Experimental Study on a Novel Linear Electromagnetic Pumping Unit

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Abstract—High loss of energy is a common problem in all oil fields. It is mainly caused by the intrinsic disadvantage of traditional beam-pumping units, such as complex transmission devices, short stroke, low efficiency, etc. The aim of this paper is to apply Electromagnetic Launch technology in oil-pumping unit. Both Electromagnetic Launch technology and Linear Motor technology are combined to develop a novel direct-driven Electromagnetic pumping unit (EMPU) in which each coil is driven and controlled separately. The principles and working process of the electromagnetic pumping unit are described. With the conditions of work environment being taken into consideration, experiments were conducted to test and verify the performance of the model prototype. The disadvantages of a traditional oil-pumping unit are overcome by the novel linear electromagnetic pumping unit.

Index Terms—Electromagnetic launch (propulsion), electromagnetic pumping unit (EMPU), energy conservation, linear motor.

I. INTRODUCTION

SUCKER-ROD oil pumping is one of the conventional methods, and, at the same time, the dominant method used in the present world petroleum industry. More than 90% of the mechanical oil pumping wells all over the world are sucker-rod pumping wells [1].

The above-ground sections of sucker-rod pumping equipment are called pumping units, most widely used of which are beam-pumping units. With the development of related techniques, performance of sucker-rod pumping units have their advantages, such as simple structure, easy manufacture and maintenance, enduring performance in all kinds of weathers, high reliability, etc. At the same time, they have many deficiencies. Speed reducers and four bar linkages are required to convert the motors’ rotational motion to linear motion. The suspension centers of the horseheads accelerate quickly and are difficult to balance. Efficiency of the units is quite low because of the existence of speed reducers and four bar linkages. When the stroke is long, the pumping units become large, heavy and costly. There are some beam-less pumping units, such as chain drive pumping units, hydraulic pumping units, pneumatic pumping units and flexible transmission pumping units [1]. Although their driving pattern and structure are different, they bear similar deficiencies as the beam pumping units.

The load fluctuation pattern of sucker-rod pumping equipment is much more complex than that of common equipment. Complex load fluctuation patterns and a long drive chain lead to a very low efficiency of the whole system. Nowadays, in most Chinese oil fields, pumping equipment costs about 1/3 of the whole energy supply. High loss of energy and low output make reducing the great expense of electricity a very urgent problem. Most pumping units use rotational motors, mainly asynchronous motors, as their prime mover. Many improvements have been made on the rotational motors to save energy. There are several typical methods [2]: 1) high slip motor; 2) frequency control motor; 3) permanent magnetic synchronous motor; 4) multiphase motor with large starting torque; 5) multi power motor. Much research work has been done to save energy by using a wound-rotor asynchronous motor, Y-delta transmission motor, and energy conservator or accumulator. Efforts made on motors can be divided to two categories: One is to improve the mechanical characteristics of motors by altering their power supplies or structure. In other words, efficient coordination between the motors and pumping units are improved to save energy; the second way is to raise the efficiency of the motors by increasing their power factor and duty ratio. It is obvious that the former category has more latent capacity. It is also the current main research direction.

Besides efforts made on motors, much experimental work has been done on altering the mechanical structure, such as mounting overruning clutches to the pumping units, adding springs to the beam pumping units, etc. In general, innovations and improvements are made primarily on the conventional beam pumping units. Some other types of pumping units, such as chain drive pumping units and planetary geared pumping units also rely on speed reducers and bar linkages to convert the motors’ high speed rotational motion into the polished rods’ low speed linear motion. Therefore, they remain with intrinsic disadvantages, such as complex transmission devices, bad controllability and low efficiency.

In order to overcome these difficulties, both linear motor technology and driving technology of electric coil guns are employed to develop a novel direct-driven linear electromagnetic pumping unit.

II. WORKING PRINCIPLES OF LINEAR ELECTROMAGNETIC PUMPING UNIT

Coil guns—one kind of linear electromagnetic guns—were originally called “coaxial launcher” or “mass driver.” They rely on the magnetic coupling of the excitation coil and the projectile to work. The projectile can be coil or permanent magnets. The coil projectile is driven by a magnetic travelling wave, which is produced by pulse or alternating current. Therefore, coil guns can be regarded as a special kind of linear motor [3].
Fig. 1. The working principle of the electromagnetic pumping unit.

Fig. 1(a) shows the working principle of the electromagnetic pumping unit. Two coils are placed co-axially. The coils can be circular or other shapes. One of the two coils should be fixed as field coil. Suppose coil 2 is the field coil and the currents through coil 1 and coil 2 are respectively $I_1$ and $I_2$. According to classical theory on electromagnetic field, the magnetic fields excited by the two coils interact with each other. In other words, there is an interaction of electromagnetic force between the two coils. The force on coil 1 can be computed through the following formula:

$$F_1 = B_2 \times l_1$$

$I_1$, $B_2$ and $l_1$ are respectively the current through coil 1, the magnetic field excited by coil 2 and the perimeter of coil 1. Because coil 2 is fixed, coil 1 moves along the axis under the action of the axial component of $F_1$. Therefore, the direction in which coil 1 moves is decided by the direction of $I_1$ and $I_2$. A high performance circular permanent magnet may be employed to replace one coil to reduce excitation loss and improve efficiency. The radial component of $F_1$ can be reduced by choosing proper direction of the charging magnetism. Therefore the system’s efficiency can be further improved, as is shown in Fig. 1(b).

