Research and application of key technology of electric submersible plunger pump

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Abstract. Electric submersible plunger pump is a new generation of rodless oil production equipment, whose improvements and upgrades of key technologies are conducive to its large-scale application and reduce the cost and improve the efficiency. In this paper, the operating mechanism of the unit in-depth study, aimed at the problems existing in oilfield production, to propose an optimization method creatively, including the optimal design of a linear motor for submersible oil, development of new double-acting load-relief pump, embedded flexible closed-loop control technology, research and development of low-cost power cables. 90 oil wells were used on field application, the average pump inspection cycle is 608 days, the longest pump check cycle has exceeded 1037 days, the average power saving rate is 45.6%. Application results show that the new technology of optimization and upgrading can further improve the reliability and adaptability of electric submersible plunger pump, reduce the cost of investment.

1. Introduction

With the development of oilfields, the artificial lift is mainly based on the two rod-lifting methods of pumping units and screw pumps, which account for about 90% of the total number of wells. The technology is very mature, however, a series of problems have exposed in the application of low-permeability reservoirs and heavy-oil reservoirs: big one-time investment, high useless energy consumption; sucker rod and tubing eccentric wear is very serious; ground equipment there is a security risk; In the flood season, low-lying areas affect normal production; There is a lot of work to manage and maintain [1,2].

In China, cylindrical permanent magnet synchronous linear motor used in underground as pumping drive has formed a small-scale field trials [3,4]. In response to the above problems Daqing peripheral oil field low yield and permeability zone block, through the development of electric submersible plunger pump and its supporting technology research, has initially formed a new energy-saving, efficient rodless oil recovery system, with good adaptability. However, there is a general lack of hoisting force in the oil well, vibration larger, which is caused by the design of the submersible linear motor [5,6]; Open-loop control leads to higher energy consumption, system efficiency is low, overload frequently [7]; Power cable is easy to breakdown, high cost caused by checking the pump cycle is shorter, big one-time investment and other issues [8,9]. Therefore, there is still a gap between the
technology and scale application in terms of technology, economy and adaptability, so it is urgent to conduct in-depth research and optimization of key technologies.

Based on this, this paper carry out an in-depth study of key technology of electric submersible plunger pump. First, deeply study the operating principle of the unit, then proposed the optimization method of the unit creatively in response to the above shortcomings in the field test, including the optimal design of a linear motor for submersible oil, development of new double-acting load-relief pump, embedded flexible closed-loop control technology, carry out cable design of special materials. Then carried out a large number of oilfield application tests, objective evaluation the application effect, and find a breakthrough technology in the application of large-scale.

2. Operation mechanism and key technology optimization

Electric submersible plunger pump is a new generation of rodless oil production equipment [10], it has gone through three stages: experiencing technological exploration and manufacturing, technical optimization and on-site testing, improving of the supporting technology, now it has entered the stage of further research of key technology and application expanding . Shown in figure 1, the process consists of submersible linear motor, plunger pump, ground control system, dedicated cable and other components, making linear motor as the power-driving device, integrate the linear motor with the tubing pump, dived into the underground oil reservoir. In this process: the linear motor is at the bottom, the tubing pump is at the top; The stator of the motor is connected with the oil pipe and the motor mover is connected with the plunger of the oil pump; The control system transfers the AC power to the downhole motor after the conversion of AC; The use of motor mover reciprocating motion consistent with the characteristics of the plunger to drive the plunger reciprocating cyclically to achieve crude oil lift.

![Figure 1. Electric submersible plunger pump lifting process schematic.](image)

2.1. Optimization design of submersible linear motor

The submersible linear motor is a kind of electromagnetic device that can use the electric energy directly to drive the load to do the linear motion without the intermediate conversion mechanism [11,12]. It belongs to a cylindrical permanent magnet synchronous linear motor. It is a structural evolution of a permanent magnet rotating electrical machine, it mainly consists of a stator, a mover and a motor leading wire. According to actual needs and downhole conditions, it is designed as a short junior long secondary, shown in figure 2, the motor stator is N and S interactive, consisting of the outer shell, the winding iron core and the inner cylinder, where the motor mover consists of a circular permanent magnet, a ring-iron core and a core shaft. The winding is in a radial twisting and axial
distribution structure, after the assembly of the winding iron core, it is placed in the oil-filled sealed chamber consisting of the inner tube and the shell. By controlling the frequency and direction of the power supply, the traveling wave magnetic field with periodic alternation of the stator interacts with the excitation magnetic field generated by the permanent magnet of the mover to generate the electromagnetic thrust and achieve the linear reciprocating motion of the mover.

