

# Mathematical modeling and analysis of energy conversion efficiency of particle jet accelerating nozzle

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**Abstract.** The impact kinetic energy of particle jet determines rock-breaking effect and velocity, and as acceleration device of particle jet, the energy conversion efficiency of nozzle determines rock-breaking efficiency. According to three different types of nozzles of the straight-taper nozzle, the pressure drop model and energy conversion efficiency of particle jet was established, and the energy conversion efficiency under different type nozzles was studied. And then, the acceleration ability of different nozzles for was analyzed with simulation. The results of model calculation and simulation show that constant-acceleration nozzle has the best acceleration ability and energy conversion efficiency. The rock-breaking experiment was carried out with the adopted nozzle, and comparison analysis between experimental results and numerical calculation prove that the applicability of mathematical model.

## 1. Introduction

Particle jet impact rock breaking technology is a rather efficient non-contact rock-breaking method which can solve the problem of difficult drilling in deep-well and hard formation. Its working principle is that drilling fluid and steel particles are mixed at certain ratio, and then the acceleration action with nozzle would form high-velocity particle jet to destroy and impact rock [1]. In particle jet impact rock-breaking system, the nozzle plays a role of energy conversion [2], which can convert pressure of the system into kinetic energy of particle water jet, thus particle jet would have high velocity and can greatly improve drilling speed of deep well and hard formation. Therefore, as the key component of the particle jet impact rock breaking device, the acceleration capability and energy conversion efficiency of the nozzle determine the drilling speed and rock breaking effect.

At present, the majority of researchers changed the nozzle cone angle and length to diameter ratio to improve the acceleration capability of nozzle [3]. Shen [4], Huang [5] et al. analyzed the relationship between cone angle and nozzle diameter on jet velocity. Liu et al. researched the relationship between energy loss and flow coefficient and verified experimentally [6]. Ren et al. studied the acceleration effects of four different nozzle structures [7].

The studies on energy conversion efficiency in acceleration process of nozzle are less at present, so it is necessary to select the appropriate nozzle type, so as to improve energy conversion efficiency and rock-



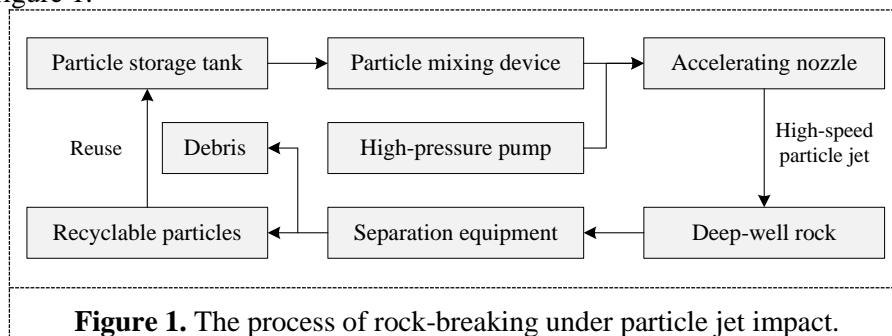
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breaking efficiency. In this paper, the effect factors of energy conversion efficiency can be analyzed with the establishment of mathematical model of energy conversion efficiency and CFD simulation, so as to optimize the nozzle type of flow channel. Based on adopted nozzle type, the comparative analysis of experiment and numerical calculation could be used to verify the correctness of mathematical model.

## 2. Modeling and analysis

### 2.1. The accelerating mechanism of the nozzle

Particle jet impact rock-breaking technology is inspired by projectile impact rock-breaking technology, and it is proposed to add a certain proportion of steel particles into high-speed mud, and through the acceleration of drill pipe and nozzle to form high-speed particle jet. The high-speed particle jet impacts on rock surface to form hole or groove, which could release the compaction effect at the bottom of deep-well and reduce rock strength, and then quickly break rock under the grinding effect of drilling bit. Debris and steel particles formed by rock-breaking are carried to surface separation equipment by drilling fluid for particle recovery and separation. The process of rock-breaking under particle jet impact is shown in figure 1.



According to the rock-breaking mechanism of particle jet, the rock-breaking effect depends on impact kinetic energy of particle jet, and the acceleration of particle jet mainly depends on the nozzle. Therefore, it is of great significance to study energy conversion efficiency of particle jet in different type of nozzles.

### 2.2. Energy conversion efficiency model

The structural model of nozzle refers to the shape and geometry of the flow channel. At present, the widely used high-efficiency nozzles are composite nozzles, which are composed of contraction section and cylinder section. In this paper, the flow channel shape is mainly studied of straight-taper nozzle, constant-acceleration nozzle and streamline nozzle.