III. CONSTITUTION AND STRUCTURE OF THE MODEL ELECTROMAGNETIC PUMPING UNIT

Linear electromagnetic launch technology has been successfully used in many fields since it was developed. With the rapid development of permanent magnetic material, power electronics and modern control technology, the research and manufacture of a direct-driven linear electromagnetic pumping unit becomes practical. Fig. 2 shows the constitution of a model of the EMPU.

Fig. 2. Diagram of constitution of EMPU.

It is composed of a derrick, beam, balance weight, cable drum, control casing and the main body of the pumping unit [4].

In order to raise the system’s efficiency, several measures can be used, such as minimizing the loss of energy by choosing a proper balance weight, which balances the thrust force in the upward-stroke and down stroke so as to reduce the fluctuation range of the peak value.

As is shown in Fig. 3, a cylindrical structure is adopted in the main body of the unit to diminish lateral end effect. The stator is a co-axial coil assembly composed of $N$ coils and a core. The active cell is composed of mild steel pipe, which is used as field yoke, and a permanent magnet mounted on its surface [5].

The circular permanent magnet is Nd–Fe–B whose maximum product of magnetic energy $(BH)_{max}$ is 397.9 KJ/m$^3$ and maximum remanent magnetism is 1.47 T, which is enough to generate the necessary air gap induction. The permanent magnet is charged radially. The mild steel pipe, which is used as the active cell’s field yoke, also serves as rack. At the end of the model, oily slide bearings are adopted because of the low working speed. Specific sizes of the model are shown in Fig. 3 and Table I. On-and-off Hall units are used as position transducers, which detect the position of the moving cell. Coils under different magnetic polarity are energized with different-direction currents according to the polarity of the magnet to generate a uniform force, which pushes the active cell in certain direction. The currents through the coil under the neutral line will be reversed in order to generate a continuous thrust in the same direction. During the upward-stroke, the electromagnetic force generated by the pumping unit’s active cell and the gravity of the balance weight, which functions through the steel cable and the polished rod eye, work together to raise the sucker-rod to its maximum stroke. While during the downward stroke, the electromagnetic force of the unit and the gravity of the sucker rod work together to raise the balance weight and increase its energy storage, which will help balance the force of the pumping unit during the upward and downward stroke.

Like the working principles of some kinds of coil guns, each coil of the electromagnetic pumping unit is energized and controlled separately. Only those coils in the magnetic field work and thus reduce the copper loss of the coils compared with the case in which all the coils are energized. This characteristic becomes more obvious when the stroke is longer. Fig. 4 shows the diagram of the control system. Modulized design is used in the motor so that the maximum stroke of the electromagnetic pumping unit can be easily adjusted by adding or removing
The regulation of the frequency of stroke can be achieved by controlling the speed of the sucker rod.

Therefore, the design conforms with the requirement of the pumping units—long stroke and low frequency.

### IV. RESULTS AND ANALYSIS

According to the parameters shown in Fig. 3 and Table I, experiments were conducted on the model prototype of the linear electromagnetic pumping unit. Figs. 5 and 6 show the diagrams of the control system and basic configuration of testing system respectively. In the testing system, an optical grating is used to detect location and velocity of EMPU, and a foilgauge is used as the pull transducer to test the thrust of EMPU. A DC torque motor is employed to supply the variable load required in the testing process. Because the coils of the unit work intermittently, the amount of current through these coils should be large. The theoretical and experimental thrust versus current characteristic and speed versus load characteristics are shown in Figs. 7 and 8 respectively.

The value of the thrust is 1655 N when the value of the current is 15 A, Fig. 7. The correspondent thrust-to-mass ratio and thrust-to-volume ratio are respectively 29.7 N/kg and 52.9 N/L. Fig. 7 shows that thrust $F$ of the pumping unit can be controlled by regulating the current through the coils, consequently, the whole system's efficiency can be raised by adapting thrust to the variation of the size of load. The speed of the pumping unit should meet the requirement of the working environment.
The pumping unit’s load is affected by many factors, but it remains stable during a certain period. A diagram of a simulated load variation-dynamic-dynagraph is shown in Fig. 9. The load fluctuation is simulated by a DC torque motor. Fig. 10 shows the speed versus location of stroke characteristic of the model EMPU. Experiment results of the prototype and the principle of the similarity of motors show that it’s feasible to develop a practical engineering prototype.

V. CONCLUSION

Electromagnetic Launch Technology and Linear Motor Technology are combined by the researchers to develop a novel direct-driven EMPU. The rapid development of permanent magnetic material and power electronics in recent years lays a solid foundation for this project. Compared with conventional pumping units, the novel electromagnetic pumping unit greatly reduces the length of the drive chain from the prime mover to the sucker rod, which is different from improvements made on conventional pumping units. A novel approach is proposed to solve the problem of high loss of energy in oil fields. The novel EMPU has advantages, such as simple structure, high efficiency, long and adjustable stroke, adjustable speed etc. These advantages are in accordance with the present developing trends of pumping units. Small volume and compact structure make the novel pumping unit more accommodating to some special working environments, such as, offshore oil exploitation, cluster well, etc. Expected thrust and controllability are acquired in experimental research on the prototype, while the reliability is still to be tested. These experimental results lay a foundation for the development of the engineering prototype of a linear electromagnetic pumping unit.

REFERENCES