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Effect of Gangue Distributions on Cutting Force and Specific Energy in Coal Cutting

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Coal consists of diverse materials, and gangue is one of the most common ones. At present, most mathematical models about cutting force and specific energy in the cutting process have not taken gangue minerals in coal seams into consideration. The gangue distribution function is proposed to simulate situations in which gangue minerals are in different distributions. Moreover, the cutting force due to gangue mineral at different heights is also obtained with the finite element method. Combined with the gangue distribution function, the increased cutting force due to gangue minerals can be obtained for any gangue distribution. The present paper also proposes a new mathematical model to calculate the increased specific energy under different gangue distributions. The results show that the gangue distribution function is useful for simulating various situations of gangue distributions in coal seams. Under dispersive gangue distribution in coal seams, the increased mean cutting force, as well as the increased specific energy, is less influenced by gangue distribution, and it tends to be a constant. These results can be useful for the related research on coal cutting under complicated conditions.
Keywords: cutting force, specific energy, single cutter, gangue distributions

Highlights
- *We proposed the theoretical model for increased specific energy consumption on single cutter, in which gangue minerals in the coal seam and their distributions are firstly taken into consideration.*
- *It has been determined that the increased specific energy is closely related to the amount of gangue minerals in the coal seam and their distributions.*
- *It has been determined that the smaller mean and variance of gangue distributions are able to weaken the influence of traction speeds on the increased mean cutting force and specific energy consumption.*

0 INTRODUCTION

Coal is one of the most important fuels in the world, and it is not a homogeneous material [1]. Gangue minerals usually can be found in coal seams [2]. However, in previous research, the influence of gangue minerals, especially gangue distributions on the cutting performance, are usually ignored [3] and [4]. The differences in material parameters between coal and gangue minerals lead to different mechanical behaviours [5]. For instance, load on cutter usually performs with larger fluctuation when there are some gangue minerals in the coal seam, and this can be attributed to the differences of material parameters, such as hardness between coal and gangue minerals [6] and [7]. Working in this situation over a long time, the cutter tends to be subjected to different degrees of wear and tear [8] and [9]. Therefore, it is essential to study the influence of gangue minerals on cutting performance.

Recently, many approaches have been developed to deal with gangue minerals in coal seams. In earlier research, it was found that cutting load can be reduced when the traction speed decreases [10] and [11]. A method of manual intervention to change the speed is proposed when gangue minerals exist in the cutting process [12]. To reduce the burden on the workers, strategies of self-adaptive control proposed; such strategies will be pre-formulated on traction speed and rotation speed, and then autonomic decision-making will be achieved with the shearer drum according to the cutting conditions. Hu et al. [13] put forward some cutting strategies to deal with different suddenly changing loads. Liu et al. [14] proposed a control system to achieve the goal of self-adaptation. With the particle swarm optimization, the motion parameters can be optimized adaptively according to the variation of cutting resistance.

In addition, coal-rock recognition technology is also popular, and cutting load is no longer the only method to distinguish gangue minerals from coal. Acoustic wave detection technology [15] and image analysis technology [16] are also widely used in coal-rock recognition. Xu et al. [17] proposed a method in which the fuzzy C-means and hybrid optimization algorithm are applied.

Furthermore, other researchers proposed some coal-gangue models, and the positions of gangue minerals in these models satisfy different distributions such as normal distribution and long-tailed distribution [18] and [19]. With the proposed models, the cutting performance can be predicted in advance

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and some strategies, which are used to improve cutting performance, can be made under different complicated conditions.

Cutting load [20] and [21], specific energy consumption [22] and cutting productivity [23] are the critical parameters for the evaluation of cutting performance. Kurochkin [24] and Dogruoz et al. [25] explored the effect of mechanical properties of different materials on specific energy consumption. Gencay and Erkan [26] found that there is a significant relationship between specific energy and the physical and mechanical properties of rock. Tiryaki and Dikmen [27] found that Poisson's ratio, Brazilian tensile strength, Shore sclera scope hardness, and Schmidt hammer hardness showed very strong linear correlations against specific energy (SE) at confidence levels of 95 %.

At present, although there are many research studies about the specific energy consumption of coal cutting, most do not take gangue minerals and their distributions in coal seam into consideration. Based on this, the paper put forwards the new mathematical model of the increased specific energy, in which gangue minerals in coal seam will be taken into consideration. Then, combined with the number of gangue minerals and their distributions in coal seams, the increased mean cutting force (I_{MCF}) and increased specific energy (I_{SE}) can be obtained under different gangue distributions. Further, it will be useful to make strategies according to the gangue minerals and their distributions in coal seam.

