Article ID: 1003- 6326(2000)01- 0109- 05

Energy transmission of down-hole hammer tool and its conditionality[①]

LI Xi-bing(李夕兵)[1,2], G. Rupert[2], D. A. Summers[2]

1. College of Resource, Environment and Civil Engineering Central South University of Technology, Changsha 410083, P. R. China;

2. Rock Mechanics and Explosives Research Center, University of Missouri-Rolla, MO65401, USA

Abstract: By analyzing the efficiency of transmission of impact energy in down-hole hammers and its affecting factors, it has been revealed that the percussive action of down-hole hammers can greatly increase the rate of penetration in shallow well drilling, but its efficiency will be deeply decreased in very deep well drilling. Further analysis showed that there exists a reasonable mass matching of the piston to the bit for different formations. Meanwhile, in an effort to effectively transmit the impact energy from rotary-percussive drilling, it is suggested that the roller-conical bits widely used in petroleum industry and the recently developed flat-fixed PDC bits should be changed into parabolic-fixed diamond enhanced bits.

Key words: down-hole hammer; bit design; impact energy; efficiency **Document code:** A

1 INTRODUCTION

In percussive drilling, which is widely used for hard rock mining, rock is fragmented by repetitive impact of hammer on drill rod or bit. Typical examples of percussive drilling include conventional rock drills for relatively shallow holes and down-the hole drills for deep holes, as shown in Fig. 1.

In oil/gas well, and geothermal drilling, most of wells are drilled by rotary drill machines with roller-conical bits or PDC cutting bits. These kinds of drills can obtain a high rate of penetration at a low cost for soft and medium hard formations, but its rate of penetration will greatly decrease in very hard rock. To improve the rate of penetration in hard formations, since the 1950s, considerable effort has been made to develop a rotary-percussive combined drills into a dependable oil field tool, which are able to be successfully used in hard formations[1~5]. In these kinds of tools, impact action can be provided by down-hole motors that use the drilling fluid to drive a reciprocating piston against a bit or bit sub. Obviously, the structure and geometry of the piston and bit will determinatively affect the rate of penetration. The analysis and discussion of the efficiency of energy transmission in the down-hole hammer tool will be beneficial to designing hammers and bits, and understanding its range of application. This is the purpose of the paper.

2 ENERGY TRANSMISSION IN DOWN-THE-HOLE DRILLING

In down-the hole drilling, the hammer or piston strikes directly on the bit, which sets up a compressive pulse, causing it to penetrate and fragment the rock. Because the pulse acts on the bit, not the rod, it does not suffer attenuation produced through the drill rod sting and rod joints in conventional percussive drills. The down-the-hole drills can drill very deep holes, compared with conventional percussive drills.

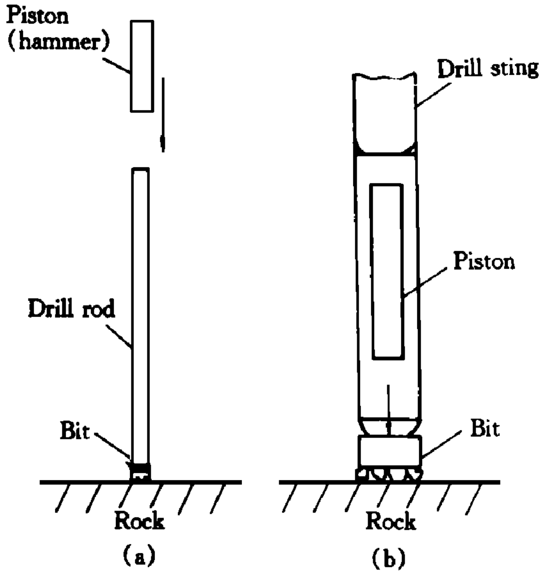

Fig. 1 The principle of percussive drilling
(a) —Rock drill; (b) —Down-the-hole drill

2.1 Bit motion equation

As shown in Fig. 2, denoting the mass, the length, cross-section area, longitudinal wave velocity and density of the hammer as m_h, L_h, A, c and ρ, respectively, and the mass of the bit as m_b, we can obtain the bit motion equation as follows:

① **Received date:** Oct. 13, 1999; **accepted date:** Nov. 23, 1999

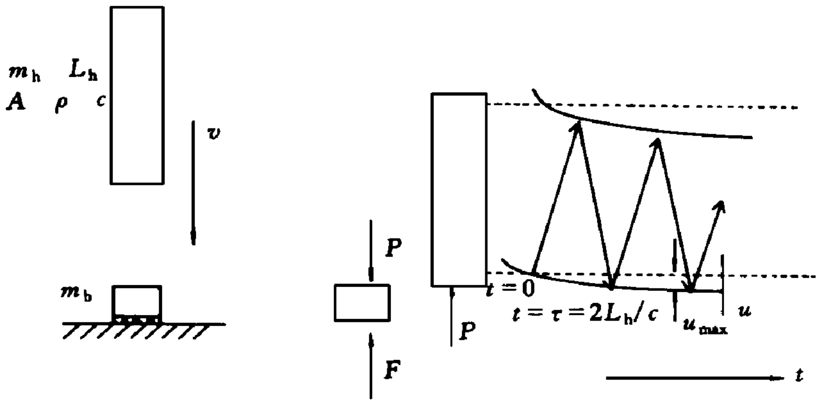

Fig. 2 The motion of the bit and the hammer in the down-the hole

$$m_b \cdot \frac{d^2}{dt^2}u(t) = P(t) - F(t) \tag{1}$$

where u is the penetration depth (displacement) of the bit, P is the force acting on the impacting end of the bit and the hammer, F is the penetration force on the interface of rock and bit.

When $du(t)/dt \geqslant 0$, the relationship of F and u can be assumed as

$$F = Ku \tag{2}$$

where K is the penetration resistance coefficient, which mainly depends on the properties of rock and contacting condition between rock and bit.

Since the propagated stress σ is given by $\sigma = \rho c v$, we have

$$P(t) = A\sigma(t) = -\rho c v' \tag{3}$$

where v' is the relative longitudinal particle velocity at any point on the impacting end.

According to the continuous condition of velocity at the impact end, the following equation is derived:

$$\frac{d}{dt}u(t) = v - \frac{\sigma(t)}{\rho c} \tag{4}$$

Combining Eqns. (1), (2), and (4), we obtain the bit motion controlling equation as follows:

$$\frac{m_b}{K} \cdot \frac{d^2}{dt^2}u(t) + \frac{\rho c A}{K} \cdot \frac{d}{dt}u(t) + u(t) = \frac{\rho c A}{K} \cdot v \tag{5}$$

where the initial condition is $u(0) = 0$, $du(0)/dt = 0$.

2.2 Energy transmission efficiency

The energy transmission efficiency η is defined as the ratio of the energy transmitted into rock to the kinetic energy of the hammer, that is

$$\eta = \frac{(F_{max})^2}{\rho \cdot A \cdot L_h \cdot v^2 \cdot K} \cdot \left(\frac{\gamma - 1}{\gamma}\right) \tag{6}$$

where γ is an unloading constant as shown in Fig. 3. Let $\xi = K/(\rho c A)$, $\alpha = 4 m_b \xi/(\rho c A)$, and $\beta = 2L_h \xi/c$. As long as $\alpha > 1$, solving the differential Eqn. (5) yields the maximum penetration force, F_{max}, with respect to the maximum displacement of bits, u_{max}, and the time, t_{max}, corresponding to F_{max}.

