Influence of high temperature demagnetization on lifting capacity of linear motor reciprocating pump

Cheng Jian\(^{1a*}\)  Lei Ma\(^{1b}\)  Weifeng Yang\(^{2a}\)  Qing Huang\(^{1c}\)  Jing Xu\(^{1d}\)  Huan Zhai\(^{3a}\)  Guangsheng Cao\(^{4a}\)

\(^{1a}\) China Natl Offshore Oil Corp, Zhanjiang Branch Co, Zhanjiang, Peoples R China
\(^{2}\) CNOOC Energy Technol & Serv, Engineering Technology, zhanjiang, Peoples R China
\(^{3}\) China Oilfield Services Limited, Tianjin, Peoples R China
\(^{4}\) Key Laboratory of Enhanced Oil & Gas Recovery of Ministry of Education, Northeast Petroleum University, Daqing 163318, P. R. China

\(^{1a}\) jiancheng@cnooc.com.cn, \(^{1b}\) malei1@cnooc.com.cn, \(^{2a}\) ex_yangwf@cnooc.com.cn, \\
\(^{1c}\) huangqing@cnooc.com.cn, \(^{1d}\) xujing11@cnooc.com.cn, \(^{3}\) ex_zhaihuan@cnooc.com.cn, \\
\(^{4}\) nepucgswz@163.com,

Abstract—The submersible linear motor reciprocating pump is a new type of artificial lift. The demagnetization effect of its permanent magnet at high temperature will reduce the lifting capacity of the linear motor reciprocating pump. In this paper, the thermal stability of NdFeB permanent magnet material was studied by simulating the underground temperature and pressure conditions in a high-temperature and high-pressure reactor and combining with a Tesla instrument. The results show that NdFeB material loses its magnetism rapidly at high temperature, and the residual magnetism is proportional to the ambient temperature of the magnet. The high temperature demagnetization effect of large magnets is more serious due to eddy current loss and hysteresis loss.

1. Introduction

NdFeB permanent magnet material is a high-performance permanent magnet material that came out in 1983. It has the characteristics of high remanence density, high magnetic energy product and high coercivity. Its magnetic property is higher than that of rare-earth cobalt permanent magnet and it is the permanent magnet material with the highest magnetic property in nowadays. There are two main reasons for electromagnetic field to affect magnetic loss of magnets: hysteresis loss and eddy current loss. Hysteresis loss refers to the hysteresis loop that occurs between the magnetic induction intensity of the magnet and the external field intensity when the maximum flux density generated by the external magnetic field at the magnet exceeds the residual magnetism of the permanent magnet itself. The hysteresis loss is numerically equal to the area of the hysteresis loop. In general, hysteresis loss is not considered. However, due to the high operating temperature of the linear motor in deep Wells, the hysteresis loop will change, and the hysteresis loss generated will also increase, and even exceed the eddy current loss, which becomes the main cause of permanent magnet loss or even failure.

The current research on permanent magnet linear motor focuses on the performance of the motor as a whole, and mainly analyzes the interaction of permanent magnets in the motor to establish digital and physical models. Professor Zhang Bingyi analyzed the eddy current heating and magnetization loss of permanent magnet linear motor in detail by means of physical experiment and digital simulation,
and put forward the solution [1]. Based on 12 years of experiments, Parilov drew the conclusion of logarithmic loss of magnetic force of magnets in a very long time [2]. Liu Guozheng et al. made a comparison between the performance of the sweater cobalt magnet and NdFeB magnet and drew the conclusion of strengthening the anti-corrosion coating of NdFeB material [3]. Lin Dehua et al. concluded by simulation calculation that the magnetic field on the surface of the permanent magnet body is a non-uniform magnetic field, and gave the optimal magnet size [4]. However, for linear motors used downhole, no studies have taken into account the higher environmental requirements in the formation. In this paper, the thermal stability of NdFeB permanent magnet material was studied by simulating the downhole temperature and pressure conditions with high-temperature and high-pressure reactor combined with Tesla instrument.