1 METHODS

1.1 Model Simplification of Gangue Minerals in Coal Seams

Gangue minerals in coal seams appear in different shapes. However, the purpose of the present paper is mainly to explore the relationship between gangue distribution and cutting performance. Therefore. the shape of gangue minerals is not covered in this paper. Combined with the research purpose, the following assumptions on gangue minerals in coal need to be made at first:

(I) As the dimensions of gangue minerals are much smaller than that of the coal seam, the gangue in the coal seam will be simplified as a single point, as seen in Fig. 1a;

(II) The gangue minerals, only situated in the same plane, such as Section γ in Fig. 1b, will be considered and the amounts of these gangue

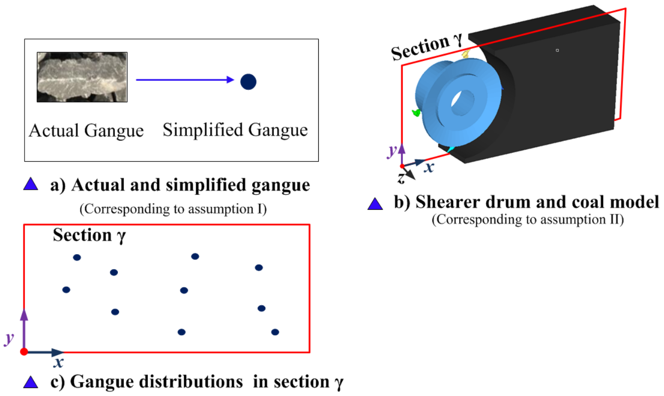

Fig. 1. *Simplified model of gangue minerals in a coal seam*

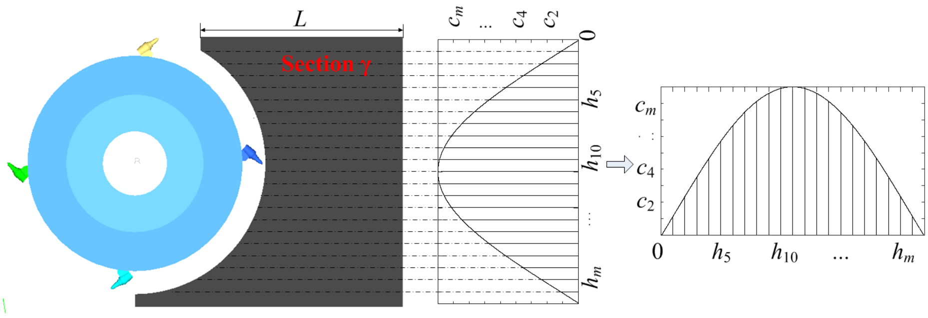

Fig. 2. *Gangue positions in coal seam expressed with mathematical model*

minerals at different heights, as shown in Fig. 1c, will be counted for the description of gangue distribution in the coal seam.

Based on the mentioned assumption, the positions of gangue minerals in the same plane can be marked with [h_1, h_2, h_3, …, h_i, …, h_m], as Fig. 2 shows; the proportion of gangue minerals at the heights can be marked with [c_1%, c_2%, c_3%,..., c_i%, …, c_m%]; the increased mean cutting force due to single gangue mineral when they are at different heights can be marked with [F_1, F_2, F_3, …, F_N]. According to hi and the corresponding F_i, the mathematical relationship between the increased mean cutting force due to single gangue mineral and the height of gangue mineral can be obtained using the fitting method, and the mathematics formula can be expressed in the following:

$$F_i = f_{(h_i)}. \tag{1}$$

According to Eq. (1), the increased mean cutting force due to single gangue mineral can be obtained when gangue minerals are at different heights and then the increased mean cutting force due to all gangue minerals in coal seam (namely I_{MCF}) can be expressed by Eq. (2) .

$$I_{MCF} = N \cdot \sum_{i=1}^{m} \left(c_i \cdot F_i\right), \tag{2}$$

where N is the total number of gangue minerals in coal seam at different heights.

1.2 Expression of Gangue Distributions with Mathematical Method

It is mentioned that the cutting force on the cutter due to gangue mineral can be obtained according to its position. Therefore, the I_{MCF} is calculable when the positions of all gangue minerals in the same plane are identified. However, to date, there is no reference on how to locate gangue minerals in a coal seam. Therefore, gangue distribution trends, instead of the precise positions, are used in the paper.

