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Simulation Algorithm of Multiple Indicator Diagram Based on Pumping Well Principle

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Abstract: At present, the acquisition of indicator diagram is relatively difficult, and many oil companies do not disclose indicator diagram resources. Therefore, in order to obtain a large number of indicator diagram research data of different working conditions, a simulation algorithm based on the pumping principle of oil rod pump is proposed for various working conditions, such as gas influence, insufficient liquid supply, disconnection, piston stuck, leakage, etc. Based on the mechanical model of the upper and lower stroke of the rod, the force analysis, deformation analysis and motion process analysis are carried out, and the displacement and load law of the rod in the pumping unit are studied. A special calculation program is written, and the simulation algorithm of indicator diagram under various working conditions is obtained through a lot of repeated verification and calculation. The result of sample generation shows that there is little difference with the actual working condition indicator diagram, which can be used as research data to improve the working condition fault identification efficiency.

1. Introduction

The dynamometer card is a closed curve graph with displacement on the horizontal axis and polished rod load on the vertical axis. It can reveal various conditions of the pumping unit during operation. This type of graph is crucial for promptly detecting and eliminating faults, enhancing the efficiency of the pumping unit. By observing the shape of the dynamometer card, it is possible to qualitatively analyze the working conditions of the pumping unit, thus determining whether any malfunctions have occurred. This method effectively replaces traditional manual inspections, providing a more efficient means of fault detection[1].

With the rapid development of intelligent technology, the intelligent diagnosis of pumping unit conditions has become mainstream. Especially in the field of artificial intelligence, deep learning has shown significant potential in image classification [2]. However, deep learning algorithms typically require a large amount of sample data, which is particularly challenging in the petroleum industry. Obtaining a large number of sample data is difficult due to confidentiality and other reasons.

Research has shown [3-6] that there is a wealth of research results in the field of dynamic calculation and simulation of pumping unit rods. However, these studies did not cover the generation methods for pumping unit dynamometer cards under various operating conditions. The intelligent analysis of dynamometer cards using deep learning technology can overcome the difficulty of obtaining sample data and improve the accuracy and efficiency of diagnostics. This approach is of significant value for real-time monitoring and fault diagnosis of oil well conditions.

In this regard, this paper proposes a method for generating dynamometer cards under various operating conditions based on static and dynamic data from different wells, considering random parameter conditions. By generating a large number of dynamometer card data under different operating conditions and comparing it with field test results, the method analyzes the actual working conditions of oil wells and performs fault diagnosis.

2. Establishment of the Displacement and Load Model for the Pumping Unit Well

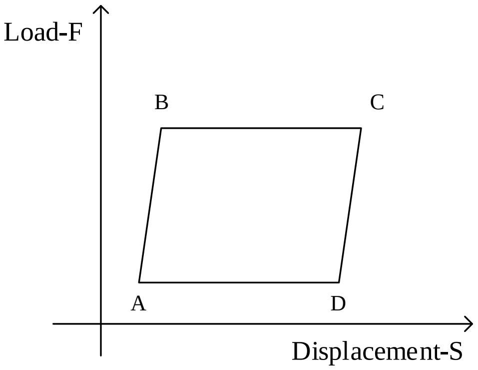

Figure 1: Theoretical Dynamometer Card

As shown in Figure 1, at the initial position A, the traveling valve is open, and the standing valve is closed. The pump pressure is equal to the outlet pressure above the pump, and the load at the plunger includes: the weight of the rod and the buoyancy of the rod. The load on the tubing includes: the static weight of the tubing, buoyancy, and the pressure difference pressure on the fixed valve. At this point, the displacement at the plunger is 0, and the displacement at the standing valve is 0. The formulas for calculating the load on the plunger and tubing during this process can be expressed as:

$$\mathrm{F0} = Hb * Mrodperm - Pbup * Srod \tag{1}$$

$$\mathrm{Ftub0} = Htub * Mtubperm - Pbdown * Stubb + (Pbup - Pbdown) * Sbb + (Pbin - Pbdown) * \mathrm{Sb} \tag{2}$$

F0:The load on the plunger in the initial state
Ftub0:The load on the oil tube in the initial state
Hb:The pump setting depth,m
Mrodperm:weight per meter of pumping rod,N/m
Pbup:pump discharge pressure,MPa
Srod:cross-sectional area of the pump rod,m2
Htub:depth of the tubing shoe,m
Mtubperm:static weight per meter of tubing,N/m
Stubb:cross-sectional area of tubing wall,m2
Sbb:cross-sectional area of pump barrel wall,m2
Sb:cross-sectional area of pump,m2
Pbin:pressure inside the pump,MPa
Pbdown:pressure at the pump inlet below,calculated by the following formula[7]:

$$\mathrm{Pbdown} = Ptop * \exp\left(\frac{0.03415 * RdGas * H}{Zavg * T}\right) + \mathrm{RdOil} * g * Hl \tag{3}$$