When $\beta > 0.5\pi\alpha/(\alpha - 1)^{0.5}$,

$$0 < t_{max} = \frac{\pi\alpha}{2\xi\sqrt{\alpha - 1}} < 2L_h/c \tag{7}$$

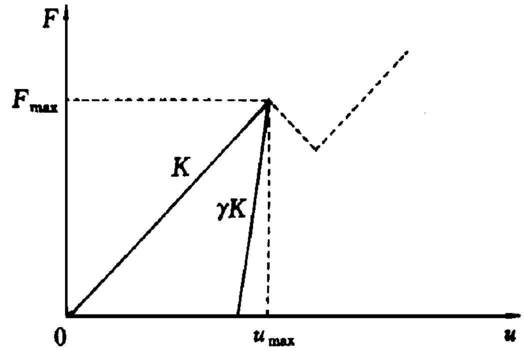

Fig. 3 The penetration force and displacement curve

$$F_{max} = \rho c A v\left[1 + \exp\left(-\frac{\pi}{\sqrt{\alpha - 1}}\right)\right] \tag{8}$$

Inserting Eqn. (8) into Eqn. (6), the energy transmission efficiency is expressed as

$$\eta = \frac{2\left[1 + \exp\left(-\frac{\pi}{\sqrt{\alpha - 1}}\right)\right]^2 \cdot (\gamma - 1)}{\beta \cdot \gamma} \tag{9}$$

Neglecting the effects of unloading, then the energy transmission efficiency η is

$$\eta = \frac{2\left[1 + \exp\left(-\frac{\pi}{\sqrt{\alpha - 1}}\right)\right]^2}{\beta} \tag{10}$$

When $\beta < 0.5\pi\alpha/(\alpha - 1)^{0.5}$,

$$t_{max} = \frac{2L_h}{c} \tag{11}$$

$$F_{max} = \rho c A v\{1 + e^{-4\beta/\alpha} + \frac{2}{\alpha - 1} \cdot \left[\sin\left(\frac{2\beta}{\alpha}\sqrt{\alpha - 1}\right) + \sqrt{\alpha - 1}\cos\left(\frac{2\beta}{\alpha}\sqrt{\alpha - 1}\right)\right] \cdot \left[e^{-4\beta/\alpha}\sin\left(\frac{2\beta}{\alpha}\sqrt{\alpha - 1}\right) - e^{-2\beta/\alpha}\sqrt{\alpha - 1}\right]\}^{1/2} \tag{12}$$

$$\eta = \frac{2}{\beta}\{1 + e^{-4\beta/\alpha} + \frac{2}{\alpha - 1} \cdot \left[\sin\left(\frac{2\beta}{\alpha}\sqrt{\alpha - 1}\right) + \right.$$

$$\sqrt{\alpha-1}\cos(\frac{2\beta}{\alpha}\sqrt{\alpha-1})] \cdot$$
$$e^{-4\beta/\alpha}\sin(\frac{2\beta}{\alpha}\sqrt{\alpha-1})-$$
$$e^{-2\beta/\alpha}\sqrt{\alpha-1}]\} \quad (13)$$

Because $\alpha = 2\beta(m_b/m_h)$, from $\beta = 0.5\pi\alpha/(\alpha-1)^{0.5}$ we can obtain the range of β suitable to Eqns. (8) and (10) for calculating the maximum penetration forces and the energy transmission efficiencies, and we can also obtain the range of β suitable to Eqns. (12) and (13). These ranges of β with different ratios of m_b to m_h are given in Table 1 and Table 2, respectively.

The maximum penetration forces and the energy transmission efficiencies calculated with different ratios of m_b to m_h are shown in Figs. 4 and 5.

It is noted that in a fixed rock drill β is directly proportional to the penetration resistance coefficient, K. From Fig. 4 and Fig. 5 it can be seen that the maximum penetration force will increase with K (or the rock hardness). However, in any case, the maximum penetration generated by impact of down

Table 1 Range of β suitable to Eqns. (8) and (10)

m_b/m_h	1/20	1/10	1/4	1/2	1	2	4	10	20	50
β	> 10.25	> 5.49	> 3.23	> 3.47	> 5.44	> 10.12	> 19.86	> 49.40	> 98.71	> 250

Table 2 Range of β suitable to Eqns. (12) and (13)

m_b/m_h	1/20	1/10	1/4	1/2	1	2	4	10	20	50
β			2~ 3.23	1~ 3.47	0.5~ 5.44	< 10.12	< 19.86	< 49.4	< 98.72	< 250