The normal distribution, which proves to be common distribution in nature and has become an important forecasting model in mathematics, physics and engineering areas, is employed for simulating gangue distribution; it is called "the gangue distribution" function in this paper and is shown in Eq. (3). By adjustment of the mean and variance of the gangue distribution function, the potential distributions of gangue minerals in a coal seam might be approximately simulated.

$$f\left(h_i\right) = \frac{1}{\sqrt{2\pi\sigma}} \exp^{\left(-\frac{\left(h_i-\mu\right)^2}{2\sigma^2}\right)}, \tag{3}$$

where μ is the mean in the normal distribution. In this paper, it is the mean height of gangue distribution in a coal seam; σ is the variance in a normal distribution. In this paper, it is the height variance of gangue distribution in a coal seam.

With the gangue distribution function, potential gangue distributions in coal seam can be simulated by adjustment to the mean and variance of the gangue distribution function. In this paper, the following gangue distributions on the influence of cutting performance will be studied: a) gangue minerals in concentrative distributions (σ=0.05 m); b) gangues in dispersive distributions (σ=0.90 m); c) most gangue minerals at the top of coal seam with different dispersions (μ=0.15 m); d) most gangue minerals at the middle of coal seam with different dispersions (μ=0.90 m).

1.3 Mathematical Model for Specific Energy Consumption

According to the previous conclusions, the formula for the specific energy consumption is as follows:

$$H_{WC} = 2.78 \times 10^{-4} W / V. \tag{4}$$

In the formula, H_{WC} is the specific energy consumption of the cutter in the cutting process [kW·h/m³]; W is the mechanical energy of the cutter in the cutting process [kN·m]; V is the volume of coal crushed by the cutter in the cutting process, [m³].

After simple calculation, the specific energy consumption in coal-cutting process without any gangue minerals H_{WC} and specific energy consumption in gangue-cutting process I_{SE} can be expressed in Eqs. (5) and (6).

$$H_{WC} = 2.78 \times 10^{-4} \frac{F_{C,ave} \cdot t_c}{H \cdot L}, \tag{5}$$

$$I_{SE} = 2.78 \times 10^{-4} \frac{N \cdot \sum_{i=1}^{m}\left(c_i \cdot F_i\right) \cdot t_R}{H \cdot L}. \tag{6}$$

2 RESULTS

2.1 Relations between Cutting Force and Gangue Positions

Gangue minerals in a coal seam usually lead to much larger cutting force on conical picks; in this paper, the cutting force increased due to single gangue F_i is studied when gangue minerals are at different heights. For research, the rotary cutting model with a coal seam [4] is established with the finite element method. In the simulation, material similar to gangue minerals is added at different heights in the coal seam. Four kinds of gangue positions (0 m, 0.3 m, 0.6 m, and 0.9 m are selected. in the simulation, the traction speed of cutter is 0.06 m/s, 0.08 m/s, and 0.10 m/s. The diameter of the shearer drum is 2.2 m and the rotational speed is 3 rad/s. Fig. 3 shows the cutting force due to a single gangue mineral under different traction speeds and gangue positions. The increase of mean cutting force F_i due to a single gangue mineral is shown in Table 1, according to the results in Fig. 3.

From Table 1, the F_i increases with the traction speed, and it also increases when gangue minerals are closer to the middle of the coal seam. This is because, in these situations, the thickness of gangue chips separated from coal seam is larger, and there is a positive correlation between the cutting force and the thickness of separated chips. Therefore, high traction speed should be avoided, especially in the situations in which gangue minerals are closer to the middle of the coal seam.

Some gangue positions have been simulated with the finite element model and the corresponding cutting force due to gangue minerals can be obtained. However, with the limited groups of simulation, it is impossible to obtain the corresponding F_i when gangue minerals are at any positions. Therefore, with the results in Table 1, the mathematical model that reveals the relations between the F_i and h_i, is established with the data-fitting method. The fitting results are shown in Fig. 4. A power law relation between the F_i and h_i is shown, and the determination coefficients (the square of the correlation coefficient, referred to as [R^2]) in the mathematical model are all beyond 0.98. Eqs. (7) to (9) show the mathematical model between the F_i and the h_i under traction speeds of 0.06 m/s, 0.08 m/s and 0.10 m/s.

