

Optimal algorithm of mean radiant temperature in mine roadway based on Monte Carlo method

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Abstract. With the shallow deposit resources decreasing, the mining depth gradually increases, resulting in more and more high-temperature mines with heat damage. The mean radiant temperature is taken as an important parameter to calculate and evaluate the thermal comfort in high-temperature mine roadway. Therefore, it is necessary to study and optimize the calculation method of mean radiant temperature. The calculation method of mean radiant temperature in mine roadway as an open space is significantly different from that in a closed space. Herein, a modified algorithm of mean radiant temperature in an open space is put forward based on the normalization principle in combination with the geometric characteristics and radiation conditions in mine roadway. In order to optimize the calculation process of the modified algorithm, this paper also proposes a numerical algorithm for the radiation angle coefficient of roadway wall to human body surface on the basis of Monte Carlo method. Moreover, the numerical algorithm accuracy is verified by the contrastive analysis between numerical solutions and theoretical solutions. The verification results show that when the number of energy beams reaches up to 5 million, the maximum error between the theoretical solution and the numerical solution of the radiation angle coefficient is only 0.13%.

Keywords: mine roadway; mean radiant temperature; Monte Carlo; modified algorithm; error analysis.

1. Introduction

With the improvement of mining mechanization, the shallow deposit resources decrease day by day. Thus, the mining depth gradually increases in China, resulting in more and more high-temperature mines with heat damage, a total of about 300 until now [1, 2]. Some researches have reported that the miners, who work in a high-temperature environment for a long period of time, are prone to the psychological discomfort such as psychological fatigue, anxiety and mental distraction, as well as abnormal physiological functions such as the decreases in the excitability of the central nervous system, the body's response speed and coordination. Accordingly, there would easily occur production safety accidents [3-6], e.g., personnel shock and inappropriate operation of equipments. Therefore, it is of great significance to ensure safe mining in mines to calculate and evaluate the thermal comfort of the environment in the high-temperature mine roadway [7].

The scholars at home and abroad have carried out more researches on evaluation index of human thermal comfort [8]. In addition to the dry bulb temperature and wet bulb temperature, the effective temperature (ET) has been used to evaluate the environment in mines. But it is not suitable for the high-temperature and high-humidity environment in mines, because the influence of humidity is underestimated in the high temperature area [9]. In 1971, Gergorzuk put forward a concept of net effective temperature (NET) by combining the wind speed and ET, and established the comfort grading standard [10]. Later, Yaglou proposed the wet bulb globe temperature (WBGT), with indoor and outdoor conditions for the calculation formula, which is the thermal comfort evaluation index most widely used at present [11]. Likewise, a "comfort model" was proposed by Maurice Sunkpal et al., and then the comfort parameters were extensively used to evaluate the deep, hot and humid conditions in mines [12]. The above studies on human thermal comfort under thermal environment in mines are conducted mostly based on the predicted mean vote (PMV). Notably, the

PMV comprehensively considers the environmental factors, i.e., air temperature, humidity, wind speed and mean radiant temperature, as well as the human factors, i.e., human activity metabolism and clothing [13-16]. Therefore, it is necessary to study and optimize the calculation method of mean radiant temperature as an important parameter to calculate and evaluate the thermal comfort in mine roadway with PMV method.

In view of the above research objectives, this paper firstly puts forward a modified algorithm of mean radiant temperature in an open space based on the algorithm of mean radiant temperature in a closed space in combination with the space characteristics and radiant conditions in mine roadway. Secondly, an optimal algorithm is proposed to calculate the radiation angle coefficient of roadway wall to human body surface based on Monte Carlo method. Finally, the accuracy of radiation angle coefficient calculated by Monte Carlo method is verified by the contrastive analysis between numerical solutions and theoretical solutions under different working conditions.

2. Algorithm of mean radiant temperature in mine roadway

2.1 Algorithm of mean radiant temperature in a closed space

According to the heat transfer amount between cavity and inner cladding wall, the radiation heat transfer between human body and the indoor environment is calculated as follows.

$$Q_{b-a} = \frac{A_{eff}\sigma(T_{cl}^4 - \bar{T}_r^4)}{\frac{1}{\varepsilon_b} + \frac{A_{eff}}{A_a}\left(\frac{1}{\varepsilon_a} - 1\right)} \quad (1)$$

Where A_{eff} is the effective radiation area of the human body, m^2 . σ is the blackbody radiation constant, $5.67 \times 10^{-8} \text{ W}/(m^2 \cdot K^4)$. T_{cl} is the surface temperature of clothing, K. \bar{T}_r is the mean radiant temperature, K. ε_b is the emissivity of human body surface. A_a is the total area of roadway surrounding the human body, m^2 . ε_a is the mean emissivity of the environment.