![Submersible linear motor structure](image)

**Figure 2.** Submersible linear motor structure.

In practical application process, the motor contacts corrosive oil underground, the mover permanent magnet is gradually eroded, and the remanence of the cobalt rare earth permanent magnet material is too low, which seriously affects the back electromotive force constant of the motor and indirectly affects the carrying capacity of the motor; the resistance function of the stator is poor, the magnetoresistance on the yoke is high, the magnetic flux leakage seriously, the magnetic field utilization is low, thrust density is low; When the motor is running, the mover magnet and the spacer ring are easy to rotate, the concentricity with respect to the center connecting rod is poor, causing the inner cylinder of the stator to be worn. Based on this, according to the existing measured data of the motor and the actual demand of field application, this paper optimizes the motor on the basis of stable and mature mechanical structure so as to improve the continuous working performance of the motor in complex environment downhole, reduce vibrations during work.

Linear motor seal design: the stator inner cylinder closed welding, the inner cylinder spray welding nickel alloy powder, a thickness of 0.1 ~ 0.2 mm; Chrome plating on the surface of the mover enhances abrasion resistance and studies on the overall closed process of the mover permanent magnet to ensure complete separation of the mover and the stator from the oil; improve the processing technology, reduce the stator and the rotor axial dimension error, reduce unit vibration at the same time. For 5.5-inch casing design motor diameter 114 mm, 7-inch casing design motor diameter 143 mm, the stator magnetic field strength increased by 20%.

Movable permanent magnet anti-rotation design: movable strut material selection 1Cr18Ni9Ti, after the ring and the permanent magnet with the laser welding as a whole, to ensure that the external body and the strut at the same time, increasing the diameter of the strut, the central spar milling keyway, corresponds to the permanent magnet turning keyway, after assembly to enhance positioning, to prevent radial rotation. At the same time, under the premise of ensuring lifting force, according to the requirements of air gap magnetic field, the air gap is optimized from the original 0.05 mm to 0.3 mm. Avoid motor mover stuck phenomenon.

Thrust output capability improved: movable structure selection axial magnetic circuit structure, optimizing the axial length of the permanent magnet and pole pitch, magnet manufacturing simple magnetization; In order to avoid the influence of temperature and electromagnetic performance on the insulation of the motor, NdFeB permanent magnet with high coercivity is selected as the mover.
permanent magnet to improve the motor air gap magnetic field index; Under the same thrust index, the winding coil circular cross-section into a rectangular cross-section, in order to increase the coil full slot rate; Meanwhile, on the premise of ensuring the current passing rate, the outer diameter of the winding coil is optimized and the number of turns of the winding is increased, thereby remarkably reducing the thermal load index of the motor and enhancing the reliability of the motor operation.

For the submersible linear motor with rated voltage 1140 v, the motor diameter 114 mm, supporting Φ32 mm pumping pump test indoor evaluation. The results show: the optimized submersible linear motor is tested in an oil-water medium at 30 mpa for 24 hours without deformation and leakage; Winding in the hot state of ambient temperature 200℃, the application of AC 50 hz, 3300 v voltage, one minute after the test dielectric strength, no flashover and breakdown; apply a megohmmeter with a range of 2500 volts to test the insulation resistance, the insulation resistance of no less than 1000 megohms; Winding sintering temperature of 380℃, the motor temperature is not higher than 150℃ in the media run, to ensure that the rated thrust output. The optimized motor mover does not deform under the action of 4.5 t radial force, the maximum lift reaches 3220 m, which enlarges the applicable range of the technology. The comparison of motor performance before and after the optimization is shown in table 1.

