Accurate Calculation Method for Mechanical Specific Energy of Horizontal Well

Shuangshuang Wang* and Qian Li*
Southwest Petroleum University, Chengdu, China

*Corresponding author e-mail: 1012831003@qq.com, *liqianswpi@vip.sina.com

Abstract. The existing drilling efficiency-monitoring model based on the theory of mechanical specific energy is only applicable to vertical wells. When it is used to monitor the drilling efficiency of horizontal wells, the impact of high friction in horizontal wells is not considered, so the monitored specific energy of the machine is not real specific energy of horizontal wells. Based on the previous research results, this dissertation uses the micro-element method to segment the drill string into micro-elements, and considers the influence of the friction torque of the horizontal well. For the existing horizontal wells, rotary drilling, sliding drilling and the characteristics of compound drilling have derived the mechanical specific energy calculation models of horizontal wells based on these three different drilling conditions for real-time monitoring of drilling efficiency of horizontal wells.

1. Introduction
There are more than 40 factors that affect the ROP [1]. Therefore, under the interference of many factors, it is difficult to objectively evaluate the drilling efficiency and take corresponding technical measures to increase the ROP. At present, most of the drilling optimization measures are based on the drilling data of adjacent wells to optimize the undrilled construction parameters. Due to the differences in geological and engineering factors of different wells, the pre-drill optimization calculation workload is large, and sometimes the application effect is not significant. Mechanical specific energy is defined as the mechanical energy consumed to break a unit volume of rock. Therefore, greater mechanical specific energy indicates lower drilling efficiency, poorer adaptability between the drill bit and the formation, and the need to optimize drilling parameters.

\[ M_{SE} = \frac{W}{A_{b}} + \frac{120\pi Tn}{A_{p}v_{pc}} \]  \hspace{1cm} (1)

The mechanical specific energy model established by Teale et al [2, 3]. Only considers the impact of weight on bit and speed on rock breaking efficiency, and ignores the effect of friction on weight on bit and torque, which will greatly affect the true weight on bit and torque at the bottom of the well, thus making The monitored drilling efficiency is not the actual drilling efficiency at the bottom of the well. As we all know, due to the high friction in horizontal wells and the possibility of wall collapse in horizontal sections, it greatly affects the improvement of drilling efficiency of horizontal wells.
Therefore, in order to use mechanical specific energy to monitor drilling efficiency more accurately, we must consider friction.

2. Derivation of mechanical specific energy model based on horizontal well

The original mechanical specific energy calculation formula does not consider the influence of friction torque. It can be used for vertical well analysis, but when it is used in horizontal wells, extended reach wells, and directional wells, the friction resistance will cause a large error. Therefore, in order to obtain the real torque downhole as much as possible, and the actual drill bit pressure, and then to obtain the true mechanical specific energy model, we have introduced a two-dimensional curved well section friction torque calculation model for horizontal wells to calculate rotary drilling. Mechanical specific energy under continuous conditions [4].

2.1. Mechanical specific energy model under rotary drilling conditions

In the two-dimensional curved well section, any length of the Li string unit is taken. As shown in Figure 1, according to the differential equation of the equilibrium and deformation of the elastic beam, the deformation of the pipe string is described by a true arc curve. The friction torque calculation model, the difference between its mechanical model and the soft rod model is that the upper and lower ends of the casing unit body have bending moments and shear forces. The following basic assumptions are made for the calculation model derivation:

(1) The deformation curve of the tubular string coincides with the borehole axis, and the tubular string unit body is in continuous contact with the borehole wall;

(2) Regardless of the influence of the deformation of the well wall, the friction between the drill string and the well wall is regarded as sliding friction;

(3) On the column unit, the linear density is the same and the cross-sectional area is the same.