In Formula (1), the surface area of human body is far smaller than the total area of indoor environment surrounding the human body, and generally, the emissivity of materials in indoor environment is approximately equal to 1. Hence, the second term in denominator of Formula (1) can be ignored. Then, the new formula of radiation heat transfer between the human body and the environment is

$$Q_{b-a} = A_{eff}\varepsilon_b\sigma(T_{cl}^4 - \bar{T}_r^4) \quad (2)$$

Where A_D is the surface area of naked body, m^2 . f_{cl} is the surface area coefficient of clothing, a dimensionless number.

As can be seen from the literature [17], the Formula (3) can be used to calculate the heat transfer amount between human body and single radiant surface in indoor environment.

$$Q_{b-p} = A_{eff}F_{b-p}\varepsilon_b\varepsilon_p\sigma(T_{cl}^4 - T_p^4) \quad (3)$$

The abstract geometric model of the roadway unit control body has six faces, so the total of radiation heat transfer amount between human body and roadway unit control body is

$$\begin{aligned} Q_{b-a} &= Q_{b-p1} + Q_{b-p2} + Q_{b-p3} + Q_{b-p4} + Q_{b-p5} + Q_{b-p6} \\ &= A_{eff}\varepsilon_b\sigma \sum_{i=1}^{i=6} F_{b-pi}\varepsilon_{pi}(T_{cl}^4 - T_{pi}^4) \end{aligned} \quad (4)$$

Formula (2) is combined with Formula (4), and then

$$T_{cl}^4 - \bar{T}_r^4 = \sum_{i=1}^{i=6} F_{b-pi}\varepsilon_{pi}(T_{cl}^4 - T_{pi}^4) \quad (5)$$

Because the human body is in a closed space, the radiation angle coefficient of human body to environment is complete, namely,

$$\sum_{i=1}^{i=6} F_{b-pi} = 1 \tag{6}$$

Assuming that the emissivity of radiant surface in the roadway is equal to 1, the Formula (6) is substituted into Formula (5), then the mean radiant temperature can be calculated by

$$\bar{T}_r^4 = \sum_{i=1}^{i=6} F_{b-pi} T_{pi}^4 \tag{7}$$

From Formula (7), if the roadway unit control body is regarded as a closed cuboid, the mean radiant temperature in the roadway unit control body can be figured out as each wall temperature and the radiation angle coefficient of human body to each wall are known. However, it is worth noting that the emissivity of the roadway surface is close to 1 rather than equal to 1. Hence, the error is inevitable, as solving the mean radiant temperature with the above method. Moreover, the emissivity is infinitely close to 1, so the error can meet the requirement of engineering precision.

2.2 Modified algorithm of mean radiant temperature in a closed space

As mentioned above, if the roadway unit control body is regarded as a closed space, the mean radiant temperature can be obtained by Formula (7) as each wall temperature and the radiation angle coefficient of human body to each wall are known [18]. However, different from other indoor spaces, as a closed space, two faces of the roadway unit control body are the air rather than the rock. In general, the radiation effect of air to the human body can be ignored, and accordingly, there are only four radiation surfaces for the roadway unit control body.

Here, as the wall temperatures of four radiation surfaces and their radiation angle coefficients to human body are directly substituted into Formula (7) to solve the mean radiant temperature, the air surface temperature of the roadway unit control body is regarded as 0. As a result, the calculated mean radiant temperature is less than the wall temperature of each radiation surface, which is obviously contradictory to the common sense. Therefore, the above method can't be used to solve the mean radiant temperature. After analyzing the calculation process of mean radiant temperature, it is found that the sum of the radiation angle coefficients of roadway unit control body is not equal to 1. If the Formula (7) is still used to calculate the mean radiant temperature, the radiation angle coefficients of roadway unit control body should satisfy Formula (6).

