Design and Efficiency Analysis of Small Displacement Pump

Tiancai Cheng1*, Minzheng Jiang1

1School of Mechanics Science & Engineering, Northeast Petroleum University, Daqing, Heilongjiang, 163318, China

*Corresponding author’s e-mail: tiancai0926@126.com

Abstract. To address the common issues of low-production oil wells like unbalanced supply and output, low pump efficiency and system efficiency and high energy consumption, a small-displacement oil pump has been developed. The pump has an enhanced structural strength with solid plunger and the mobility of the pumping oil with offset outlet valve. The outlet valve is located at the highest point of pump chamber when the plunger is at the bottom dead center, which is preferable for the discharge of gas and high gas-liquid and pump efficiency improvement. Combined with the distribution law of oil and gas in vertical pipe flow, it is assumed that the dissolved gas is linearly distributed from the oil inlet valve to the bottom end of the plunger after the pump is introduced. According to the position of the oil pumping valve of the oil pump, the efficiency calculation formula is derived. Then through reasonable matching of working conditions, the influence of various factors on pump efficiency is analyzed. The pump's pump efficiency is about 10% higher than the API minimum pump diameter (32 mm), which is important for energy saving in oil fields.

1. Introduction

At present, the number of low-yield oil wells in China exceeds 100 thousand, and the efficient mining of unconventional oil and gas reservoirs such as low permeability and ultra-low permeability has become one of the main directions of high-yield and stable production of oil fields. However, since this part of the reservoir has a daily production of less than 2m³, the application of the API minimum pump diameter (32 mm) will result in uncoordinated supply and discharge, resulting in system efficiency below 15% [1-2].

Through the analysis of the structure and principle of small displacement pump used in today’s oil fields [3], the main reasons for limited application in low-yield oil wells are: ① Solid plunger structure makes the highest part of the pump chamber always in a sealed state, the suction gas is difficult to discharge, and severely causes air lock [4]; ② The thickness of the cover wall of the upper outlet valve, especially the cover rib is too small, which is easy to break and affects the normal production [5]; ③ The pump travel valve is externally installed, eliminating the downstream moving valve, and the clearance volume is too large, which is only suitable for large submerged conditions [6]. In view of the above shortcomings, a small displacement oil pump is developed, which is solid and reliable, with small clearance volume and easy to discharge the gas out of the pump cavity.

2. Technical analysis

2.1 Structural design
The designed small displacement pump consists of a plunger assembly, a pump cylinder assembly, a biasing oil outlet valve assembly and an oil inlet valve assembly and so on. The pump adopts a solid plunger structure, and the oil discharge valve is biased to the pump axis, which enhances the structural strength of the pump and the fluidity of the pumped crude oil. When the plunger is at the bottom dead center, the oil discharge valve is located at the highest point of the pump chamber, which is beneficial to the discharge of the gas and the high gas-containing liquid in the pump chamber and the improvement of the pump efficiency. The basic structure is shown in Figure 1.

2.2 Working principle

When the air content of the oil well is high or the liquid supply is insufficient, there is a part of gas or high gas liquid in the pump cavity, as shown in Figure 3. During the upstroke, gas or high gas liquid will accumulate at the bottom of the plunger and occupy a part of the pump cavity. When the plunger moves downward, the plunger pushes the crude oil downward. When the lower end face of the plunger moves downward below the oil outlet valve, the plunger speed decreases to the minimum. The gas or high gas liquid close to the lower end face of the plunger will be transferred to the bottom end of the oil outlet valve due to the buoyancy. When the plunger runs to the lengthened nipple and enters a part, the gas or high gas liquid will be completely discharged from the pump cavity. The inlet passage of the pump is straight, the gas escaping from crude oil is reduced, and the oil outlet valve is ensured to be at the highest position of the pump cavity when the oil is discharged, so as to solve the influence of the difficult discharge of the dissolved gas from crude oil on the working performance of the solid plunger pump.

3. Pump efficiency analysis

3.1 Pump efficiency calculation
The pump efficiency $\eta$ directly reflects the oil recovery effect of the pump, and its value is the ratio of the actual displacement $Q_s$ to the theoretical displacement $Q_t$. 

Figure 1. Overall structure of small displacement pump

Figure 2. Exhaust schematic diagram of small displacement pump
Where $A$ is cross-sectional area of the plunger, m$^2$; $S$ is the stroke, m; $n$ is the frequency, min$^{-1}$.