Figure 1. Analysis of the force of a two-dimensional curved well section under rotating steering

According to Figure 2-1, based on the above basic assumptions, the deformation equilibrium differential equation of the elastic beam and the static balance and moment balance of the unit body are used to analyze the force of the unit body. The mechanical model of the pipe column unit body is established as follows:
The radial supporting force of the i-th unit body is $N_i$:

$$N_i = \frac{(F_{i-1} + F_i)}{2r_i} \cos \frac{\Delta \alpha_i}{2} \pm q_n L_i \sin \bar{\alpha}_i$$  \quad (3)

If the curved well section is a slope-increasing section, the “−” term in the above formula is taken as “−”; if it is a slope-down section, it is taken as “+”. Shear force difference between the upper and lower ends of the unit body:

$$M_{i} = \frac{2(M_{i-1} - M_i) + [(F_{i-1} - F_i) \sin \frac{\Delta \alpha_i}{2}]}{L_i \cos \frac{\Delta \alpha_i}{2}} L_i + M_{N_i}$$  \quad (4)

Shear force by radial support force $N_i$:

$$M_{N_i} = \frac{\mu L_i}{6\tau_i} \left[ \frac{(F_{i-1} + F_i)}{2r_i} \cos \frac{\Delta \alpha_i}{2} \pm q_n \sin \bar{\alpha}_i \right]$$  \quad (5)

If the curved well section is a slope-increasing section, the “−” term in the above formula is taken as “+”; if it is a slope-down section, it is taken as “−”. among them:

$$\tau_i = \frac{L_i}{\Delta \alpha_i}$$  \quad (6)

$$M_{i-1} = EI_{i-1} \frac{\Delta \alpha_{i-1}}{L_{i-1}}$$  \quad (7)

$$M_i = EI_i \frac{\Delta \alpha_i}{L_i}$$  \quad (8)

If the curved well section is a slope-increasing section, $F_i$, $T_i$ can be obtained according to formulas (1), (2), (3), and (4).

$$F_i = F_{i-1} - \frac{1-\delta}{1+\delta} F_{i-1} - \frac{1}{1+\delta} \frac{2A}{B^2L_i} (M_{i-1} - M_i) + \frac{1}{1+\delta} \frac{q_m (DA \mu - CL_i + \mu D L_i)}{6\tau_i}$$  \quad (9)

If the curved well section is a descending section, the same can be obtained:
\[ F_i = \frac{1 - \delta}{1 + \delta} F_{i-1} - \frac{2A}{1 + \delta} (M_{i-1} - M_i) - \frac{1}{1 + \delta} \frac{q_m}{B} (\frac{DA}{B} + CL_i + \mu DL_i) \]  

(10)

In the formula, \( A = \sin \frac{\Delta \alpha_i}{2} \), \( B = \cos \frac{\Delta \alpha_i}{2} \), \( C = \cos \bar{\alpha}_i \), \( D = \sin \bar{\alpha}_i \)

Coefficient \( \delta = \frac{A^2 + A \mu}{B^2} + \frac{1}{B \frac{6 \tau_i}{2 \tau_i}} + \frac{\mu L_i}{2 \tau_i} \)

Boundary conditions: when \( i = 1 \),

\[ F_0 = W \]

(11)

\[ T_0 = T \]

(12)

\( W \) Drilling pressure measured on the ground (hook load), kN

\( T_0 \) Turntable torque, \( kN \cdot m \)

The effect of borehole friction is mainly reflected in the torque load, \( \mu_i \approx \mu \). The meaning of the main symbols is as follows:

- \( E \) Modulus of elasticity of drill string steel, \( N \cdot m^2 \)
- \( I \) Moment of inertia of interface of unit body, \( m^4 \)
- \( q_m \) Floating weight of drill pipe in drilling fluid, \( N / m \)
- \( Q \) Shear forces at both ends of the unit body of section \( i \), kN
- \( N_i \) Positive pressure of the unit body on the wall of the section \( i \), kN
- \( F_{i-1}(F_i) \) Axial tensile force at both ends of the unit body of section \( i \), kN
- \( T_{i-1}(T_i) \) Torque load at both ends of the unit body of section \( i \), \( kN \cdot m \)
- \( M_{i-1}(M_i) \) Bending moment at both ends of the unit body of section \( i \), \( kN \cdot m \);
- \( \alpha_i \) Inclination angle of wells at both ends of the unit body of section \( i \), \( \circ \)
- \( \Delta \alpha \) Increasing amount of inclination of wells at both ends of the unit body of section \( i \), \( \circ \)
- \( \bar{\alpha}_i \) average value of well inclination angles at both ends of the unit body of section \( i \)
- \( \mu \) Coefficient of friction, dimensionless
- \( \mu_i \) Friction coefficient in the circumferential direction
- \( \tau_i \) Bending curvature radius at both ends of the unit body of section \( i \), m
- \( r_i \) Drilling string radius of the unit body of section \( i \), m