As such, the modified algorithm of mean radiant temperature is to normalize the radiation angle coefficients of human body to four radiation surfaces in the roadway unit control body. Concretely, the radiation angle coefficients, F_{b-p1} , F_{b-p2} , F_{b-p3} and F_{b-p4} , of human body to four radiation surfaces in the roadway unit control body as well as their sum are firstly worked out. Then, the following Formula (8) is utilized to obtain the values of four radiation angle coefficients via normalization.

$$\frac{F_{b-pi}}{\sum_{i=1}^{i=4} F_{b-pi}} = \frac{F'_{b-pi}}{1} \tag{8}$$

After normalization, the sum of the radiation angle coefficients of human body to the four radiation surfaces in the roadway unit control body is equal to 1. Later, the mean radiant temperature in the roadway unit control body can be directly solved by the following formula.

$$\bar{T}_r^4 = \sum_{i=1}^{i=4} F'_{b-pi} T_{pi}^4 \tag{9}$$

3. Monte Carlo algorithm of radiation angle coefficient

As can be seen from Formula (9), only when the radiation angle coefficient of human body surface to each roadway wall is firstly figured out can the mean radiant temperature in the roadway unit control body be obtained. In fact, Fanger has proposed a method to calculate the radiation angle

coefficient of human body surface to each roadway wall, but with more complicated calculation process and limited spatial geometric position for calculation. Moreover, due to the simple geometric positions of roadway wall and human body, the Monte Carlo method is adopted to calculate the radiation angle coefficients. In order to simplify the geometric model and calculation process, several assumptions are needed as follows.

- (1) The roadway wall can be regarded as the diffuse gray body.
- (2) The wall temperature of the roadway unit control body uniformly distributes, without axial temperature difference.
- (3) The reflection, refraction and absorption of the air medium in the roadway should be ignored.
- (4) Each energy beam carries the same amount of radiant heat energy.
- (5) The radiant surface of the human body is the cylindrical side, without the top surface.

3.1 Construction of geometric model

Firstly, a three-dimensional Cartesian coordinate system A-xyz is established, and moreover, the A point is taken as the origin to draw a cuboid to represent the roadway unit control body. As shown in Figure 1, L_d is the length of the roadway unit control body, H_d is the height of the roadway unit control body, and W_d is the width of the roadway unit control body. Then, a cylinder is drawn at the center of the roadway unit control body to represent a miner working in the roadway. Here, the diameter of the cross section of the cylinder can be considered as the shoulder width of the miner. The height of the cylinder can be considered as the miner height. Based on the Human dimensions of Chinese adults (GB10000-88), the ratio of shoulder width of the miner to the height is 1:4, and thus that of the diameter of the cylinder to the height is 1:4.

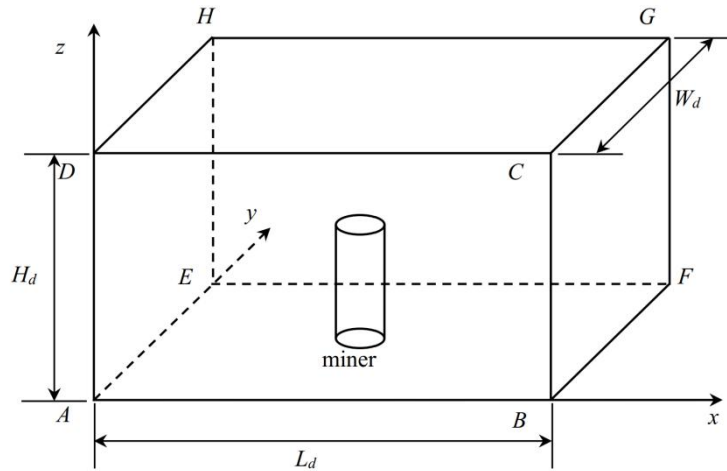


Figure. 1 The geometric model of radiation heat transfer in the roadway

3.2 Calculation process of angle coefficient

In terms of the Stefan-Boltzmann law, the radiant energy Q_p of the roadway wall can be solved by the following formula.

$$Q_p = \varepsilon_p \sigma T_p^4 A_p \quad (10)$$

Where F_{b-p} is the angle coefficient between human body and radiation surface. ε_p is the emissivity of radiation surface. σ is the radiation constant of blackbody, $5.67 \times 10^{-8} \text{ W}/(\text{m}^2 \cdot \text{K}^4)$. T_p is the roadway wall temperature, K. A_p is the surface area of the roadway wall, m^2 .