When drilling fluid flows through nozzle, firstly, it will be accelerated by contraction section, and then flows cylinder section. Fluid mechanics is applied to analyze the particle jet accelerating process [8]. The resistance of drilling fluid flowing through nozzle mainly consists of contraction resistance and on-way resistance, namely:

$$h_w = h_j + h_f \quad (1)$$

Where,  $h_w$  is resistance of drilling fluid;  $h_j$  is contraction resistance;  $h_f$  is on-way resistance.

The contraction resistance refers to the resistance when fluid flows through contraction section. The calculation formula is as follows:

$$h_j = \zeta_j \frac{u_f^2}{2g} \quad (2)$$

Where,  $\zeta_j$  is local resistance coefficient;  $g$  is gravity acceleration.

Because local resistance coefficient varies with the shape of contraction section, and its value is determined by experimental measurement and empirical formula [9].

The flow state of particle water-jet is turbulent, and the energy loss is mainly due to overcoming the on-way resistance. The on-way resistance mainly includes the on-way resistance of contraction section and cylinder section, and the expression is as follows:

$$h_f = \int \lambda \frac{L_1}{2y} dx \frac{u_f^2}{2g} + \lambda \frac{L_2}{d_2} \frac{u_{f1}^2}{2g} \quad (3)$$

Where,  $\lambda$  is on-way resistance factor, which is related to nozzle roughness and fluid pattern[8];  $L_1$  is length of contraction section;  $L_2$  is length of cylinder section;  $d_2$  is outlet diameter of nozzle.

The expression of total resistance coefficient when particle jet flows through bit nozzle could be calculated:

$$\zeta = \zeta_j + \int \lambda \frac{L_1}{2y} dx + \lambda \frac{L_2}{d_2} \quad (4)$$

Where,  $\zeta$  is total resistance coefficient.

According to energy equation of fluid flow, the relationship between flow coefficient of nozzle and total resistance coefficient  $C$  can be deduced:

$$C = \sqrt{1/(1+\zeta)} \quad (5)$$

The water power at the nozzle inlet and outlet could be obtained:

$$N_i = Q \nabla P \quad (6a)$$

$$N_o = \frac{1}{2} \rho Q u_{f1}^2 \quad (6b)$$

Where,  $N_i$  is water power at the nozzle inlet;  $N_o$  is water power at the nozzle outlet;  $\nabla P$  is pressure drop of nozzle.

When drilling fluid flows through nozzle, the pressure difference between inlet and outlet of nozzle will generate, which called pressure drop. It is an important parameter to determine kinetic energy of particle water-jet, and the expression is:

$$\nabla P = \frac{\rho_f Q^2}{2nC^2 A_1^2} \quad (7)$$

Where,  $\rho_f$  is fluid density;  $Q$  is flow rate;  $n$  is the number of nozzle;  $A_1$  is sectional area of inlet.

As energy conversion element in acceleration of particle jet, the performance of nozzle can be expressed by energy conversion efficiency:

$$\eta = \frac{N_o}{N_i} = C^2 = 1/(1+\zeta) \quad (8)$$

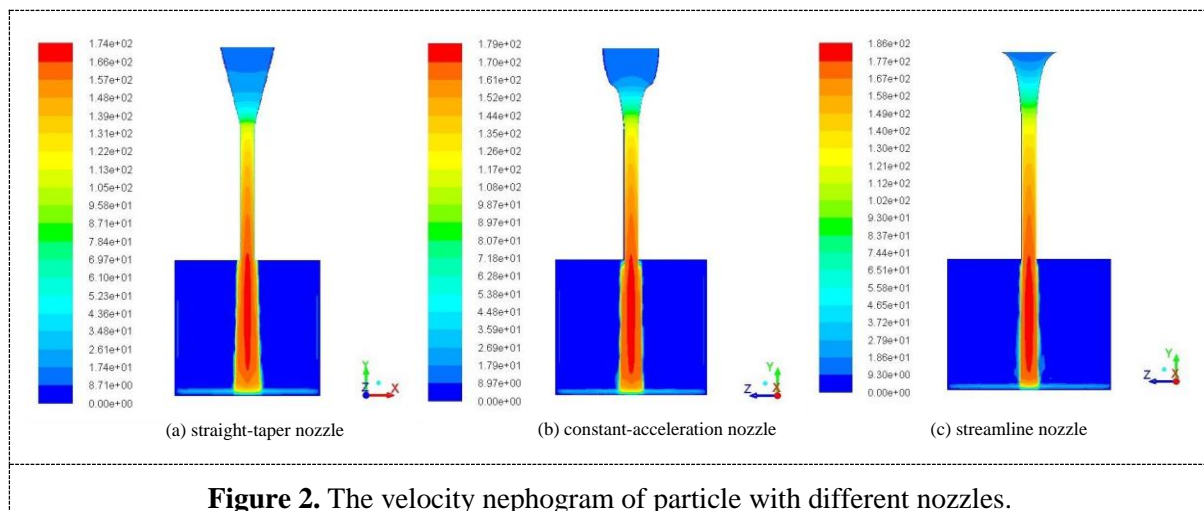
Where,  $\eta$  is energy conversion efficiency.

