovery technology.

| Comparison project | Swash plate plunger pump drainage gas recovery technology | Plunger drainage gas recovery technology |
|--------------------|----------------------------------------------------------|----------------------------------------|
| Working principle  | The mixture of gas and water enters the pneumatic motor. Through this motor, the natural gas is discharged from the oil casing annulus, the produced liquid enters the swash plate piston pump, making it discharged to the ground through the oil pipe. | Taking the plunger as the mechanical section between gas and liquid, the plunger moves up and down in the tubing to discharge liquid depending on the original gas pressure of the gas well, which improves the efficiency of intermittent gas lift. |
| Drainage tool      | Swash plate plunger pump [11-12] (As is shown in Figure 2). | Plunger tools. |
The swash plate plunger pump drainage gas recovery technology mainly includes pneumatic pump, gas lift valve, double slip valve, swash plate pump, pneumatic pump reducer and other devices [7-8]. The main functions of each part are as follows:

- Pneumatic pump: provide power support for the swash plate plunger pump as the drainage tool;
- Gas lift valve: a special tool for drainage and gas recovery by recycling use of exhausted gas;
- Double slip valve: a special tool to prevent blowout during operation [9];
- Swash plate pump: the liquid in the wellbore is discharged to the surface by this tool [10];
- Pneumatic pump reducer: a downhole device that decelerates the high-speed rotating fluid in pneumatic pump.

2.2. The advantages and disadvantages of swash plate plunger pumps

The advantages of swash plate plunger pumps include:

1. High volumetric efficiency. Its volumetric efficiency can reach up to 90% or more;
2. Long service life. Its service life can reach more than 10000 hours under the condition of ensuring the stable quality of each component;
3. Convenient to adjust variables. For the swash plate plunger pump, its structure is diverse, and the variable can be adjusted by adjusting the swash plate, which is easy to control;
4. Wide range of application. It is applicable to a wide range of media such as all kinds of mineral oil, emulsion and pure water, etc.

The disadvantages of swash plate plunger pumps include mainly include:

1. The structure is relatively complex. Compared with ordinary plunger pump, the swash plate plunger pump has more parts;
2. High cost. On the one hand, high requirements of the production process result in high manufacturing costs; on the other hand, high requirements on the operating environment lead to high cost of use and maintenance.

Although there are the above shortcomings, by virtue of its advantages and the continuous improvement of the design and manufacturing level, the use of swash plate plunger pump is becoming more and more extensive. It will also provide reference to the production of oil and gas fields.

2.3. Calculation of main parameters of swash plate plunger pump

![Diagram of swash plate plunger pump](image)

1-Plunger  2-Cylinder  3-Valve plate  4-Transmission shaft  5-Swash plate  6-Slipper  7-Retainer plate  8-Center spring

**Figure 2.** Schematic design of swash plate plunger pump.
① Displacement
The displacement of axial piston pump $q_b$ refers to the volume of the oil discharged from all the piston cavities when the cylinder body rotates for one circle, that is

$$q_b = F_Z s_{\text{max}} Z = \frac{\pi}{4} d_z^2 s_{\text{max}} Z$$  \hspace{1cm} (1)

② Flow rate
When the volume loss is not taken into account, the theoretical pump flow $Q_{ib}$ is

$$Q_{ib} = q_b n_b = \frac{\pi}{4} d_z^2 s_{\text{max}} Z n_b$$  \hspace{1cm} (2)

In the formula
- $d_z$ — the outer diameter of the plunger, mm;
- $F_Z$ — The cross-sectional area of the plunger, mm$^2$;
- $s_{\text{max}}$ — The maximum stroke of the plunger, mm;
- $Z$ — The number of plungers;
- $n_b$ — The speed of transmission shaft, r/min;

③ The volumetric efficiency of the pump
The volumetric efficiency of the pump $\eta_{ib}$ is

$$\eta_{ib} = \frac{Q_{ib}}{Q_{\text{theoretical}}}, \hspace{1cm} (3)$$

According to the structure of swash plate plunger pump and the setting of relevant parameters, the theoretical discharge flow under different conditions is simulated and calculated by the author, as is shown in Table 3. The actual flow rate on site needs to be further verified.