Herein, the total radiant energy Q_p has been known. It is assumed that the total number of energy beams on the radiant surface is N_a . On the basis of Hypothesis (4), the energy of each energy beam is

$$e = \frac{Q_p}{N_a} \tag{11}$$

Based on the definition of angle coefficient, if the number of energy beams emitted from the radiation surface and the number of the energy beams received by the human body surface are obtained, the angle coefficient between the roadway wall to the human body surface would be

$$F_{p-b} = \frac{sum \cdot e}{Q_p} = \frac{sum}{N_a} \tag{12}$$

Where sum is the number of energy beams received by the human body surface.

3.3 Calculation flow of angle coefficient

The Monte Carlo calculation model of angle coefficient is based on the geometric model of radiation heat transfer in the roadway. The calculation flow of angle coefficient is as follows. Firstly, the rays are generated on the roadway wall, and simultaneously, whether the rays directly fly away from the system should be determined. If the rays enter the research system, it is needed to determine whether the rays are from an effective energy beam. Then, the landing point locations of the energy beams should be determined, and moreover, the number of energy beams in the radiated region should be figured out. Finally, the angle coefficient values can be obtained. Furthermore, the heat flux of radiated location can be worked out based on the radiant energy and angle coefficient of roadway wall. The calculation flow of angle coefficient is presented in Figure 2 [19, 20].

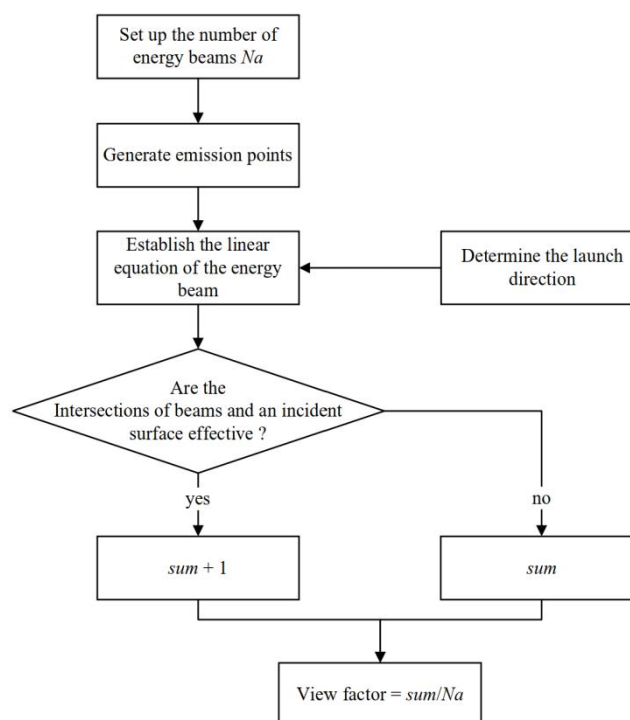


Figure. 2 The calculation flow of angle coefficient with Monte Carlo method

3.4 Generation of energy beam emission points

As can be seen from Hypothesis (2), the wall temperature of the roadway unit control body evenly distributes, and thus the energy beam emission points on the roadway wall should evenly distribute. Owing to six rectangular surfaces of the geometric model of roadway, in order to ensure the even distribution of energy beam emission points on each surface, the rand () function in C++ language needs to be used to generate two random numbers R1 and R2 in a range of 0~1. Subsequently, the R1 and R2 are multiplied with the length and width of the rectangle, respectively, as illustrated in Figure 3.

By means of the generation method of the energy beam emission points, the coordinates of the energy beam emission points on six surfaces of geometric model can be determined as follows.