According to established mathematical model, the energy conversion efficiency of nozzle is directly proportional to the square of flow coefficient.

### 3. Simulation analysis of acceleration effect

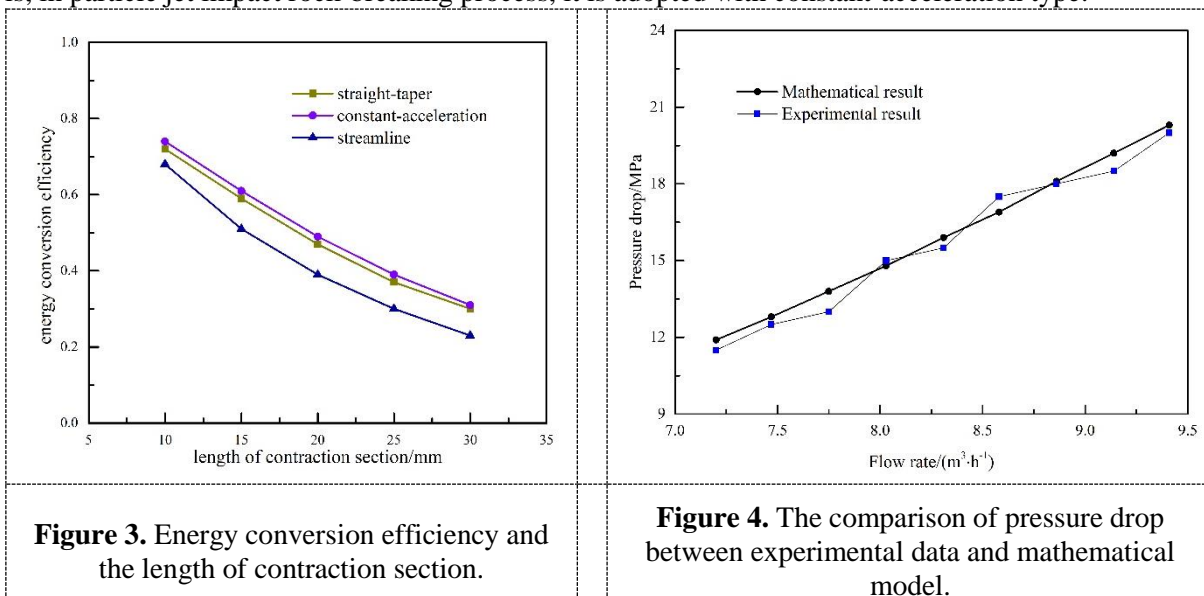
In order to simulate the acceleration and pressure change of particle jet, the computational fluid dynamics (CFD) method is used to simulate the internal flow field of different types of nozzles, as shown in figure 2. In simulation process, the boundary conditions are velocity inlet and outflow [10]. The velocity of particles and drilling fluid at the inlet is 14 m/s, and the volume fraction of particles is 0.2%. The standard  $k-\varepsilon$  equation and Eulerian model are used in simulation.

According to simulation results, the acceleration of particles is obviously different. The acceleration process runs through contraction section and cylinder section, and the acceleration effect of constant-acceleration nozzle is the best.



#### 4. Results and analysis

According to the established mathematical model, the relationship between energy conversion efficiency of different nozzles and contraction section is shown in figure 3. With increase of contraction section length, the energy conversion efficiency would gradually decrease. When the length of contraction section is fixed, energy conversion efficiency of constant-acceleration nozzle is the best. Because pressure drop is inversely proportional to energy coefficient, the nozzle with the highest energy conversion efficiency should be selected at the same time to meet the rock breaking requirements, that is, in particle jet impact rock-breaking process, it is adopted with constant-acceleration type.



Particle jet impact rock-breaking tests were carried out with constant-acceleration nozzle. The comparison between experimental data and mathematical model is shown in figure 4. According to comparison results, experimental value is basically consistent with mathematical calculation, which proves the applicability of mathematical model. The results are of great significance to study of energy conversion of nozzles and rock breaking efficiency.

#### 5. Conclusion

- (1) The mathematical model of energy conversion efficiency of particle and water jet in nozzle is established, and the influence of different types of nozzle on energy conversion efficiency is analyzed
- (2) The type of nozzle is determined by model calculation and simulation, and the applicability of mathematical model is verified by comparison of experiment and numerical simulation. The results are of great significance to study of energy conversion of nozzles and rock breaking efficiency.

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