$$F_i = 47.69 h_i^{0.4196}, \quad R^2 = 0.9903, \tag{7}$$

$$F_i = 55.37 h_i^{0.4172}, \quad R^2 = 0.9946, \tag{8}$$

$$F_i = 62.51 h_i^{0.4163}, \quad R^2 = 0.9895. \tag{9}$$

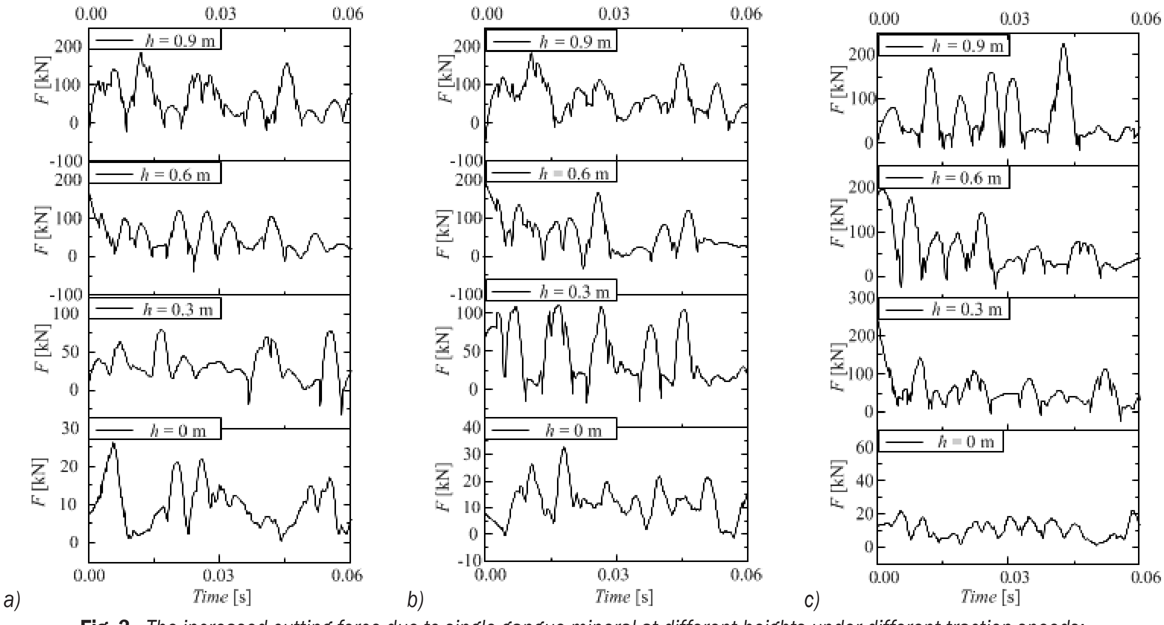

Fig. 3. *The increased cutting force due to single gangue mineral at different heights under different traction speeds; a) v = 0.06 m/s; and b) v = 0.08 m/s; and c) v = 0.10 m/s*

Table 1. *The increased mean cutting force due to single gangue mineral at different heights under different traction speeds*

v [m/s]	h_i [m]	F_i [kN]	v [m/s]	h_i [m]	F_i [kN]	v [m/s]	h_i [m]	F_i [kN]
0.06	0	9.52	0.08	0	10.84	0.10	0	11.85
	0.3	29.11		0.3	32.75		0.3	37.87
	0.6	37.82		0.6	45.33		0.6	45.88
	0.9	45.99		0.9	52.68		0.9	57.79

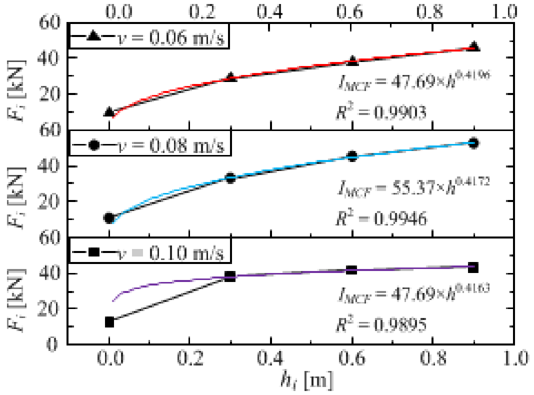

Fig. 4. *Relationship between the F_i and h_i under different traction speeds*

2.2 Relations between the increased mean cutting force and gangue distributions

2.2.1 Effect of μ on I_{MCF}

According to Eq. (2), the I_{MCF} is the sum of F_i, and it is not only related to gangue positions but also the total number of gangue minerals in the coal seam and gangue distributions. From Eq. (2), it is obvious that there is a non-linear relationship between the I_{MCF} and gangue distributions. Therefore, the study on the I_{MCF} under different gangue distributions is essential.

As mentioned, with the gangue distribution function, the simulation of the gangue potential distributions in a coal seam can made be possible by adjustments to the mean and variance of gangue distributions in the coal seam. Figs .5 and 6 show concentrative gangue distributions (σ=0.05 m) and dispersive gangue distributions (σ=0.90 m), and the corresponding I_{MCF}.