| Motor diameter | Frequency (Hz) | 14 | 12 | 10 | 9 | 8 |
|---------------|---------------|----|----|----|---|---|
| Before optimization | Lifting force (t) | 1.9 | 2.1 | 2.4 | 2.6 | 2.7 |
| Φ110 mm | Head (m) | 1560 | 1710 | 2180 | 2290 | 2430 |
| | Safety factor | 1.0 | 1.1 | 1.4 | 1.6 | 1.7 |
| After optimization | Lifting force (t) | 2.0 | 2.5 | 2.9 | 3.3 | 4.5 |
| Φ114 mm | Head (m) | 2120 | 2560 | 2870 | 2950 | 3220 |
| | Safety factor | 1.2 | 1.4 | 1.7 | 1.8 | 2.0 |

2.2. Development of new double-acting load relief pump

Electric submersible plunger pump used in deep wells or supporting the pump diameter is large, it is easy to cause the plunger rod instability, resulting in plunger overload operation or card pump, for this reason we designed a new double-acting load relief pump. The upper and lower stroke of the pump all discharge oil, and the unidirectional load is reduced; The up plunger cross-sectional area of about twice the down cross-sectional area of the plunger, the plunger load up and down roughly the same load, the mover force reduced by about half; For example, a double acting pump with a diameter of 57/38 mm exerts the same force as a conventional piston pump with a diameter of 38 mm. The theoretical displacement corresponds to a conventional piston pump with a diameter of 57 mm; Upper and lower cylinder designed centralizer, to ensure the proper coaxiality, while reducing motor vibration. In order to avoid loosening of motor mover by large load pulling force and design of overcurrent passage in motor influence casing space and motor performance, will double-acting pump fixed valve design at the top, oil from the bottom of the sieve tube into the pump cylinder, traveling valve in internal plunger, all valve balls open in the same direction. Double-acting pump can effectively reduce the operating load, reduce motor power and investment costs, as shown in figure 3, when the plunger at the top dead center or bottom dead center, the leak-proof valve 2 is closed, effectively prevent pump loss, to ensure that the pump is full.

In order to adapt to the lifting of directional well and horizontal well better and to improve the pump efficiency of the new double-acting load relief pump, a spring return pilot valve, as shown in figure 4, in the fixed valve cover and travel valve cover is provided with four-in-one reinforcement bar, where the valve ball is only one degree of freedom, the valve ball can only move along the axis of the mask, the liquid flows around the four reinforcing bars. The structure has a larger flow area and a smaller opening degree, which can reduce the suction resistance and valve ball set lag time.
1. Coupling; 2. Leak-proof valve assembly; 3. Outer tube; 4. Fixed valve assembly; 5. Up Pump barrel; 6. Up plunger; 7. Swimming valve assembly; 8. Down plunger; 9. Centralizer; 10. Down Pump barrel; 11. Screening; 12. Pump down connector

Figure 3. New double-acting load relief pump.

Figure 4. Spring return pilot valve.

2.3. Embedded flexible closed-loop control technology

Through the optimization design of submersible linear motor and development of new double-acting load relief pump, unit vibration is reduced, the basic performance has improved. However, the original control system is open-loop control and belongs to a constant rigid drive. In overload operation, the motor mover will not keep up with the speed of the synchronous driving magnetic field and can not make a normal response to the load change, hard start, severe commutation and other issues, affecting the life of units, cables and downhole tools. For the above, the research on flexible closed-loop control of submersible oil linear motor based on the original frequency control technology is carried out. Its core is the long distance sensorless vector control technology, based on the vector control, the induction control is pulled in, and the flexible control algorithm is embedded in the sensorless vector control program, through the advanced intelligent adjustment of PID: automatic generation of full-stroke within the best operating speed distribution and output power distribution programs, and according to changes in operating conditions automatically optimize the operation of the program; Throughout the best speed distribution and power output distribution plan to do continuous variable speed operation, the electrical machinery and the controller completely realizes the closed-loop control by the software method.