The coordinates of the energy beam emission points on surface ABCD are

$$P_x = L_d \cdot R_1$$

$$P_y = 0$$

$$P_z = H_d \cdot R_2$$

The coordinates of the energy beam emission points on surface DCGH are

$$P_x = L_d \cdot R_1$$

$$P_y = W_d \cdot R_2$$

$$P_z = H_d$$

The coordinates of the energy beam emission points on surface EFGH are

$$P_x = L_d \cdot R_1$$

$$P_y = W_d$$

$$P_z = H_d \cdot R_2$$

The coordinates of the energy beam emission points on surface ABFE are

$$P_x = L_d \cdot R_1$$

$$P_y = W_d \cdot R_2$$

$$P_z = 0$$

The coordinates of the energy beam emission points on surface AEHD are

$$P_x = 0$$

$$P_y = W_d \cdot R_1$$

$$P_z = H_d \cdot R_2$$

The coordinates of the energy beam emission points on surface BFGC are

$$P_x = L_d$$

$$P_y = W_d \cdot R_1$$

$$P_z = H_d \cdot R_2$$

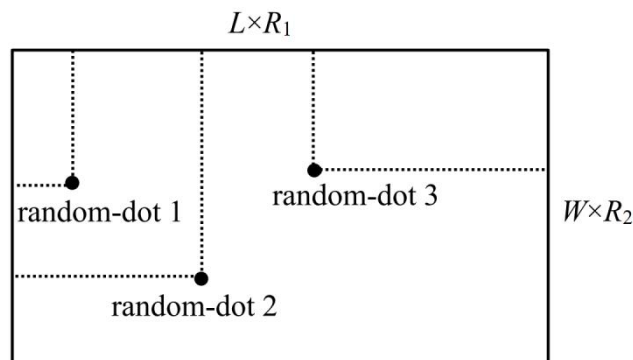


Figure. 3 Generation method of energy beam emission points

It is worth noting that the emission points in circles o1 and o2 in Figure 4 are invalid. The reason is that the points of intersection between energy beam rays from the emission points in circles o1 and o2 and human body surface run through the human body, inconsistency with the practical conditions.

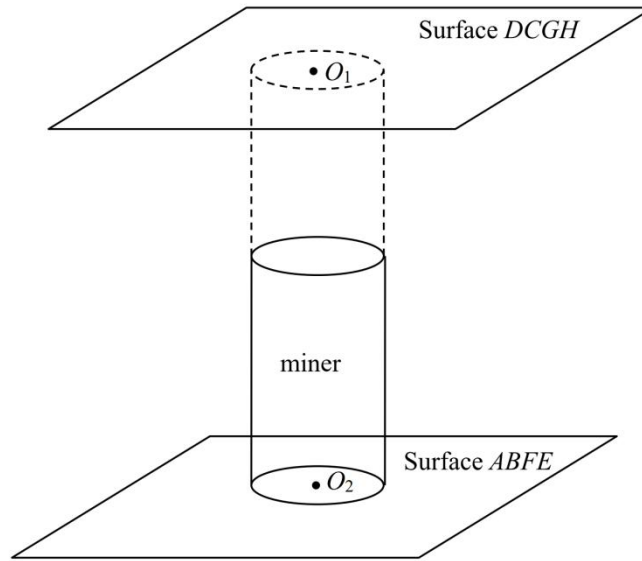


Figure. 4 Schematic diagram of invalid emission points

3.5 Determination of energy beam emission direction

When the emission point P is located on the surface of geometric model of roadway control body, the Cartesian coordinate system should be established to clearly describe the direction vector \vec{e} of radiant energy beam e . Moreover, the unit direction vector $\vec{e} (k_x, k_y, k_z)$ of energy beam e is determined by space angle ω and angle of circumference δ . Thus,

$$k_x = \sin \omega \cdot \cos \delta \tag{13}$$

$$k_y = \sin \omega \cdot \sin \delta \tag{14}$$

$$k_z = \cos \omega \tag{15}$$

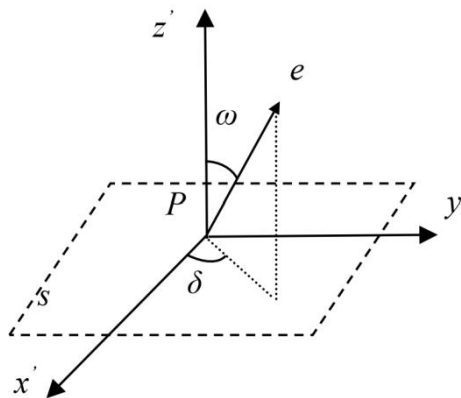


Figure. 5 Direction vector of radiant energy beam

As shown in literatures [21-23], the space angle ω and angle of circumference δ can be determined by Formulas (18) and (19), respectively. Furthermore, $R\omega$ and $R\delta$ are the random numbers generated by the rand () function in C++ language, ranging from 0 and 1.