Ptop:pressure at the top of the gas column,MPa
RdGas:relative density of gas
H:height of gas column,m
Zavg:local compressibility factor of gas
T:temperature at the top of the gas column,K
RdOil:relative density of crude oil
Hl:column height of liquid,m

During the movement of the pump from point A to point B, which is the loading process with the traveling valve closed, the fixed valve remains closed. The pump pressure decreases, going from the pump outlet pressure to the pump inlet pressure. As a result, the pump volume changes, and the piston displacement and fixed valve displacement also change. In this process, the load at the hanging point is mainly composed of the static weight of the pumping rod, the buoyancy of the rod, the pressure on the traveling valve, frictional force, and inertia load. The load on the tubing includes the static weight of the tubing, the buoyancy of the tubing, the pressure difference at the pump bottom, and the pressure difference on the pump barrel. The formulas for calculating the load and displacement during this process can be expressed as:

$$\mathrm{Ftub} = Htub*Mtubperm+(Pbin[i]-Pbdown)*Sb-Pbdown*Stubb+(Pbup-Pbdown)*Sbb \tag{4}$$

$$\mathrm{xr} = \frac{Ftub0-Ftub}{Ktub} \tag{5}$$

$$\mathrm{v}\_change = Vb\_t - Vb0 \tag{6}$$

$$\mathrm{xp} = \frac{v\_change}{Sb} + xr \tag{7}$$

$$\mathrm{F} = \mathrm{Hb}*Mrodperm - Pbin[i]*Sb + Pbip*(Sb-Srod) + Pf + Pa \tag{8}$$

$$\mathrm{xs} = \frac{F-F0}{Krod} + xp \tag{9}$$

Pbin[i]:The pump pressure at time i is represented by,MPa
xr:Displacement of the fixed valve,m
Ktub:Elastic modulus of the tubing,N/m
v_change:Volume change inside the pump barrel,m3
Vb0:Initial state of the pump barrel volume,m3
xp:Piston displacement,m
Pa:Inertia and acceleration load,Pa
Pf:Friction load,Pa
xs:Traveling valve displacement,m
Krod:Elastic modulus of the sucker rod,N/m
Vb_t:The volume of the pump at time i,calculated by the following formula:

$$\mathrm{Vb\_t} = Vst*[B_o + RWOst + (RGOp - Rs\_t)*B_g] \tag{10}$$

Vst: Volume at standard conditions,m3
Rs_t :Gas-oil ratio (GOR) corresponding to pressure at time t
$\mathrm{RWO}st$:Water-oil ratio (WOR) at standard conditions,sm3/m3
$\mathrm{RGO}p$:Gas-oil ratio (GOR) at production conditions,sm3/m3
B_g :Gas compressibility factor

The sucker rod moves from point B to point C, which is the liquid discharge process. The traveling valve is closed, and the standing valve is open. The pump barrel takes in oil, and the wellhead discharges fluid. The pressure inside the pump is equal to the pressure at the pump's inlet. The piston moves along with the hanging point to the top dead center. The loads on the hanging point include the static weight of the sucker rod, the buoyancy of the rod, the pressure on the traveling valve, frictional forces, and inertial loads. The loads on the tubing include the static weight of the tubing, the buoyancy of the tubing, and the pressure difference at the pump's bottom. The formulas for calculating the loads and displacements in this process can be expressed as follows:

$$\mathrm{Ftub} = Htub * Mtubperm - Pbdown * Stub + (Pbup - Pbdown) * Sbb \tag{11}$$

$$\mathrm{xr} = \frac{Ftub0 - Ftub}{Ktub} \tag{12}$$

$$\mathrm{F} = Hb * Mrodperm - Pbdown * Sb + Pbup * (Sb - Srod) + Pf - Pa \tag{13}$$