Fig. 5a shows the proportion of gangue minerals at different heights. Fig. 5b shows the I_{MCF} under the concentrative gangue distributions shown in Fig. 5a. When gangue minerals are in concentrative distributions, the I_{MCF} is influenced by the mean of gangue distributions. Because concentrative distribution means that most of the gangue minerals are at or around a certain position, which can be seen in Fig. 5a, and the F_i differs greatly when gangue minerals are at different positions. Therefore, when

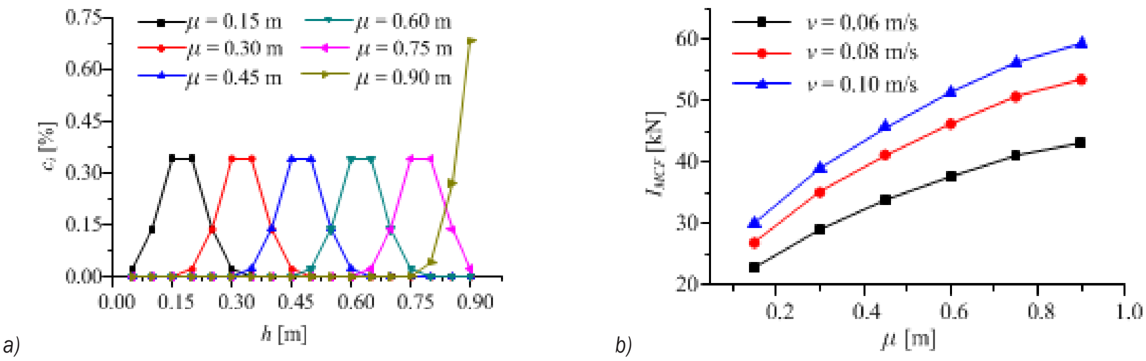

Fig. 5. Gangue minerals in concentrative distributions (σ = 0.05 m) and the corresponding IMCF; a) proportion of gangue minerals at different heights; and b) the IMCF varied with the mean of gangue distributions

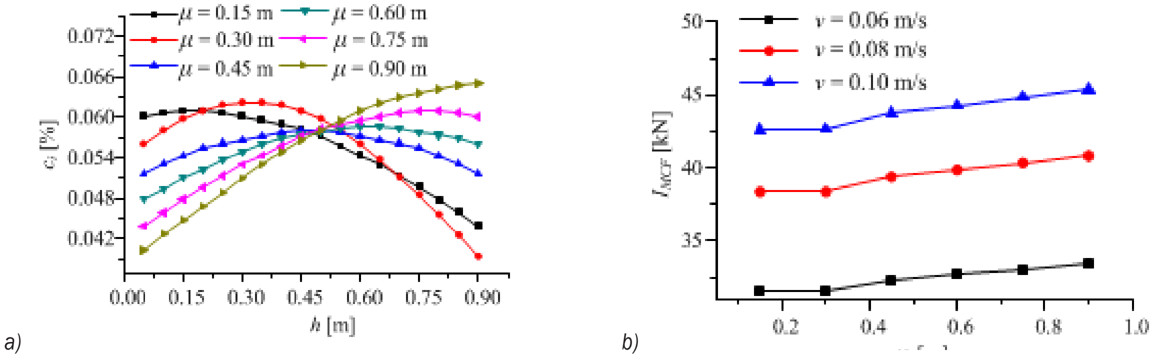

Fig. 6. *Gangue minerals in dispersed distribution (σ = 0.90 m) and the corresponding I_{MCF}; a) proportion of gangue minerals at different heights; and b) the I_{MCF} varied with the mean of gangue distributions*

the mean of gangue distribution varies, the I_{MCF} also differs greatly.

When gangue minerals in a coal seam are dispersed as shown in Fig. 6a, the I_{MCF} is slightly influenced by the mean of gangue distributions, as Fig. 6b shows, because the larger dispersion means the number of gangue minerals at different heights is closer to each other. In this case, there is little difference in the number of gangue minerals at the same positions even if gangue minerals are in different distributions. Therefore, under dispersive distributions, it is pointless to study the influence of gangue positions on I_{MCF} and, in this case, the I_{MCF} will approach a certain result, which is only related with the traction speed of cutter and the total number of gangue minerals in the coal seam.

2.2.2 Effect of σ on I_{MCF}

The variance of gangue distributions is another variable reflecting the characteristics of gangue distributions in a coal seam. Fig. 7 shows the I_{MCF} under different variances when the mean of gangue distributions is smaller (μ=0.15 m). Fig. 8 shows the I_{MCF} under different variances when the mean of gangue distributions is larger (μ=0.90 m).