Calculated from the above derivation:

\[ W_e = F_i \]

(13)

\[ T = T_i \]

\( W_e \) Effective bit pressure, kN

\( T_i \) Drilling Torque, \( N \cdot m \)

Therefore, the modified mechanical specific energy under the condition of rotary steering drilling is introduced as:
2.2. Mechanical specific energy model for sliding drilling

Sliding drilling is a directional drilling method used in horizontal or directional well construction [5]. Sliding drilling can change the direction of the wellbore, increase and decrease the slope, so sliding drilling is often used in horizontal well construction operations. Sliding drilling mainly uses high-efficiency drill bits, downhole power drilling tools (screw drilling tools), and wireless drilling-while-drilling mud pulse measurement technology (MWD), and uses a certain method of feed pressure to make the drill rod slide and the drill bit forward [6]. Feed to achieve the purpose of directional drilling.

In the sliding drilling process, the friction between the drill string and the borehole wall caused the reduction of the large hook load to be inconsistent with the weight on bit of the drill bit [7, 8, 9]. Part of the reduction in hook load is the friction between the drill string and the borehole wall, and the rest is added to the drill bit. This phenomenon that the bit pressure of the drill bit is less than the reduction of the hook load is called the problem of the holding pressure of the sliding drilling [10]. Based on this special force state of the drill string during the sliding drilling process, in order to more accurately calculate the mechanical specific energy in the sliding drilling state, we should first carry out a Force analysis.

\[ M_{SE} = \frac{4F_t}{\pi d_p^2} + \frac{480T_n}{d_p^3 \nu_{pc}} \]  

(14)

2.2.1. Force analysis of sliding drilling

During the sliding drilling process, the turntable is fixed and the drill bit is driven by the screw rotor, so the speed and torque required for rock breaking are provided by the screw drill. During the drilling process, after the bit touches the bottom of the well, the weight on bit gradually increases, the neutral point gradually moves up, and it stops after the design weight on bit is added. At this time, the drilling tool is stationary and in a critical state. Taking the drilling tools below the neutral point as the research object, the soft rod mode [11] was used for force analysis.

According to the principle of statics, when an object is at rest, the forces acting on the object should be balanced. The force analysis of the research object is shown in Figure 3.
The force balance equation is
Axial:
\[ G \cos \alpha - F_c - N_1 = 0 \]  
(15)

Axial torque:
\[ T_r = T_c + T_u \]  
(16)

Radial:
\[ N_2 = G \sin \alpha \]  
(17)

According to the friction force, it is defined as:
\[ F_c = \mu_s N_2 \]  
(18)

\[ T_c = \mu_s r N_2 \]  
(19)

In the formula, \( G \) is the floating weight of the lower drilling tool, kN; \( N_1 \) is the reaction force of the drill bit, which is opposite to the direction of the weight on the bit, kN; \( N_2 \) is the bearing force of the well wall, kN; \( T_r \) is the counter-torque of the screw, \( kN \cdot m \); \( T_u \) is the braking torque of the upper drill, \( kN \cdot m \); \( F_c \) is the static friction, kN; \( T_c \) is the friction torque of the upper drill, \( kN \cdot m \); \( \mu_s \) is the coefficient of friction; \( r \) is the drilling tool radius, \( m \); \( \alpha \) is the well angle, °.

By taking formulas (17), (18), and (19) into (15) and (16) respectively, we get:
\[ G \cos \alpha - \mu_s G \sin \alpha - N_1 = 0 \]  
(20)

\[ T_r = \mu_s r G \sin \alpha + T_u \]  
(21)

2.2.2. Friction analysis. Because \( N_1 \) is equal in size to the weight on bit and in the opposite direction, it is a pair of acting forces and reaction forces. Therefore, the weight on bit and \( N_1 \) are equal in value, and we get:
The weight-on-bit and lower drilling tool gravity, well inclination, and friction coefficient tubing are discussed separately first:

When $45^\circ < \alpha < 90^\circ$, $\cos \alpha < \sin \alpha$, if $\mu = \cot \alpha$, then $N_1 = 0$;

When $0 < \alpha < 45^\circ$, $\cos \alpha > \sin \alpha$, $N_1$ is greater than 0 but less than $G$.