$$\cos \omega = \sqrt{R_\omega} \tag{16}$$

$$\delta = 2\pi \cdot R_\delta \tag{17}$$

The Formulas (13)- (17) are combined, and then the unit direction vector $\vec{e} (k_x, k_y, k_z)$ of the energy beam e is

$$k_x = \sqrt{1 - R_\omega} \cdot \cos(2\pi \cdot R_\delta) \tag{18}$$

$$k_y = \sqrt{1 - R_\omega} \cdot \sin(2\pi \cdot R_\delta) \tag{19}$$

$$k_z = \sqrt{R_\omega} \tag{20}$$

The coordinate transformation should be performed for the unit direction vector \vec{e} , so as to obtain the ray equation of energy beam in the global coordinate system $o-xyz$. Assuming that the coordinate transformation matrix is $T_{x'y'z'-xyz}$, the direction vector of energy beam in the global coordinate system is [24].

$$(K_x, K_y, K_z) = (k_x, k_y, k_z) \cdot T_{x'y'z'-xyz} = (k_x, k_y, k_z) \cdot \begin{bmatrix} a_1 & b_1 & c_1 \\ a_2 & b_2 & c_2 \\ a_3 & b_3 & c_3 \end{bmatrix} \tag{21}$$

Where (a_1, b_1, c_1) , (a_2, b_2, c_2) and (a_3, b_3, c_3) are the unit vectors in the global coordinate system $o-xyz$, corresponding to the x' axis, y' axis and z' axis in Cartesian coordinate system $P-x'y'z'$, respectively.

As (a_1, b_1, c_1) , (a_2, b_2, c_2) and (a_3, b_3, c_3) are represented by \vec{n}_1 , \vec{n}_2 and \vec{n}_3 , respectively, the unit direction vectors of energy beams from six surfaces of geometric model of roadway in the global coordinate system are successively

Surface ABCD:

$$\begin{aligned} \vec{n}_1 &= (-1, 0, 0) = (a_1, b_1, c_1) \\ \vec{n}_2 &= (0, 0, 1) = (a_2, b_2, c_2) \\ \vec{n}_3 &= (0, 1, 0) = (a_3, b_3, c_3) \end{aligned}$$

Surface DCGH:

$$\begin{aligned} \vec{n}_1 &= (-1, 0, 0) = (a_1, b_1, c_1) \\ \vec{n}_2 &= (0, 1, 0) = (a_2, b_2, c_2) \\ \vec{n}_3 &= (0, 0, -1) = (a_3, b_3, c_3) \end{aligned}$$

Surface EFGH:

$$\begin{aligned} \vec{n}_1 &= (1, 0, 0) = (a_1, b_1, c_1) \\ \vec{n}_2 &= (0, 0, 1) = (a_2, b_2, c_2) \\ \vec{n}_3 &= (0, -1, 0) = (a_3, b_3, c_3) \end{aligned}$$

Surface ABFE:

$$\begin{aligned} \vec{n}_1 &= (1, 0, 0) = (a_1, b_1, c_1) \\ \vec{n}_2 &= (0, 1, 0) = (a_2, b_2, c_2) \\ \vec{n}_3 &= (0, 0, 1) = (a_3, b_3, c_3) \end{aligned}$$

Surface AEHD:

$$\begin{aligned} \vec{n}_1 &= (0, 1, 0) = (a_1, b_1, c_1) \\ \vec{n}_2 &= (0, 0, 1) = (a_2, b_2, c_2) \\ \vec{n}_3 &= (1, 0, 0) = (a_3, b_3, c_3) \end{aligned}$$

Surface BFGC:

$$\begin{aligned} \vec{n}_1 &= (0, 1, 0) = (a_1, b_1, c_1) \\ \vec{n}_2 &= (0, 0, -1) = (a_2, b_2, c_2) \\ \vec{n}_3 &= (-1, 0, 0) = (a_3, b_3, c_3) \end{aligned}$$

3.6 Establishment of energy beam ray equation

In conclusion, when the energy beam emission point is located on the inner surface of geometric model of the roadway, the ray equation of energy beam in the global coordinate system can be obtained in combination with the coordinate formula of emission point P and the unit direction vector formula of energy beam, as follows.