Fig. 7a shows the proportion of gangue minerals at different heights when relatively numerous gangue minerals are at the top of coal seam with different variances. Fig. 7b shows the I_{MCF} under the gangue distributions shown in Fig. 7a. From Fig. 7b, the I_{MCF} stops increasing until the variance of gangue distribution is beyond 0.6 m when the relatively numerous gangue minerals are at the top of the coal seam. The reasons can be found in Fig. 7a, in which there is little difference between the proportions of gangue minerals at different heights under different variances when the variance is beyond 0.6 m. Therefore, the I_{MCF} is close to each other in this condition.

Fig. 8a shows the proportion of gangue minerals at different heights when relatively numerous gangue minerals are at the middle of the coal seam with different variances. Fig. 8b shows the I_{MCF} under the gangue distributions shown in Fig. 8a. From Fig. 8b, I_{MCF} almost stops decreasing and remains constant after the variance is beyond 0.3 m, because, as shown in Fig. 8a, the relatively numerous gangue minerals

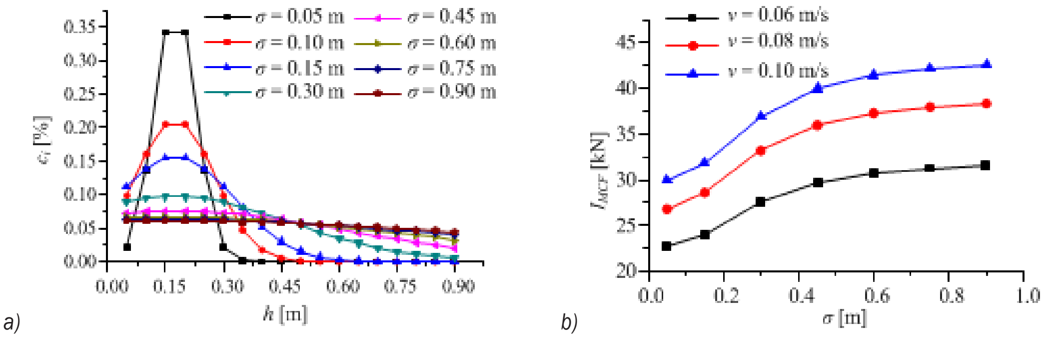

Fig. 7. *Gangue distributions with different variances under smaller mean (μ = 0.15 m) and the corresponding I_{MCF}; a) proportion of gangue minerals at different heights under different distributions; and b) the I_{MCF} varied with the variance of gangue distributions*

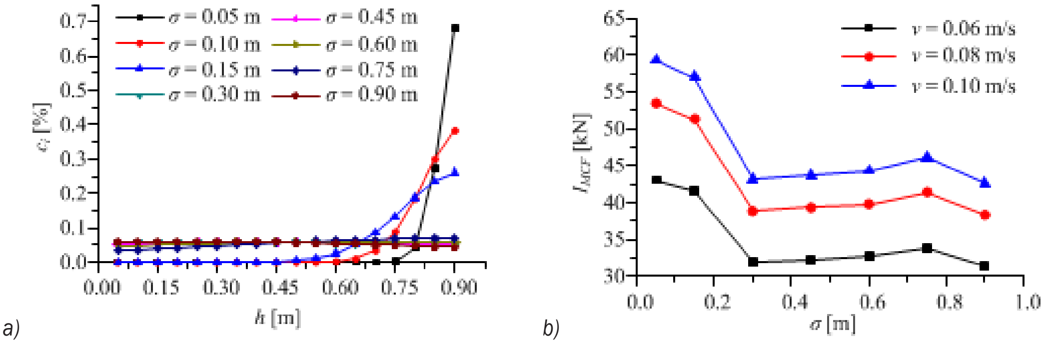

Fig. 8. *Gangue distributions with different variances under larger mean (μ = 0.90m) and the corresponding I_{MCF}; a) proportion of gangue minerals at different heights under different distributions; and b) the I_{MCF} varied with the variance of gangue distributions*

are at the middle of the coal seam when the variance is beyond 0.3 m. As mentioned the closer the gangue minerals are to the middle of coal seam, the larger the cutting force is. Therefore, the I_{MCF} is larger when the variance is beyond 0.3 m.