The control system is composed of intelligent controller, driver and so on, and possesses functions of remote data transmission. It uses filtering and actuarial elimination of various disturbances to ensure high-speed acquisition and real-time complex operation of multiple operating parameters. And using 32-bit computing processor, through the acquisition and analysis of motor power, adjust the current and voltage, calculate the speed and thrust of the mover, and then automatically analyze the appropriate drive current, to achieve the minimum current efficient operation. It can be flexibly driven in the 0.1-10 specific water-cycle range, with the downhole load changes to adjust the motor output power, reduce starting load and system vibration, achieve flexible operation, flexible start, flexible stop. At the same time, based on the combination of submersible linear motor adaptive method and rotational speed observer method, timely reference downhole pressure sensor feedback, improve the motor out of step monitoring results, improve the accuracy of closed-loop control and adaptive tuning ability. Carry out indoor tests, under the same working conditions, respectively, the use of conventional control systems and flexible closed-loop control system to control the same submersible linear motor, the vibration intensity comparison curve shown in figure 5, the reference data shown in table 2.
The test results show that the application of the closed-loop control method, start-up current and operating current significantly reduced, the reduction of 53.94% and 44.73% respectively. At the same time, the system vibration intensity is also greatly reduced, the maximum value of the vibration intensity curve of conventional control method and flexible closed-loop control method are 0.577 m/s² and 0.287 m/s², reduce the rate of 50.26%.

2.4. Development of new aluminum cables

Electric submersible plunger pump used centrifugal submersible pumps dedicated copper wire core cable, cable costs account for an investment of 1/3. Due to the design of the technology is aimed at low permeability reservoirs, requiring a one-time investment is low, in order to be able to more adapt to the scene needs, conducive to expanding the scale of on-site applications.

In this paper, the characteristics of the operation of the integrated process, for the optimization of the submersible linear motor proposed selection of rare earth aluminum alloy wire instead of copper core, at the same time optimize the cable insulation and sheath material, design active filtering system, filter out the reflected voltage. From the cost input, size standards, material properties and other aspects can meet the site requirements, compared with the conventional copper cable, the cost reduction of about 20%. The new aluminum alloy cable indoor testing evaluation, as shown in table 3, the main indicators meet the relevant performance requirements.

| Control method  | Stroke (m) | Stroke times (min⁻¹) | Motor thrust (t) | Maximum current (A) | Average current (A) | Maximum power (kw) | Average power (kw) |
|-----------------|------------|-----------------------|-----------------|---------------------|---------------------|-------------------|-------------------|
| Routine         | 1.23       | 8                     | 1.22            | 58.71               | 35.17               | 51.57             | 29.74             |
| Flexible        |            |                       |                 | 27.04               | 19.44               | 23.02             | 16.30             |
| Reduce the rate (%) |         |                       |                 | 53.94               | 44.73               | 55.36             | 45.19             |

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| Cable type         | Width (mm) | Thickness (mm) | Diameter (mm) | Insulation resistance (MΩ, 1000m) | Three-phase imbalance rate (%) | Pressure resistance (kV) | DC Leakage (μA) |
|--------------------|------------|----------------|---------------|-----------------------------------|-------------------------------|--------------------------|-----------------|
| Copper core        | 37.56      | 15.21          | 4.42          | 5714                              | 0.048                         | 22                       | 4.7             |
| Aluminum alloy     | 39.15      | 14.98          | 5.59          | 4762                              | 0.055                         | 22                       | 7.5             |
3. Field application

In the low permeability zone of a certain oilfield, a field test was conducted on the optimized electric submersible plunger pump to evaluate its application effect in production. On-site optimization of the submersible linear motor total of 90 wells, among them, 4 wells are used in combination with the new double-acting load relief pump, 12 wells are used in combination with the flexible closed-loop control technology, 1 wells are used in combination with the new aluminum cables.

Up to now the overall application effect is as follows: the average pump hanging 1199 m, the deepest 1865 m; The average liquid level 1032 m, nissan liquid 2.7 t, pump efficiency 55.4%; average pump inspection period 608 days, the longest 1037 days; the average free repair period 438 days, among them, 22 oil wells which were put into trial operation in the early stage have an average maintenance-free period of more than 1000 days and a maximum of 1485 days, respectively, compared with the same displacement rod pumping method, the average saving rate reached 45.6%. Among them, 1 oil well with new cable has been running smoothly for 578 days, after 5 times of normal well washing, the cable did not break down, which initially showed that the performance indexes of the new cable meet the field application requirements.