$$\frac{x - P_x}{K_x} = \frac{y - P_y}{K_y} = \frac{z - P_z}{K_z} \tag{22}$$

3.7 Effectiveness determination of energy beam landing points

It is needed to combine the effective energy beam ray equation and cylindrical surface equation $(x-x_0)^2+(y-y_0)^2=r_p^2$ to find the point of intersection J, and thus determining whether the landing point of energy beam ray is inside of the straight cylinder side. In this regard, there may be one or two points of intersection. Furthermore, when the Z-coordinate value of the point of intersection J is in a range of $0 \leq z \leq H_p$ (H_p refers to the average height of miners), the landing points are located on the straight cylinder side. It should be noted that when there are two points of intersection between the energy beam rays and the straight cylinder side at the same time, as exemplified in Figure 6, the point of intersection far away from the emission point P should be abandoned. This is because the energy beam rays can't run through the human body, and inconsistent with the actual situation. Hence, the landing points of energy beam rays left are effective, and the total sum of energy beam received on the surface of human body should increase by 1.

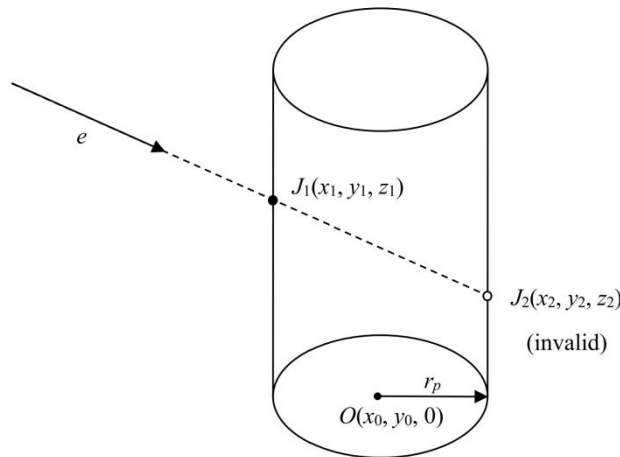


Figure. 6 Schematic diagram of energy beam landing points on cylinder surface

4. Accuracy verification of numerical solution of radiation angle coefficient

In order to verify the accuracy of Monte Carlo calculation model of the angle coefficient, the calculated angle coefficient can be compared with the theoretical solution under geometric conditions shown in Figure 7.

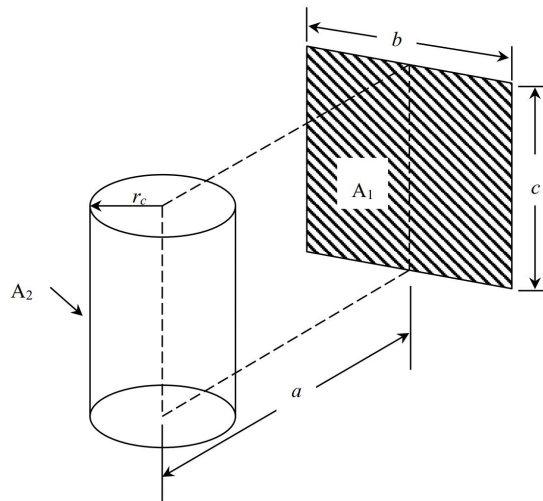


Figure. 7 Geometric conditions of angle coefficient between vertical plate surface and straight cylinder surface

According to the literature [25], the angle coefficient FA1-2 between vertical plate surface and straight cylinder surface is

$$F_{A1-2} = \frac{2}{Y} \int_0^{Y/2} f(\xi) d\xi \tag{23}$$

Where

$$f(\xi) = \frac{X}{X^2 + \xi^2} - \frac{X}{\pi(X^2 + \xi^2)} \left\{ \cos^{-1} \frac{B}{A} - \frac{1}{2Z} \left[\sqrt{A^2 + 4Z^2} \cos^{-1} \left(\frac{B}{A\sqrt{X^2 + \xi^2}} \right) + B \sin^{-1} \left(\frac{1}{\sqrt{X^2 + \xi^2}} \right) - \frac{\pi A}{2} \right] \right\}$$

$$X = \frac{a}{r_c}; \quad Y = \frac{b}{r_c}; \quad Z = \frac{c}{r_c}; \quad A = Z^2 + X^2 + \xi^2 - 1; \quad B = Z^2 - X^2 - \xi^2 + 1$$

Where a is the vertical distance from the straight cylinder to the vertical plate, m. b is the length of the vertical plate, m, c is the height of the vertical plate and the straight cylinder, m. A2 is the surface area of the straight cylinder, m2. A1 is the surface area of the vertical plate, m2. rc is the radius of the straight cylinder, m.