2. Experimental design of high temperature permanent magnet demagnetization

The permanent magnet is heated in a water bath at different temperatures and times to evaluate its magnetism. The Gaussian value of each part of the permanent magnet is measured by a Tesla instrument to evaluate the value numerically. By the influence of the magnet on the attraction of iron, change its value in the balance, for a more intuitive evaluation. In order to prevent the magnet from sticking to the wall of the high temperature reactor, the permanent magnet was protected by wrapping with wood blocks. Tesla meter was used to measure the minimum Tesla values of the center points of the upper surface, short side and long side of the magnet, and the maximum value of the permanent magnet angle was recorded. Use a balance to measure a regular iron block, add a magnet on top of the iron block to measure its weight, and then measure the mass of the empty balance affected by the magnet.

![Figure 1 Schematic diagram of experimental engineering](image)

3. Experimental results and analysis

![Graph 1](image)

![Graph 2](image)
At 60℃, the magnetic flux density of NdFeB permanent magnet at each position decreased about 40mT. The magnetic flux density decreased rapidly in the first two hours, and then fluctuated slightly. The magnetic flux density of the magnet decreases by about 60mT at 80℃. The magnetic flux density of the Angle increased slightly after heating for 3-4 hours, indicating that the magnetic induction intensity did not only show a downward trend at a certain temperature. At 100℃, the magnetic flux density at the angular position decreased more, about 100mT, and about 70mT at the middle position. This indicates that the magnetic loss of the magnet at high temperature does not decrease uniformly as a whole, and the magnetic loss at the Angle is more serious than that at other positions. Combined with the problem that the magnetic force drops too fast in the previous experiment, at 120℃, it was decided to measure the magnetic flux density every ten minutes. Within ten minutes the flux density had dropped dramatically, and within twenty minutes some of the domains inside the magnet had been redirected.

The flux density of the large magnet changes faster at high temperature than that of the small magnet. The domain transition was completed in ten minutes. The relation curve between the final residual flux density at each position of the magnet and the temperature, Under the intercept temperature, the final remanence at each position will be reduced to zero. According to the regression curve equation, the curve intercept of the Angle position is 166.16℃, the midpoint of the short side is 148.68℃, the midpoint of the long side is 147.27℃, and the middle position is 145.81℃.
Magnet suction varies greatly at different reaction times, and magnet magnetism will decrease significantly at about 4h. Therefore, for linear motors with high formation temperature, it is particularly important to select magnetic materials with good heat resistance for permanent magnet actuators, so as to prevent permanent magnet failure caused by high underground temperature.

4. The influence of high temperature permanent magnet on the service life of linear motor

It can be seen from the experiment that the loss of magnetization of permanent magnets at high temperature is not gradual loss of magnetization over a long period of time, but the remanent magnetism of magnets at the temperature has been reduced in a very short period of time. Therefore, deduce linear motor, eventually fails, perhaps because the outer magnetic field, the electromagnetic constitute the central branch produce material losses, such as iron loss, copper loss, magnetic hysteresis loss and eddy current loss and so on to generate heat, cause temperature rise gradually, magnet remanence decreases with the rise of temperature, and also after reaching a certain threshold, the remanent magnetism of magnets will no longer be able to support work, then the motor is damaged.

The motion process of the actuator of the linear motor reciprocating pump is relatively stable, and the displacement presents an approximate linear change in the up-stroke or down-stroke process. The change rule is first acceleration, uniform speed, and then deceleration. The relation of acceleration time of linear motor is as follows:

\[ a(t) = b \omega \cos(\omega t) \quad 0 \leq t \leq t_0 \]  
\[ a(t) = 0 \quad t_0 \leq t \leq \frac{T}{2} - t_0 \]  
\[ a(t) = -b \omega \cos(\omega t) \quad \frac{T}{2} - t_0 \leq t \leq \frac{T}{2} \]