2.3 Relations between the Increased Specific Energy and Gangue Distributions

The increased specific energy consumption (referred to as I_{SE}) due to gangue cutting is also obtained in this paper. To study the I_{SE} under different gangue distributions, I_{SE}/H_{WC} is introduced, as shown in Eq. (10). H_{WC} is the specific energy consumption when there are not any gangue minerals in the coal seam.

$$\frac{I_{SE}}{W_{WC}}=\frac{N\cdot\sum_{i=1}^{n}(c_i\cdot F_i)\cdot t_R\cdot v}{F_{C,ave}\cdot L}. \tag{10}$$

According to Eq. (10), I_{SE}/H_{WC} is the variable associated with many factors such as gangue distributions, the number of gangue minerals in the coal seam, traction speed of cutters, and the length of coal, which contains gangue minerals. For the convenience of research, further derivation is made on Eq. (10) and then Eq. (11) is obtained, as follows:

$$\frac{I_{SE}}{W_{WC}}=\frac{N\cdot t_R}{L}\cdot\frac{\sum_{i=1}^{n}(c_i\cdot F_i)\cdot v}{F_{C,ave}}. \tag{11}$$

According to Eq. (11), the I_{SE}/H_{WC} is divided into two main parts. One is related to the number of gangue minerals in a coal seam, the length of coal where gangue minerals distribute, and the average time of gangue cutting. There is a linear relation between I_{SE}/H_{WC} and $N{\cdot}t_R/L$. The other is related to gangue distribution, the traction speed of cutters, and the mean cutting force under coal cutting condition.

Fig. 9 shows I_{SE}/H_{WC} under different gangue distributions. Fig. 9a shows I_{SE}/H_{WC} when gangue minerals are as concentrated as shown in Fig. 5a. According to the figure, the I_{SE}/H_{WC} varies greatly with the mean of gangue distribution. The difference on the I_{SE}/H_{WC} under different mean of gangue

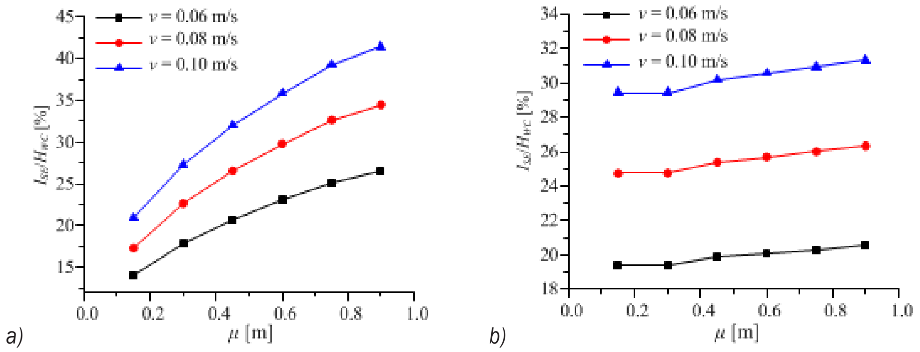

Fig. 9. *Relationship between I_{SE}/H_{WC} and gangue distributions;*
a) I_{SE}/H_{WC} varied with the mean of gangue distributions under concentrative gangue distributions (σ = 0.05 m); and
b) I_{SE}/H_{WC} varied with the mean of gangue distributions under dispersed gangue distributions (σ = 0.90 m)

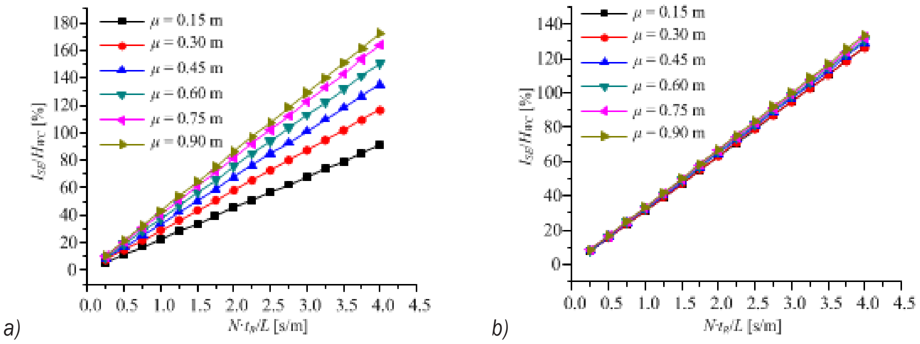

Fig. 10. *Relationship between I_{SE}/H_{WC} and ; a) I_{SE}/H_{WC} varied with in concentrative gangue distributions (σ = 0.05 m); and*
b) I_{SE}/H_{WC} varied with under dispersed gangue distributions (σ = 0.90 m)

distributions is about 15 % to 20 %. Fig. 9b shows I_{SE}/H_{WC} when gangue minerals are in dispersive distributions, as shown in Fig. 6a. According to Fig. 9b, the I_{SE}/H_{WC} rarely varies with the mean of gangue distribution. The difference in the I_{SE}/H_{WC} under different means of gangue distributions is no more than 5 %. Therefore, when gangue minerals are dispersive, the results on the II_{SE}/H_{WC} are close to each other wherever the most gangue minerals are in the coal seam.