The main factors affecting pump efficiency are pump fullness coefficient $\eta_c$, piston stroke loss coefficient $\eta_s$, leakage loss coefficient $\eta_l$ and liquid shrinkage coefficient $\eta_b$, as shown in formula (3). Among them, in addition to the fullness factor, structural changes have less impact on other factors. Therefore, assuming that the piston stroke loss coefficient is 88%, the leakage amount (including gap leakage and valve gap leakage) coefficient is 96%, and the liquid shrinkage coefficient is 95%.

\[
\eta = \eta_c \eta_s \eta_l \eta_b
\]  

(3)

The typical formula for calculating the filling coefficient of pump barrel is[7]:

\[
\eta_c = \frac{1}{1 + R} \left\{ 1 - \frac{KR}{1 + R \left( \frac{P_c}{P_d} \right)^{\frac{1}{2}}} \left[ 1 - \left( \frac{P_c}{P_d} \right)^{\frac{1}{2}} \right] \right\}
\]  

(4)

Where $R$ is gas liquid ratio; $K$ is clearance volume ratio, clearance volume to plunger yield volume ratio; $P_i$ is submergence pressure, MPa; $P_d$ is outlet pressure, MPa.

Formula (4) shows that the dissolved gas of crude oil in the pump cavity is always uniformly distributed, which obviously does not conform to the distribution law under the actual working condition. Combined with the distribution law of oil and gas in vertical pipe flow, it is assumed that the dissolved gas is linearly distributed from the oil inlet valve to the bottom end of the plunger after entering the pump. According to the position of the oil pumping valve of the oil pump, the following pump efficiency calculation formula is derived.

When the plunger is at the bottom dead center, the oil discharge valve is not at the bottom end of the pump chamber, and the pump efficiency calculation formula is:

\[
\eta = \frac{0.80256 \cdot \left( 1 - \frac{2KR}{1 + R \left( \frac{P_c}{P_d} \right)^{\frac{1}{2}}} \left[ 1 - \left( \frac{P_c}{P_d} \right)^{\frac{1}{2}} \right] \right)}{1 + R}
\]  

(5)

When the plunger is at the bottom dead center, the oil discharge valve is at the bottom end of the pump chamber, and the pump efficiency calculation formula is:

\[
\eta = \frac{0.80256 \cdot \left( 1 - \frac{2KR}{1 + R \left( \frac{P_c}{P_d} \right)^{\frac{1}{2}}} \left[ 1 - \left( \frac{P_c}{P_d} \right)^{\frac{1}{2}} \right] \right)}{1 + R}
\]  

(6)

### 3.2 Influence of well conditions on pump efficiency

The designed pumping pump diameter is 25mm, and the theoretical displacement is calculated according to formula (2). At this time, the factors affecting the displacement are mainly stroke and frequency. The effect of stroke and frequency on theoretical displacement is shown in Figure 3.

The reasonable submergence and gas-liquid ratio are selected for low production wells, and the effect of submergence and gas-liquid ratio on pump efficiency is analyzed. The effect of submergence and gas-liquid ratio on pump efficiency is shown in Figure 4.
Figure 3. The effect of stroke and frequency on displacement

It can be seen from Figure 3 that the small displacement pump can adapt to the displacement condition of 0.707–16.96 $m^3\cdot d^{-1}$. Combined with the predicted theoretical displacement coefficient (the displacement coefficient has a certain change with the stroke), the stroke and frequency can be adjusted to complete the matching of the working conditions.

Figure 4. The effect of submergence and gas-liquid ratio on pump efficiency

It can be seen from Figure 4 that under different degrees of submergence and gas-liquid ratio, the pumping range of the small displacement pump is 32–73%. However, the effect of gas-liquid ratio on pump efficiency is relatively large, and the influence of submergence is relatively small. The pump efficiency of the small displacement pump is about 10% higher than the API minimum pump diameter (32 mm) under low-submergence conditions.

4. Conclusion

(1) The plunger of the small displacement pump adopts a solid structure, which is firm and reliable, can reduce the breakage of the plunger and reduce the cost of salvage operations. The oil discharge valve is biased, the inner flow path is straight, and the resistance loss of the pump fluid is small, which reduces the gas escape of the crude oil pumped into the pump, and improves the pumping efficiency of the pump.

(2) The pump overcomes the problem that the residual gas in the pump cavity of the solid plunger pump cannot be discharged, improves the inflow characteristics, and improves the pump efficiency and working condition adaptability. This provides a basis for the promotion and application of small displacement pump, which is of great significance for energy saving and consumption reduction in oil fields.

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