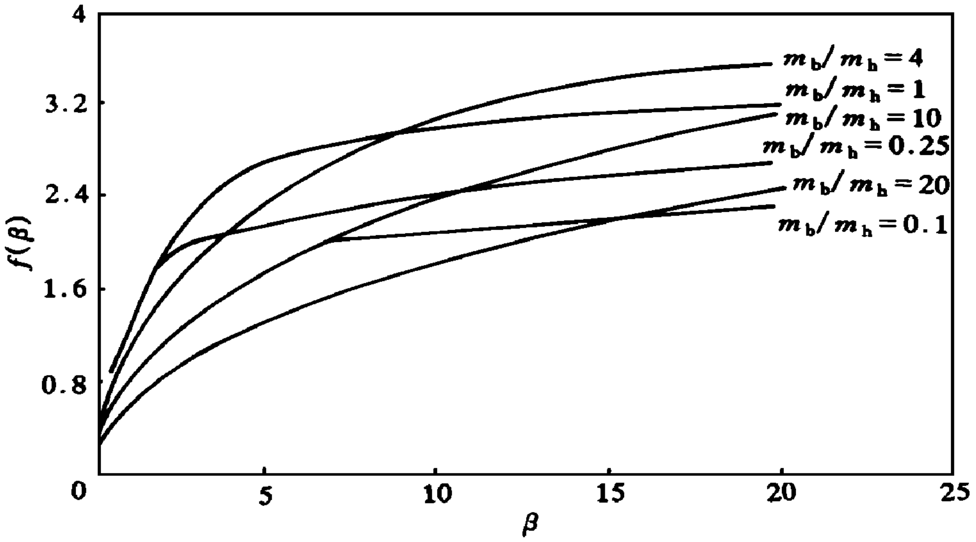

Fig. 4 $f(\beta) = F_{max}/(0.5\rho cV)$ as a function of β with different ratios of m_b to m_h

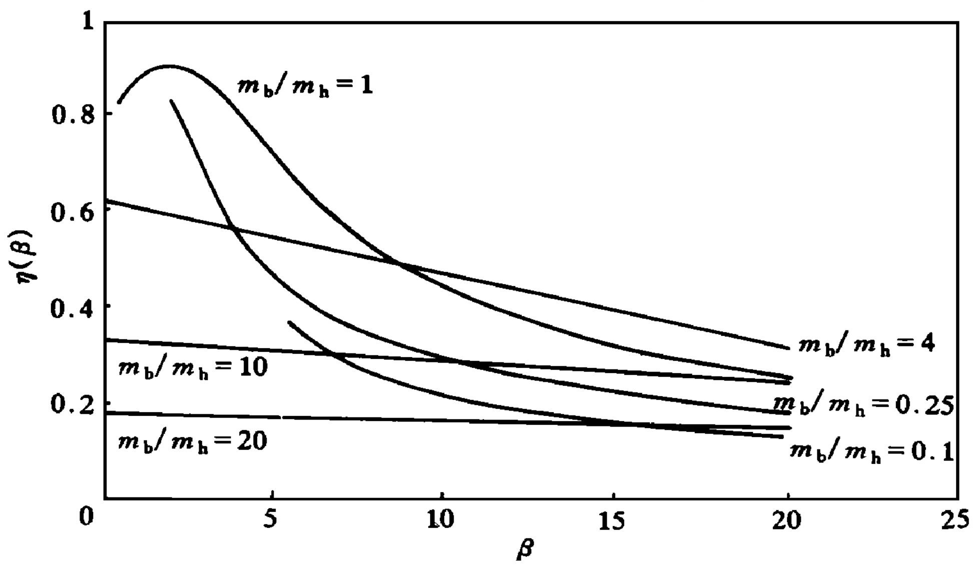

Fig. 5 Energy transmission efficiency η as a function of β with different ratios of m_b to m_h

hole hammers never surpasses $2\rho c v$. By contrast, the efficiency of energy transmission decreases with the penetration resistance coefficient or hardness of the rock. Moreover, the maximum efficiency of energy transmission also decreases with the mass ratio of the bit to the hammer. When the ratio increases to 20, the efficiency of energy transmission will be less than 20%. Generally speaking, the harder the rock to be drilled, the higher the penetration force and the lower the energy transmission efficiency.