$$\mathrm{xp} = s - \frac{F - F0}{Krod} \tag{14}$$

$$\mathrm{xs} = s \tag{15}$$

s:stroke,m

The sucker rod moves from point C to point D, which is the unloading process. The traveling valve is closed, and the standing valve is also closed. The pressure inside the pump increases from the inlet pressure at the bottom of the pump to the outlet pressure at the top of the pump. At the beginning of unloading, the loads on the hanging point include the static weight of the sucker rod, the buoyancy of the rod, the pressure on the traveling valve, frictional forces, and inertial loads. The displacement of the hanging point remains unchanged, the displacement of the standing valve remains unchanged, but the piston's displacement changes. During the unloading process, the buoyancy on the rod changes with the variation in pump internal pressure. The loads on the tubing include the static weight of the tubing, the buoyancy of the tubing, and the pressure difference between the standing valve and the pump barrel. The formulas for calculating this process can be expressed as follows:

$$\mathrm{Ftub} = Htub * Mtubperm + (Pbin[i] - Pbdown) * Sb - Pbdown * Stubb + (Pbup - Pbdown) * Sbb \tag{16}$$

$$\mathrm{xr} = \frac{Ftub0 - Ftub}{Ktub} \tag{17}$$

$$\mathrm{v\_change} = Vb1 - \mathrm{V}b\_t \tag{18}$$

$$xp = xp1 - \frac{v\_change}{Sb} + xr - xr1 \tag{19}$$

$$\mathrm{F} = \mathrm{Hb} * Mrodperm - Pbin[i] * Sb + Pbup * (Sb - Srod) - Pf - Pa \tag{20}$$

$$\mathrm{xs} = \frac{F - F0}{Krod} + xp \tag{21}$$

xp1: The position of the piston at the end of the liquid discharge process,m

xr1: The position of the fixed valve at the end of the liquid discharge process,m

The sucker rod moves from point D to point A, which is the liquid suction process. The standing valve is closed, and the traveling valve is open. At this time, the pressure inside the pump is equal to the outlet pressure at the top of the pump. The displacement of the hanging point is mainly affected by the static weight and buoyancy of the sucker rod. The loads on the tubing primarily consist of the static weight of the tubing, buoyancy, and the pressure difference on the standing valve. The formulas for calculating the loads and displacements in this process can be expressed as follows:

$$\text{Ftub} = Htub * Mtubperm - Pbdown * Stub + (Pbup - Pbdown) * Sb + (Pbup - Pbdown) * Sbb \tag{22}$$

$$\text{xr} = \frac{Ftub - Ftub0}{Ktub} \tag{23}$$

$$\text{F} = Hb * Mrodperm - Pbup * Srod \tag{24}$$

$$\text{xp} = xp1 - \frac{F - F0}{Krod} \tag{25}$$

$$\text{xs} = 0 \tag{26}$$

xp1: The position of the piston at the end of the unloading process,m

3. Generating Pump Card Sample

The values of the basic parameters are as follows:Steel's elastic modulus is 2.1 * 10^11 N/m^2.Steel's density is 7850 kg/m^3.Pump hanging depth is 2200 meters.Stroke is 5 meters.Sucker rod diameter is 0.025 meters.Tubing depth is 2500 meters.Tubing outer diameter is 0.076 meters.Tubing inner diameter is 0.062 meters.Pump diameter is 0.057 meters.Anti-slamming distance is 0.5 meters.Crude oil relative density is 0.8.Gas relative density is 0.72.Crude oil saturation pressure is 12.7 MPa.Pump outlet pressure at the top is 17.69 MPa.Casing pressure is 0.2 MPa.Oil pressure is 0.01 MPa.Pump outlet pressure at the bottom is calculated based on parameters such as gas relative density, top pressure, gas column height, and water column height.

3.1 Normal Pump Card

Input influencing parameter data: Gas-Oil Ratio (GOR): 10, Water-Oil Ratio (WOR) at standard conditions: 98, the graph approximates a parallelogram. Refer to Figure 2.

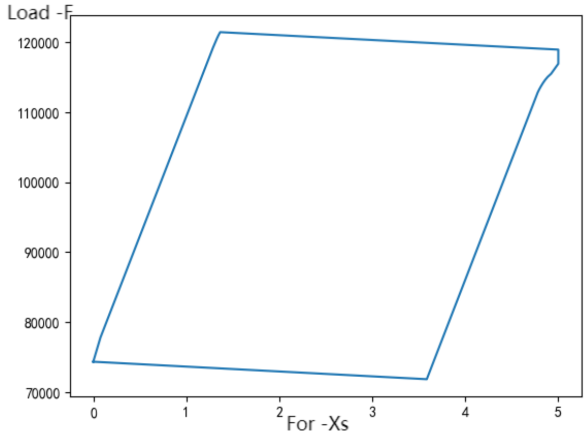

Figure 2: Normal Pump Card

3.2 Abnormal Pump Card

3.2.1 Gas Influence

Input influencing parameter data: Gas-Oil Ratio (GOR) in production: 100, Water-Oil Ratio (WOR) at standard conditions: 50, the bottom right is missing, the unloading curve forms an arc, with the center of the arc at the bottom, as shown in Figure 3.