Field application shows that compared to the optimization before, the average pump inspection cycle increased from 452 days to 608 days, the average system efficiency increased by 6.9%, enhances the reliability of the operation of the process, significantly improves the energy-saving effect and lift capacity, enlarges the applicable range of the process, and achieves cost reduction and efficiency increase.

On-site application of new double-acting load-relief pump, motor mover current value is basically balanced, compared with the conventional φ57 mm plunger pump, nissan liquid volume is basically the same. Head raised 217 m, up current down 27.9%; Compared with the conventional φ38 mm pump, nissan liquid volume increased nearly 1 times. Upstream current is basically the same. The test results show that the pump can effectively reduce the unit operating load, to reduce the motor power and investment costs to create the conditions for extending the life of the unit, the scene test comparison data is shown in table 4.

### Table 4. Double-acting pump and conventional piston pump field test comparison data.

| Hashtag | Pump type (φ,mm) | Liquid level (m) | Stroke times (min⁻¹) | Yield (m³/d) | Uplink current (A) | Downlink current (A) |
|---------|------------------|-----------------|----------------------|-------------|-------------------|---------------------|
| 1       | Conventional 57  | 453             | 3                    | 11.0        | 43                | 5                   |
| 2       | Conventional 38  | 768             | 4                    | 6.0         | 29                | 11                  |
| 3       | Double-acting 57/38 | 670           | 3                    | 11.5        | 31                | 31                  |

### Table 5. Comparison of routine and flexible control field application data.

| Control method | Working Frequency (HZ) | Uplink current (A) | Average input power (kw) | Daily consumption (kwh) | System efficiency (%) |
|----------------|------------------------|--------------------|--------------------------|-------------------------|----------------------|
| Flexible       | 8                      | 4.49               | 3.953                    | 94.90                   | 27.90                |
| Routine        | 7.55                   | 6.755              | 162.14                   | 43.25                   | 16.33                |
| Flexible       | 2.96                   | 2.552              | 61.20                    | 43.25                   | 43.25                |
| Routine        | 4.50                   | 3.927              | 94.32                    | 28.07                   | 28.07                |
For the same well, under the condition of the same well conditions and working parameters, flexible closed-loop control system and conventional control system are respectively used for testing and evaluation. Under the two kinds of control modes, the field application effect comparison is shown in table 5. One of the conventional control mode operation, occurred two overload shutdown phenomenon, flexible closed-loop control mode of operation, stable and reliable.

Field application results show: flexible closed-loop control system can well avoid overload shutdown, energy-saving effect is obvious, the unit system efficiency significantly improved. When the submarine linear motor mover uplink frequency 8 hz, downlink frequency 15 hz, under the two control modes, the uplink real-time current and power curve is as shown in figure 6 and figure 7, it can be seen that the flexible closed-loop control mode effectively reduces the starting impact and running load, and the operation of the unit is stable and reliable.

![Figure 6. Motor mover uplink real-time current curve comparison.](image)

![Figure 7. Motor mover uplink real-time power curve comparison.](image)

4. Conclusion
Electric submersible plunger pump is a new generation of rodless oil extraction equipment, the deeply study of the key technology and the large-scale application is the inevitable trend of its development. This paper proposes an optimization method for this production technology creatively: optimization design of submersible linear motor, development of new double-acting load-relief pump, embedded flexible closed-loop control technology, research and development of low-cost power cables. The field application of 90 wells, the average pump inspection cycle 608 days, the longest pump inspection cycle exceeded 1037 days, the average saving rate reached 45.6%. The application results show that the new process of optimization and upgrading can further improve the reliability of the lifting process of the electric submersible plunger pump, reduce the one-time investment cost and broaden the technical and economic adaptability. For the process to digital management, energy efficient, safety and environmental protection in the direction of development, and reasonable control of oil field development costs, improve development effectiveness provided technical support; This technology laid the foundation for the exploration and research of deep well lift.

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