3 MATCH BETWEEN BIT TO PISTON

The curves in Fig. 6 represent the relation between the energy transmission efficiency, η, and the ratio of the bit's mass to the hammer's mass, r, under different β values. For a fixed β there is a reasonable r corresponding to maximum energy transmission efficiency. The reasonable matching ratio of the bit's mass to the hammer's mass under different β values is shown in Fig. 7.

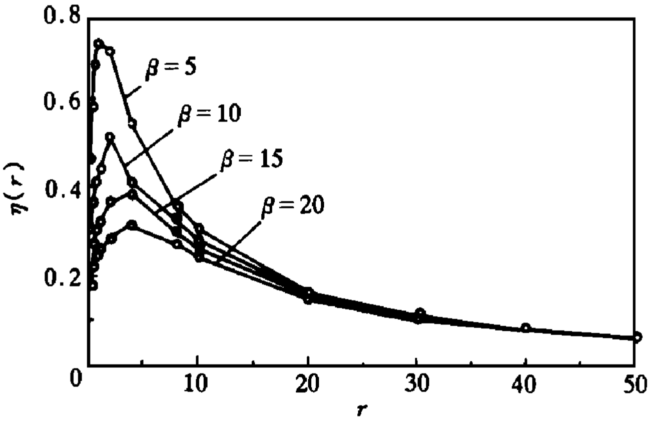

Fig. 6 η vs r under different β values ($r = m_b / m_h$)

Fig. 6 and Fig. 7 show that for the rocks with different penetration resistance coefficient or hardness, there exists a reasonable ratio of the bit's mass to the hammer's mass, which is corresponding to the maximum energy transmission efficiency. In the meantime, when the ratio of mass of the bit to the hammer unlimitedly increases to an infinite value, the efficiency of energy transmission will be less than 10%. Therefore the ordinary down-the-hole drills also have a limited depth of drilling wells.

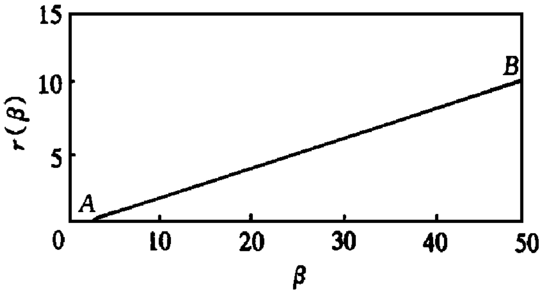

Fig. 7 Ratio of the bit's mass to the hammer's mass with maximum energy transmission efficiency
Point A: $\beta = 3$, $r = 0.303964$;
Point B: $\beta = 40$, $r = 10.1221$

4 PDC BIT PROFILE

For PDC bits used in rotary drills, there exist three basic types of bit profile: flat or shallow cone, tapered or double cone, and parabolic, as shown in Fig. 8. Although there are variations other than these types, typically these variations fall somewhere among the three basic types.

It is obvious that the flat-or shallow-cone crown profile evenly distributes the static weight of the bit among each of the PDC cutters on the bit. If the analogy of a bit being able to drill only as fast as its fastest cutter is applied, then flat-profile bits have the highest rate of penetration potential, because the cutting depth of each cutter is theoretically equal. However, field application has shown that the flat profile has two main disadvantages: limited rotational stability and uneven wear[6, 7]. Because of the shallow profile, rocking can occur at high revolutions per minute. This can cause high instantaneous point loading and loss of cooling to the PDC cutters, which is detrimental to bit life. The analysis of dull bits shows that the wear increases from the center of the bit to circumference of the bit. This means that the