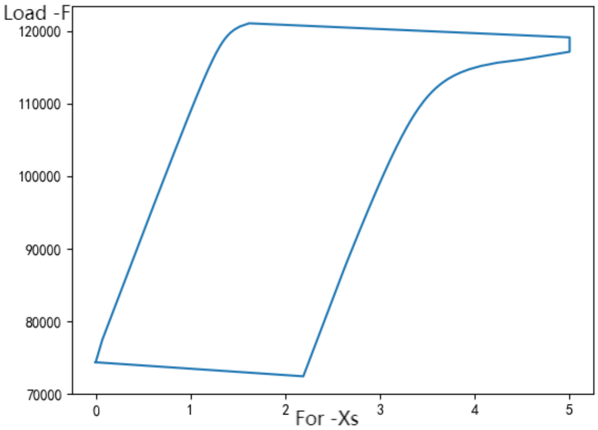

Figure 3: Gas Influence Operating Pump Card

3.2.2 Insufficient Liquid Supply

Input influencing parameter data: Gas-Oil Ratio (GOR) in production: 10, Water-Oil Ratio (WOR) at standard conditions: 98, Pump Fill Factor set to 0.3. The unloading line and loading line are parallel, and as the unloading line shifts to the left, it indicates poorer filling, worse fluid supply capacity, forming a 'sword handle' shape, as shown in Figure 4.

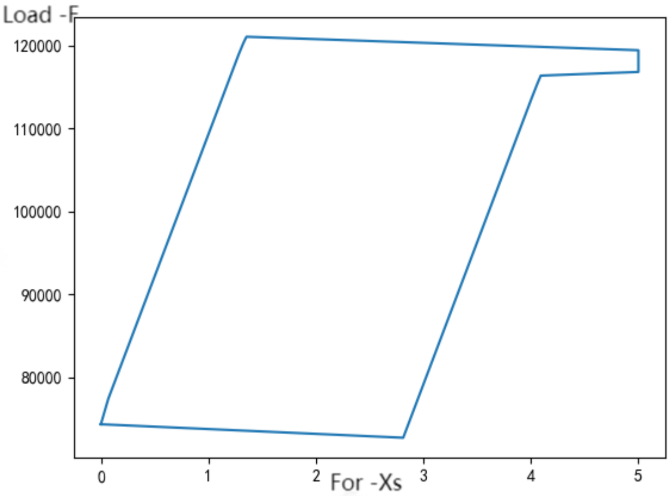

Figure 4: Pump Card under Insufficient Fluid Supply Operating Conditions

3.2.3 Breakaway

Input influencing parameter data: Remaining Rods Proportion 0.3. In this case, the sucker rod only considers its own gravity and frictional forces. The graph's position depends on the depth of the break point, as shown in Figure 5.

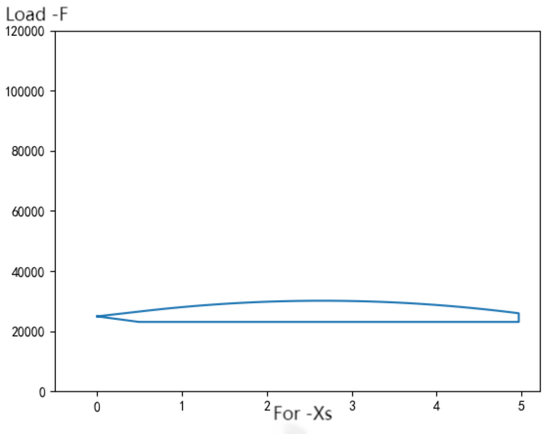

Figure 5: Pump Card under Breakaway Operating Conditions

3.2.4 Piston Seizure

Only the extension and contraction deformation of the sucker rod is considered, taking into account the static weight, elasticity, and frictional forces of the sucker rod, as shown in Figure 6.