The theoretical solution of the angle coefficient is FA1-2, and its numerical solution is Fp-b. Then, the error between the two can be calculated as follows.

$$\phi = \frac{|F_{A1-2} - F_{p-b}|}{F_{A1-2}} \times 100\% \tag{24}$$

Where ϕ is the calculation error of the angle coefficient, %.

As shown in Figure 7, the vertical distance between the vertical cylinder and the vertical plate is 1m. The length of the vertical plate is 5m. Then, with the heights of vertical plate and vertical cylinder changing, c is set to 1m, 1.5m, 2m, 2.5m and 3m, respectively, a total of five working conditions. Furthermore, there are 5 million energy beams emitted under each working condition. The results of angle coefficients calculated by Monte Carlo method are listed in Table 1.

Simultaneously, the theoretical solutions of angle coefficients for five working conditions are figured out by Formula (23). Likewise, the errors between the theoretical solutions and numerical solutions are listed in Table 1.

Table 1. Calculated results of angle coefficients

a, m	b, m	c, m	rc, m	Na	F _{A1-2}	F _{p-b}	φ, %
1	5	1	0.25	5×10 ⁶	0.0558	0.05576	0.07
1	5	1.5	0.25	5×10 ⁶	0.0703	0.07027	0.04
1	5	2	0.25	5×10 ⁶	0.0798	0.0797	0.13
1	5	2.5	0.25	5×10 ⁶	0.0863	0.0864	0.12
1	5	3	0.25	5×10 ⁶	0.0911	0.091	0.11

As is well known, the Monte Carlo method is a statistical analysis method. So, in fact, the numerical solutions of angle coefficients in Table 1 are the average values of calculation results repeated for 10 times, with a standard deviation of 0.0016. The numerical solutions of angle coefficients are compared with the theoretical solutions under five geometric conditions. As illustrated in Figure 8, it is found that when the number of energy beams is large enough (more than 5 million), the maximum error is only 0.13%, which meets the accuracy requirement for engineering.

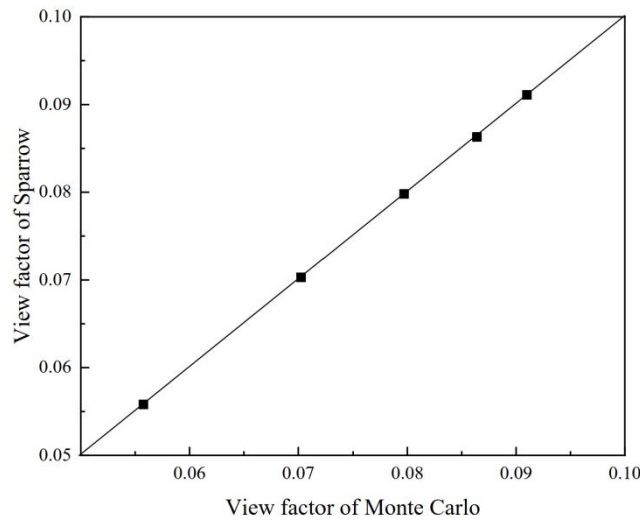


Figure. 8 Comparison between numerical solutions and theoretical solutions of angle coefficients

5. Conclusions

Based on the above study, the conclusions are as follows.

(1) As an open space, the mine roadway is significantly different from a closed space. The mean radiant temperature can't be directly obtained with the method of ISO7730 standard. Actually, a modified algorithm is needed to calculate the mean radiant temperature based on the geometric characteristics of roadway and the practical radiation situation.

(2) Monte Carlo method is a commonly-used statistical method in the field of radiation heat transfer. Moreover, it can quickly and accurately confirm the values of the angle coefficients. In this study, it is rather challenging to establish the geometric model of radiation heat transfer in roadway, effectively determine the end positions of energy beams, and coordinate transformation of energy beam emission direction for the angle coefficient calculation by Monte Carlo method.

(3) Monte Carlo method is adopted to calculate the radiation angle coefficient of roadway wall to human body surface. In addition to simple calculation way and accurate calculation results, the Monte Carlo method can optimize the calculation process of mean radiant temperature in mine roadway.

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