If the borehole is irregular, consider the effect of the centralizer, then equation (22) becomes

$$N_1 = G \cos \alpha - \mu G \sin \alpha$$

(22)

$$N_1 = G \cos \alpha - F_r G \sin \alpha$$

(23)

$N_1$ is further reduced. $F_r$ is related to the shape of the centralizer, the formation, and the regularity of the wellbore.

In addition, from equation (21):

$$T_u = T_r - \mu G \sin \alpha$$

(24)

The reverse torque is related to the coefficient of friction, the radius of the pipe, the angle of the well, and the gravity of the drill. If the reverse torque is large enough, $T_u = 0$.

So throughout the sliding drilling process:

$$N_1 = G_1 \cos \alpha_i - \mu_i G_1 \sin \alpha_i$$

(25)

Because weight on bit $W_i$ and $N_i$ are a pair of interacting forces, then,

$$W_i = N_i$$

(26)

When $\alpha = 0^\circ$, $i = 1$, $N_1 = G_1$.

$N_i$ Cumulative weight-on-bit reaction of stage $i$, kN

$\alpha_i$ Well angle corresponding to paragraph $i$, $^\circ$

$\mu_i$ Coefficient of friction corresponding to paragraph $i$

$W_i$ Bit pressure in paragraph $i$, kN

$G_i$ Hook load, kN

2.2.3. Rotating speed analysis. As mentioned above, during the sliding drilling process, the turntable is locked and should not be rotated. The drill bit is driven solely by the screw rotor, so the speed required for rock breaking should be all driven by the bottom-hole power drilling tool (here, the screw). According to the screw structure and working characteristics principle, the theoretical speed of the screw is only related to the flow rate and displacement per revolution of the drill tool, and has nothing to do with the working conditions (bit pressure, torque, etc.), that is [12],

$$n = \frac{60Q}{q} = K_n Q$$

(27)

In this formula,
Theoretical rotation speed output by the screw drill, that is, the speed of the drill bit for sliding drilling, revolutions per minute

\[ n \]

Total flow through the drill tool, L/s

\[ Q \]

Displacement per revolution of the drilling tool is a structural parameter that is only related to the linear and geometric dimensions of the stator and rotor, L/r

\[ q \]

Speed to flow ratio of power drill tool, r/L

2.2.4. Torque analysis. The theoretical torque of the screw is assumed to be \( T_L \). When the energy loss is not recorded, according to the energy conservation during the operation of the volumetric motor, the mechanical energy \( T_L \omega_r \) output by the drill bit in a unit time should be equal to the hydraulic energy \( \Delta p Q \) input by the screw drill. After unit conversion, we get:

\[ T_L \omega_r = \Delta p Q \]  \hspace{1cm} (28)

\[ \omega_r = \frac{\pi n}{30} \]  \hspace{1cm} (29)

In the formula:

\( \omega_r \) Theoretical angular velocity, rad/s

\( \Delta p \) Pressure drop at screw drill inlet and outlet, MPa

Simultaneous formulas (27)-(29), we can get:

\[ T_L = \frac{1}{2\pi} q\Delta p \]  \hspace{1cm} (30)

\[ T = T_L \cdot \eta \]  \hspace{1cm} (31)

In the formula,

\( T_L \) Theoretical torque of screw drill, kN•m

\( T \) Torque applied to the drill bit by the formation, kN•m

\( \eta \) Output efficiency of screw drill torque

If the maximum rated torque \( T_m \) (also known as the braking torque) and the maximum rated pressure difference \( \Delta p_m \) of the screw drilling tool are known, according to the torque of the screw drilling tool is proportional to the pressure drop, the theoretical output torque of the screw drilling tool (that is, the bit torque) can also be expressed as:

\[ T_L = \frac{T_m}{\Delta p_m} \Delta p \]  \hspace{1cm} (32)