Among them:

\[ \omega = \frac{4\pi}{T} \]  
\[ T = \frac{60}{N} \]  
\[ t_0 = \frac{T}{8} \]  
\[ b = \frac{s}{\frac{4\pi}{T}(1 - \cos(\omega t_0) + \cos(\frac{2\pi}{T} - \cos[\omega(\frac{T}{2} - t_0) + \sin[\omega(\frac{T}{2} - t_0)]]) + (\frac{T}{2} - t_0) \sin(\omega t_0) + \sin[\omega(\frac{T}{2} - t_0)]t_0} \]
Table 1 Actual parameters of motor operation

| Depth of lower pump | Crude oil density | Tube diameter | Oil well production |
|--------------------|------------------|---------------|--------------------|
| 2500m              | 679kg/m³         | 62mm          | 10m³/d             |
| Plunger diameter   | stroke           | Impact times  | Electromagnetic thrust |
| 38mm               | 1.23m            | 6times/min    | 6T                 |

In the process of motion, the linear motor is mainly affected by the magnetic force of the magnet, the gravity of the liquid column, the inertia force of the liquid column and the friction force of the plunger and the bushing. The above table is a hypothetical condition. According to the force and movement of the linear electromobile, the mechanical characteristics of the linear electromobile can be determined as follows [5].

\[
F = ma = F_{\text{magnetic}} - mg - ma - F_{\text{friction}} = m \times b \times \omega \times \cos(\omega t)
\]

(8)

When \( t = 0 \), the maximum acceleration is achieved. At this point, \( \cos(\omega t) = 1 \), then the acceleration of the electric motor under normal operation is:

\[
a = b \omega = 0.377386969 \text{ m/s}^2
\]

(9)

In which \( b = 0.300467332 \), \( \omega = 1.256 \), \( m = 5124.872154 \text{ kg} \), \( g = 9.8 \text{ N/kg} \). If the permanent magnet is demagnetized at high temperature, then:

\[
F_{\text{magnetic}} = mg + 2ma + 1717 \text{ N}
\]

(10)

Then, when the magnetic force of the magnet is affected by high temperature demagnetization and the magnetic force of the permanent magnet of the linear motor decreases, leading to the decrease of electromagnetic thrust, the acceleration of the linear motor changes as follows:

\[
2ma = F_{\text{magnetic}} \times \text{Decrease percentage} - mg - 1717 \text{ kN}
\]

(11)

It can be intuitively seen from the table that the acceleration of the linear motor decreases with the decrease of the magnetic force. When the magnetic decline is reduced to 94.5%, the actual actuator acceleration of the linear motor is less than the rated acceleration. When the decline of the magnetic force is reduced to 88%, the acceleration of the linear motor is negative, indicating that the actuator of the linear motor can no longer generate acceleration at this time, which means that the speed of the actuator is zero and no motion is generated, and the linear motor cannot work and its life is terminated.

![Figure 5 The relationship between magnetic force change and acceleration](image-url)
5. Conclusion

1. At a certain temperature, NdFeB loses its magnetism rapidly, rather than gradually at high temperatures. And the magnitude of the residual magnetic flux is proportional to the temperature of the environment where the magnet is located, and will not change for a long time after reaching the residual magnetic flux.

2. The loss temperature of different parts of regular magnets is different. Usually, the sharp part of the magnet with the highest Tesla strength can withstand higher temperature, and its sensitivity to temperature is relatively lower.

3. Because most of the thermal loss of magnet is caused by eddy current loss and hysteresis loss, the high-temperature demagnetization effect of large magnet with stronger overall magnetic force is more serious.

References

[1] Zhang Bingyi, Wang Sanyao, Feng Guihong. Journal of Shenyang University of Technology, 2013, 35(02): 126-132. (in Chinese)

[2] Parilov A A, Balabanov A S. A study of long-term stability of magnets produced from alloy KS37[J]. Metal Science and Heat Treatment, 2001, 43: 3-4.

[3] Liu Guozheng, Xia Ning, Zhao Mingjing, Liu Xiaoyu, Lu Fuqiang, Li Bo, Yu Xiaojun. Research progress on long-term stability of permanent magnetic materials [J]. Xitu, 2010, 31(02): 40-44.

[4] Lin Dehua, Cai Congzhong, Dong Wanchun. Study on the distribution of magnetic induction intensity on the surface of square permanent magnet [J]. Physics of Engineering Science, 1999(02): 6-10.

[5] LIU Cong. Dynamic Simulation of Submersible Linear Motor Lifting System [D]. Yanshan University, 2016.