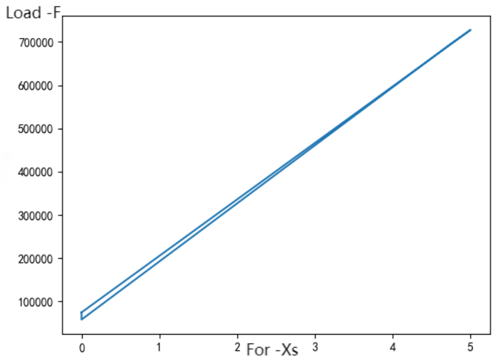

Figure 6: Pump Card under Piston Seizure Operating Conditions

3.2.5 Vibration

Adding sine functions to simulate vibration effects during the liquid discharge and liquid suction processes. The basic expression of the sine function is: $y = A\sin(wx+b)+f$, adding 2-5 cycles, with the simulated effect shown in Figure 7.

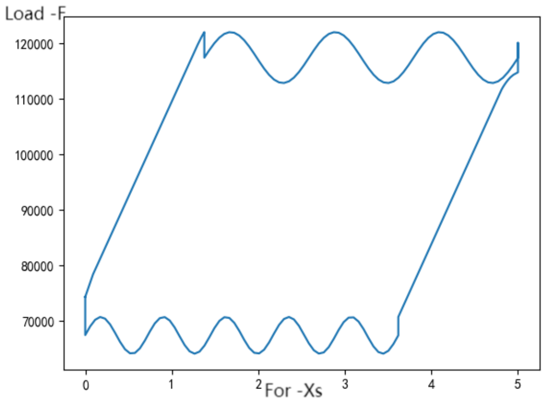

Figure 7: Pump Card under Vibration Operating Conditions

3.2.6 Traveling Valve Leakage

During the loading process, there is leakage in the traveling valve, leading to an increase in the substance volume inside the pump barrel. Adding a leakage coefficient, the volume of leakage is inversely related to pressure, expressed as a function $y = ax^2+bx+c$. Combined with the calculation of the pump barrel volume, the change in the pump barrel volume after leakage is obtained, with the upper-left corner of the graph missing, as shown in Figure 8.

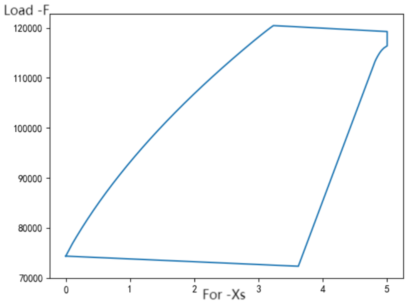

Figure 8: Pump Card under Traveling Valve Leakage Operating Conditions

3.2.7 Fixed Valve Leakage

During the unloading process, there is leakage in the fixed valve, leading to changes in the pump's internal volume and causing a pump malfunction. The simulation process is similar to the traveling valve leakage condition and will not be elaborated here. The results are shown in Figure 9.

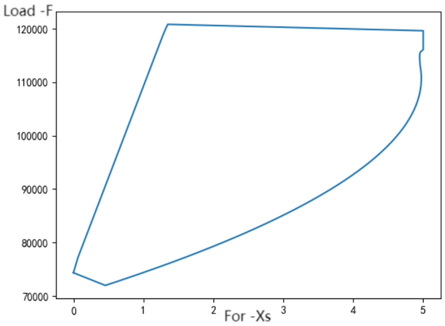

Figure 9: Pump Card under Fixed Valve Leakage Operating Conditions

3.2.8 Sand Sticking

Vibrational loads occur during the liquid discharge and liquid suction processes, forming a serrated or sawtooth-like fluctuation. As shown in Figure 10.

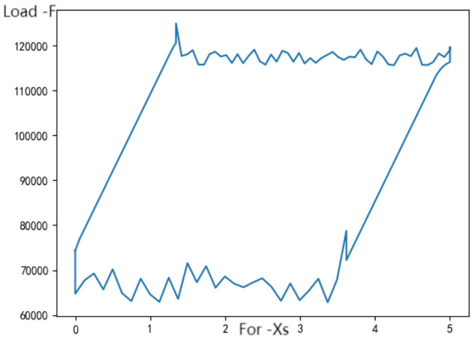

Figure 10: Pump Card under Sand Sticking Operating Conditions

4. Conclusion

This research focuses on the dynamic characteristics of the beam pumping unit's sucker rod, delving into the motion relationships between the sucker rod, pump barrel, and tubing. In order to simulate real-world situations more accurately, the study establishes equations for calculating the loads and displacements for each motion process and combines them with actual well conditions to create a comprehensive sucker rod dynamic calculation model. Based on this model, the research successfully developed methods for generating pump cards under various operating conditions. This achievement not only enhances our understanding of the dynamic system of beam pumping units but also provides a powerful tool for real-time monitoring and fault diagnosis, thereby contributing to the optimization of oil well operational efficiency and production safety.

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