DISTRIBUTION LAW FOR THE DANGER AREA FOR SPONTANEOUS COAL COMBUSTION IN A DYNAMIC GOAF WITH LOW AIR LEAKAGE SPEED

by

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This paper examines the relationship between the advancement of the working face and the distribution of spontaneous coal combustion under a low air leakage wind speed in a goaf. Based on the unsteady-state simulation method, the process of spontaneous coal combustion was simulated in a fully mechanized coal mining face at different advancing speeds. The relationship between different advancing speeds and the distribution area of the oxidation zone of spontaneous coal combustion in a goaf was clarified. A safe advancing speed was determined. Furthermore, the advancement of the working face altered the area of spontaneous high temperature inside the goaf. An increase in the advancing speed increased the length of time of spontaneous combustion in the leftover coal. An exponential relationship was demonstrated between the spontaneous combustion area and the advancement of the fully mechanized mining face. When the oxygen concentration was used as a calculation indicator, the width of the oxidation zone was asymmetrical on the inlet and outlet, and the advancing distance of the working surface increased when the distance was shorter than 90 m and the return side was smaller than the inlet side. When the advancing distance was longer than 90 m, the width of the spontaneous combustion oxidation zone distribution remained unchanged. The study clarified the relationship between the distribution of the danger area for spontaneous coal combustion and advancing speed. This could provide a theoretical basis for the prevention and control technology of the spontaneous combustion of broken coal in a dynamic goaf.

Key words: *advancing speed, coal spontaneous combustion, hazardous area, low air leakage wind speed*

Introduction

In mining, the spontaneous combustion of broken coal in a goaf is one of the main causes of accidents. It seriously affects both the safety of coal mine production and the health and safety of mine workers [1-3]. During the normal advancement of the working face, it is essential to accurately clarify the oxidation and heating process of the broken coal, assess the risk of spontaneous combustion, and identify the location of high temperature areas within the goaf. This can provide a basis for the advanced control of the spontaneous combustion of the broken coal within that area. However, human entry into the goaf is particularly difficult, and both the

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source of the fire and the location of the high temperature areas are well concealed. Current monitoring methods are unable to meet the requirements for the prevention of spontaneous coal combustion [4, 5]. Consequently, numerical simulations are used to realize the occurrence and development of this phenomenon. The relationship between the advancement of the working face and the risk distribution of the spontaneous combustion of coal within the goaf is analyzed to provide theoretical guidance for the prediction and control of the spontaneous combustion of coal within the goaf area.

Much research has been conducted on the spontaneous combustion of coal within goaves. Due to the continuous advancement over time of the working face, the location of the spontaneous combustion area has changed according to where the broken coal in a goaf is located. This process of spontaneous combustion needed to be solved simultaneously with unsteady-state equations in the dynamic goaf. Consequently, the moving co-ordinate system was introduced, and the unsteady goaf with a moving boundary was regarded as a steady goaf with a relatively constant boundary, which greatly simplified the calculation process [6]. A particle swarm optimization-support vector regression model [7] was established to predict the temperature of the spontaneous combustion of coal based on the concentration of gases in the goaf and the distance from the measuring points to the working face. An evaluation index [8], defined as the ratio of the oxygen consumption rate to the gaseous product emission rate, was proposed to assess the coal's spontaneous combustion state. Taraba *et al*. [9] studied the process of the spontaneous combustion of coal in a goaf with continuous advancement. However, their model was established based on the heat balance assumption, and it failed to consider the heat transfer process between the solid and gas phases. Su *et al*. [10] established a similar goaf model based on the actual goaf size at a ratio of 1:50 to investigate both the influence of ventilation methods and the relevance to the air leakage patterns within the goaf. To calculate the dynamic coal mining process of the working face, Xia *et al*. [11] proposed a non-steady-state simulation method of *fixed grid, dynamic attribute*. However, temperature field changes were not analyzed in the dynamic goaf. Qin *et al*. [12] investigated the influence of non-Darcy seepage on spontaneous combustion in the goaf, establishing a mathematical model of spontaneous combustion combined with air-flow, oxygen concentration, and temperature fields within a moving co-ordinate system. Rosema *et al*. [13] explored the atmospheric oxidation of coal, possible spontaneous combustion, and the daily solar radiation cycle. Additionally, the role of spontaneous combustion and mining activities during the development of coal fires in the Rujigou Coal Mine were investigated.