Therefore, the mechanical specific energy of horizontal well sliding drilling is:

\[ M_{se} = \frac{4W_c}{\pi d_b^2} + \frac{480Tn}{d_b^2 \nu_f} \]  \hspace{1cm} (33)
2.3. Mechanical specific energy model under horizontal well compound drilling conditions

Compound drilling technology is one of the main methods to greatly increase the drilling speed, and it is the key technology for the rapid leaping of mechanical drilling speed in recent years. With the improvement of the performance and model of downhole power drilling tools, coupled with the vigorous development of high-efficiency PDC drill bits suitable for various formations, at the same time, by adopting composite drilling to drill, the wellbore trajectory is smooth and the downhole drilling tool structure is maximized. Simplified, and because compound drilling can complete the construction of deflection, increase, stabilization, declination, and azimuth at one time, it can better control the wellbore quality and ensure downhole safety than conventional drilling, so more and more Oilfields are using compound drilling, so it is necessary to study the specific energy of the compound drilling conditions [13].

During the compound drilling process, the turntable and the screw drill are drilled upwards. In this working state, both the screw drill itself rotates and the turntable rotates the drill string to drive the rotation of the screw stator casing. At this time, the drill bit is driven by the screw driver to rotate, and at the same time, the screw stator is driven to rotate by the tail of the screw stator to form a composite motion mode. Therefore, in composite drilling, we can consider the drill string and the screw drill as a whole to perform the force analysis calculation.

Under the combined effect of the two speeds, the absolute speed of the drill can be significantly increased. The following describes the absolute rotation speed of the drill bit during joint drilling.

Let's take a straight screw drill as an example to introduce the combination of two speeds. Assume that the speed of the drill driven by the screw drill rotor is $n_1$, The drilling speed of the casing driven by the drill string is $n_2$. Both $n_1$ and $n_2$ turn clockwise. It is assumed that both the drill string and the screw housing are rotated at $\omega_2$ around the O axis perpendicular to the bottom of the well, and the drill is rotated by the screw rotor at a uniform angular velocity $\omega_1$ relative to the housing, as shown in Figure 4, then:

$$\omega_1 = \frac{\pi n_1}{30}$$  \hspace{1cm} (34)

$$\omega_2 = \frac{\pi n_2}{30}$$  \hspace{1cm} (35)

Take a point $M$ from the center of the bit at the distance $r$ from the center. At any instant, the traction speed at point M is:

$$v_2 = \omega_2 r$$  \hspace{1cm} (36)

The relative speed of the point $M$ is:

$$v_1 = \omega_1 r$$  \hspace{1cm} (37)

Its direction is the same as the direction of rotation of the drill string.
It can be known from kinematics that at any instant, the absolute speed of the moving point is equal to the vector sum of the traction speed and the relative speed. Then, the absolute speed of the \( M \) point is:

\[
v = v_1 + v_2 = r(\omega_1 + \omega_2)
\]  
(38)

Therefore, the absolute angular velocity of the \( M \) point on the bit is:

\[
\omega = \frac{v}{r} = \omega_1 + \omega_2
\]  
(39)

So we can get:

\[
n = n_1 + n_2
\]  
(40)

For single-turn screw, when the rotary table and single-turn screw drill are being drilled together, the bit center of the single-turn screw drill does not coincide with the center of the drill string, so there is a bit offset, which makes the speed synthesis and straight screw there are certain differences. As shown in Figure 5.

The angular velocity \( \omega \) is located between \( \omega_1 \) and \( \omega_2 \), and the included angle with the drill tool axis is \( \gamma_1 \) (\( \gamma_1 < \gamma \)). \( \omega \) shown in Figure 5 is the absolute angular velocity of the drilling tool at the
position shown, but when the drilling tool rotates at \( \omega_2 \), the direction of the absolute angular velocity \( \omega \) changes, and its size is:

\[
\omega = \sqrt{\omega_1^2 + \omega_2^2 + 2\omega_1\omega_2 \cos \gamma}
\]  

(41)

Therefore, the synthetic speed \( n \) of the drill is:

\[
n = \sqrt{n_1^2 + n_2^2 + 2n_1n_2 \cos \gamma}
\]  

(42)

Structure angle of single curved screw drill:

\[
\gamma \leq 1^\circ, \cos \gamma \approx 1
\]  

(43)