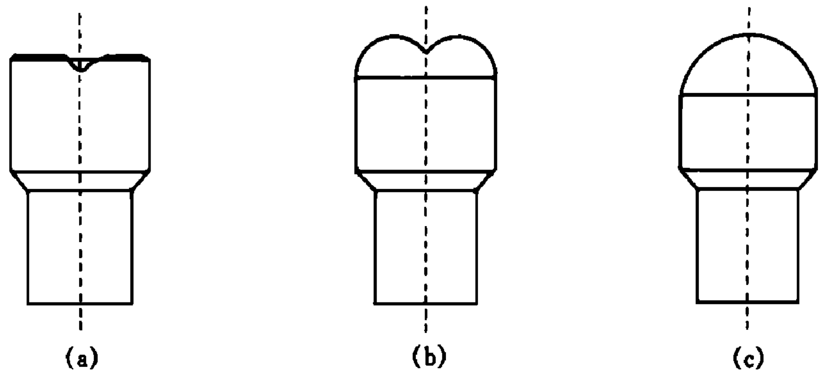

Fig. 8 PDC bit basic profile
(a) —Flat; (b) —Double cone; (c) —Parabolic

innermost cutters in the flat profile bits are not being used to their fullest potential.

The tapered, or double cone, and the parabolic profiles allow increasing distribution of the cutters toward the bit circumference. As a result, rotational and directional stability as well as more evenly distributed wear are achieved. These profiles cause the cutters near the bit center to cut more effectively. The parabolic profile is an even more aggressive profile of the absence of the center concave cone, compared with the double cone profile.

On the other hand, for PDC bits to be developed for use in rotary-percussive drills, the parabolic profile should be superior to the flat or swallow cone profile in indentation generated by percussion. This can be explained by the following simple analysis.

It is assumed that the impact force acting on the bits is $P_i(t)$, and reflected force from the rock is $P_r(t)$. Then the total force acting on the bits is

$$F(t) = P_i(t) - P_r(t) \quad (14)$$

and the force acting on a single cutter is

$$f(t) = (P_i(t) - P_r(t))/N \quad (15)$$

where N is the number of the cutters in a bit.

Because the number of the cutters in the parabolic profile can be much larger than that in the flat profile on the condition of the same diameter of the bits, the single cutters in the parabolic profile withstand a lower impact indentation force, compared with the cutters in the flat profile. However, a lower impact indentation force of the cutters does not mean a smaller indentation of the bit. Considerable experiments have shown that the impact resistance coefficient, K, of the bit with a shaped-end profile is much less than that of the bit with a flat-end profile. Moreover, it is noted that there exists an approximately linear relationship between the indentation force, F, and the indentation displacement, u. That is, $F = Ku$. It is easily concluded that the parabolic profile can penetrate a larger depth than the flat profile does. Thus, for the rotary-percussive drilling, it is suggested that the flat-fixed PDC bits should be changed into a taped or parabolic-fixed diamond enhanced bits.

ACKNOWLEDGMENTS

Financial support from the National Natural Science Foundation of P. R. China and the Novatek under U. S. Department of Energy Grant is greatly appreciated.

REFERENCES

[1] Wanamaker J A. Rotary percussive drilling in west Texas [J]. World Oil, 1951(9): 182~ 188.

[2] Finger J T. Investigation of percussion drills for geothermal applications [J]. Journal of Petroleum Technology, 1984(2): 2128~ 2136.

[3] Fear M J, Knowlton R H, *et al*. Experts discuss drill-bit design, field performance [J]. Journal of Petroleum Technology, 1995(2): 100~ 104, 142~ 143.

[4] Whiteley M C and England W P. Air drilling operations improved by percussive-bit/hammer-tool tandem [J]. SPE Drilling Engineering, 1986(10): 377~ 382.

[5] Pratt C A. Modifications to and experience with air-percussion drilling [J]. SPE Drilling Engineering, 1989 (12): 315~ 320.

[6] Kerr C J. PDC drill bit design and field application evolution [J]. Journal of Petroleum Technology, 1993(3): 327~ 332.

[7] Pain D D and Schieck B E. Evolution of polycrystalline diamond compact bit designs for rocky mountain drilling [J]. Journal of Petroleum Technology, 1985: 1213~ 1219.

(Edited by HE Xue-feng)

[redacted]