**Table 3. Simulation calculation statistical table of swash plate plunger pump parameter.**

| Inlet pressure (MPa) | Outlet pressure (MPa) | Forecast Flow Rate (L/min) | Theoretical Flow Rate (L/min) | Prediction of volumetric efficiency (%) |
|----------------------|-----------------------|-----------------------------|-------------------------------|----------------------------------------|
|                      |                       | Single         | Double   | Single | Double | Single | Double |
| 2                    | 0.1                   | 2.8            | 15       | 2.6    | 14.3   | 92.85  | 95.33  |
| 4                    | 0.1                   | 3.6            | 19.8     | 3.2    | 18.3   | 88.89  | 92.42  |
| 6                    | 0.1                   | 5.1            | 24.2     | 4.1    | 20.7   | 80.39  | 85.54  |
| 8                    | 0.1                   | 6.6            | 32.4     | 5.0    | 24.8   | 75.76  | 76.54  |
| 10                   | 0.1                   | 9.6            | 41.8     | 6.3    | 27.7   | 65.62  | 66.27  |

3. Conclusions
The pneumatic swash plate plunger pump system can not only solve the problem of external stable power supply for the implementation of drainage gas recovery technology in large water production wells, but also rely on the gas well's own energy for drainage and production without well killing, which protects the reservoir and saves the operating cost. The research and development of this technology will be of great significance to the drainage and production of wells with large water production capacity in the gas field and has a good prospect of promotion and application.

References
[1] Zhichao Z and Shumei C 2017 Optimization analysis on the cylinder of swashplate axial piston pump based on pumpinx *Hydraulics Pneumatics & Seals* (2) 35-42
[2] Hailang L 2015 Improvement of wear failure mode for swashplate and cradle bearing pair *Hydraulics Pneumatics & Seals* (10) 62-65
[3] Zhifeng L, He Y, Huanbo C and Ping X 2015 Method for determining best piston numbers of a swash plate axial piston pump China Mechanical Engineering (2) 237-242

[4] Siyuan L, Chuang W, Mengxue Y and Jianxun L 2017 Analysis of dynamic characteristics for severe wear process of swash plate axial piston pump slipper pair Chinese Hydraulics & Pneumatics (1) 1-5

[5] Wutao D and Songlin N 2014 Research on motion planning of linear motor driven piston pump China Mechanical Engineering 25(8) 1080-84

[6] Jin Z, Haoqian S, Xu'an D, Shuangqi K and Xiangdong K 2020 Analysis of influencing factors on flow pulsation of inline type double row axial piston pump Transactions of Beijing Institute of Technology 40(5) 481-490

[7] Zirong L and Xiuye W 2012 Swashplate piston pump instantaneous flow of research Coal Mine Machinery 33(7) 59-61

[8] Hu Z, Sen Z and Long Q 2013 Kinematic Simulation and analysis of axial piston pump with inclined plunger Hydraulics Pneumatics & Seals (6) 16-19

[9] Chenglie N, Wenbo Y and Yanqing N 2002 Design of valve plate of axial piston pump with compressible working medium Journal of Gansu University of Technology 28(4) 65-67

[10] Jihai J, Kun Y, Tong S, Guangwen Y, Ling J and Aoran Y 2017 Flow ripple property of double row axial piston pump Chinese Hydraulics & Pneumatics (9) 28-32

[11] Bihai Z, Xiaoyu W, Zhuang N, Xiaofeng H and Yinshui L 2013 Experimental research on the water hydraulic axial piston canned motor pump with double swash plate Journal of Mechanical Engineering 49(2) 146-150

[12] Yang P, Yibo L, Minghui H, Jun M and Dedong L 2016 Valve plate improvement and flow ripple characteristic analysis for double compound axial piston pump Transactions of the Chinese Society for Agricultural Machinery 47(4) 391-398