According to Eq. (11), I_{SE}/H_{WC} is not only related with gangue distributions, but also the formula $N{\cdot}t_R/L$. Fig. 10 shows I_{SE}/H_{WC} varied with $N{\cdot}t_R/L$ under different gangue distributions. When gangue distributions are concentrated in a coal seam, the I_{SE}/H_{WC} under different $N{\cdot}t_R/L$ is shown in Fig. 10a. From Fig. 10a, it is evident that the I_{SE}/H_{WC} increases with the $N{\cdot}t_R/L$. When the relatively numerous gangue minerals are closer to the middle of coal seam, the I_{SE}/H_{WC} varies greatly with $N{\cdot}t_R/L$. Therefore, the length of coal seam and the total number of gangue minerals should be considered, especially when most gangue minerals are closer to the middle of coal seam.

When gangue minerals are dispersed in a coal seam, the I_{SE}/H_{WC} under different $N{\cdot}t_R/L$ is shown in Fig. 10b. Unlike the situations in Fig. 10a, there are few differences among the I_{SE}/H_{WC} under different gangue distribution even if most gangue minerals are at the top of the coal seam. Therefore, in dispersive gangue distribution, the I_{SE}/H_{WC} is determinable according to the formula $N{\cdot}t_R/L$ without considering the gangue distribution. Moreover, from the figure, I_{SE}/H_{WC} reaches more than 100 % as soon as the $N{\cdot}t_R/L$ is over 4 s/m. In other words, when the $N{\cdot}t_R/L$ is over 4 s/m, the I_{SE}/H_{WC} due to gangue cutting increases by 100 % compared with that due to coal cutting without any gangue minerals.

3 CONCLUSIONS

(1) Gangue distribution function in the paper is used to simulate potential gangue distributions in a coal seam. It can be achieved and simulated by adjustments to the mean and variance of the gangue distribution function in coal seam. The results show that gangue distribution function is suitable for simulation of the situations that gangue minerals at different heights are in different proportions.

(2) The increased mean cutting force due to gangue minerals I_{MCF} is closely related to the positions of the gangue minerals. The relationship between the increased mean cutting force and the positions at which they are can be obtained with the assistance of the finite element method. The results show that there is a strong correlation between the mentioned factors and that the correlation coefficient is more than 0.98. This might be helpful to obtain the positions of gangue minerals in the coal seam according to the cutting force.

(3) The increased mean cutting force I_{MCF} due to gangue minerals is closely related to gangue distribution. With the increase of gangue dispersion in the coal seam, the increased mean cutting load I_{MCF} tends to be a constant and not greatly influenced by gangue distribution. Therefore, when gangue minerals are dispersed in a coal seam, the increased mean cutting load I_{MCF} is calculable.

(4) The increased specific energy due to gangue minerals in a coal seam is also obtained under different gangue distributions, and it is a variable that is nonlinear with gangue distribution and linear with the length of coal seam and the number of gangue minerals in a coal seam. When gangue minerals in a coal seam are dispersed, and the $N{\cdot}t_R/L$ is larger than 4 s/m, the increased specific energy increases by 100 % compared with that due to coal cutting without any gangue minerals.

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5 NOMENCLATURES

I_{MCF}	the increased mean cutting force due to all gangue minerals, [kN]
I_{SE}	the increased specific energy due to all gangue minerals, [kW·h/m³]
L	length of coal seam with gangue minerals, [m]

H height of coal seam with gangue minerals, [m]
μ the mean height of gangue distribution in a coal seam, [m]
σ the height variance of gangue distribution in a coal seam, [m]
h_i positions of gangue minerals in a coal seam, [m]
F_i the increased mean cutting force due to single gangue mineral, [kN]
N the total number of gangue minerals at the different heights, [-]
W the mechanical energy of a single cutter, [kN·m]
V the volume of coal crushed by a single cutter, [m^3]
v the linear velocity of a cutter, [m/s]
c_i the proportion of gangue minerals at different heights, [%]
$F_{C,ave}$ the mean cutting force on cutter due to coal, [kN]
t_C the total time taken in the coal-cutting process, [s]
t_R the average time taken in the gangue-cutting process, [s]
H_{WC} the specific energy consumption in the coal-cutting process, [kW·h/m^3]

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