Equations 41 and 42 can be simplified to the same expression as a straight screw:

\[
\omega = \omega_1 + \omega_2
\]  

(44)

\[
n = n_1 + n_2
\]  

(45)

This results in the same conclusion as the straight screw drill. The absolute speed of the drill bit is equal to the sum of the speed of the screw drill and the speed of the drill string. Moreover, in the complex drilling of deep or ultra-deep wells, the frictional torque of the drill string and the drilling tool is so large that it cannot be ignored, so we combined the frictional torque calculation model of the two-dimensional curved well section with the composite drilling to In order to more accurately calculate the true bit pressure and torque under compound drilling conditions.

From (2) to (11), we know that under the condition of compound drilling:

\[
W_c = F_i
\]  

(46)

\[
T = T_i
\]  

(47)

Because of the characteristics of the combined drilling of the rotary table and the screw drill in the compound drilling process, so:

\[
n = n_1 + n_2
\]  

(48)

So the mechanical specific energy model under compound drilling conditions is:

\[
M_{SE} = \frac{4F_i}{\pi d_b^2} + \frac{480T_i(n_1 + n_2)}{d_b^2 v_{pc}}
\]  

(49)

3. Conclusion

Mechanical specific energy is more and more accepted by everyone because of its real-time performance, fewer parameters required, and the simplicity of its calculation. Therefore, successful and more accurate calculation of mechanical specific energy for monitoring drilling efficiency has also been continuously developed.

In this paper, through the analysis of the three drilling conditions during the construction of horizontal wells on the site, the relevant influencing factors are discussed separately, and then the
machinery based on horizontal drilling rotary drilling, sliding dynamic drilling and compound drilling is deduced. The specific energy model is used to monitor drilling efficiency in real time.

Compared with the previous mechanical specific energy model, the mechanical specific energy model in this paper specifically considers the influence factor of friction torque for horizontal wells, thereby making the derived mechanical specific energy model closer to the site drilling conditions. Therefore, it has high reference and practical operability.

References
[1] Zongtian Li. Coiled Tubing Technical Manual [M]. Beijing:Petroleum Industry Press Agency, 2005.
[2] Teale R. The concept of specific energy in rock drilling [J]. International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, 1965, 2 (1): 57-73.
[3] FARRELLY M, RABIA H, BARR M V. A new approach to drill bit selection [R]. SPE 15894, 1986.
[4] Qian Li. and Zhongshi Chen. Calculation of Casing Friction in Highly Deviated Downhole [J]. Gas industry, 1993, 13 (5): 50-54.
[5] Shaohuai Zhang. New Progress and Development Direction of Modern Steering Drilling Technology [J]. Journal of Petroleum, 2003, 24 (3): 82-85.
[6] Yuanbo Wang, Weikun Bian, Jun Tang etc. Discussion on Principle and Technology of Sliding Drilling in Directional Wells [J]. Petrochemical technology, 2015, (06): 112-112.
[7] JOHANCSIK C A, FRIESEN D B, DAWSON R. Torque and drag in directional wells-prediction and measurement [J]. Journal of Petroleum Technology, 1984, 36 (6): 987-992.
[8] Zifeng Li. Mechanics and Application of Oil Well Rod and String [M]. Beijing: Petroleum Industry Press, 2008.
[9] Zifeng Li, Xingrui Ma, Wenhui Huang. Basic Equations of Drill String Mechanics and Their Applications [J]. Acta Mechanica Sinica, 1995, 27 (4): 406-414.
[10] Zhendong Yu, YueQiang Xu, Zifeng Li. Downhole Power Drilling Tool Sliding Drilling Drilling Bridge Plug Bit Pressurization Technology [J]. Oil drilling and production process, 2014, 36 (6): 36-38.
[11] Johancsik C A, Dawson R, Friesen D B. Torque and adrag in direction well prediction and measurement [J]. IADC/SPE, 1983, 380.
[12] Yinao Su. Performance screw drill tools [J]. Oil Drilling & Production Technology, 1998, 20 (6): 11-15, 67.
[13] Donghai Zhang, Junshan Liu. Compound drilling technology improves drilling speed in deep wells [J]. Fault block oil and gas field, 2003, 10 (6): 79-82.