Most of the previous studies assume that the goaf entity remains static and unchanged, and its geometric dimensions are believed to be in a stable state during the advancement of the working face. The wind speed is measured at the air inlet and is generally equal to 1-7 m/s. However, as the working face continually advances, the overlying coal and rock collapses in the goaf, which leads to an expansion of the physical area. Air leakage passages within the goaf are generated, which enable a low rate of fresh air infiltration into the mined-out area. This causes temporal and spatial changes in the flow and temperature fields inside the goaf. Therefore, based on the time-space effect of the hazardous area distribution of the spontaneous combustion of coal under low speed air leakage in the dynamic goaf, this study proposes a simulation using fixed co-ordinates and variable size. The oxidation zone distribution law at the 21201 working face within a specific mine under conditions of low wind speed and advancing distance and speed was simulated. The relationship between the advancing speed and the spontaneous combustion period of the coal within the goaf was calculated to determine the reference value for the safe advancing speed of the simulation object.

Construction of the spontaneous coal combustion model in a dynamic goaf

Numerical model of spontaneous coal combustion simulation

As the working face continues to advance over time, the process of the spontaneous combustion of broken coal is inseparable from the influence of time and space within the goaf. A dynamic goaf geometric model was constructed and calculated using the spontaneous coal combustion simulation method [14]:

$$-\nabla p = \frac{\mu}{k} v + \beta \rho |v| v \tag{1}$$

$$\nabla \left[-\frac{kH}{\mu + \rho \beta |v|} \nabla p \right] = Q_s \tag{2}$$

$$n \frac{\partial c_\mathrm{i}}{\partial t} + v_\mathrm{i} \nabla c_\mathrm{i} - \nabla \left(n D_\mathrm{i} \nabla c_\mathrm{i} \right) = \frac{c - c_\mathrm{i}}{c} W_\mathrm{i} \tag{3}$$

$$\rho_\mathrm{e} c_\mathrm{e} \frac{\partial T}{\partial t} - \lambda_\mathrm{e} \nabla \left(\nabla T \right) + n \rho_\mathrm{g} c_\mathrm{g} v \nabla T = Q \tag{4}$$

among them

$$\frac{1}{\lambda_\mathrm{e}} = \frac{1}{\lambda_\mathrm{g}} + (1-n) \frac{1}{\lambda_\mathrm{m}} \tag{5}$$

$$c_\mathrm{e} = n c_\mathrm{g} + (1-n) c_\mathrm{m} \tag{5}$$

$$\rho_\mathrm{e} = n \rho_\mathrm{g} + (1-n) \rho_\mathrm{m} \tag{7}$$

Numerical method of spontaneous coal combustion in the dynamic goaf

At present, most goaf research is based on stable goaf. The establishment of simulated wind speed is mainly based on the ventilation volume of the mine or the inlet wind speed of the working face as a reference value. However, with the advancement of the working face, the geometric size of the goaf constantly increases. The main oxygen source is air leakage from the working face to the goaf via the air leakage channel. Here, the leakage wind speed is extremely low. Therefore, the proposed simulation mainly modeled the spontaneous combustion process of coal remaining at the wind speed of the air leakage in the dynamic goaf.

The working face progresses at a certain advancing speed from the cut-off point. As the overlying coal and rock fall, the goaf begins to form. In this model, the advancement of the working face was assumed to be continuous and uniform, regardless of any stoppage in production. The grid scale of the goaf model was simplified into the form of fixed co-ordinates and variable size, which is a method of shifting each quantity distribution backward. Taking the 2-D physical model of the goaf as an example, the co-ordinate origin of the dynamic co-ordinate system was moved to the position of the cut eye in the dynamic goaf. The unit for advancing distance was Δd within the unit for advancing time, Δt.

Assuming that the width of the mining surface is denoted by L, the moving speed is uniform and is denoted by v. The travel stroke is denoted by Δd within the same Δt. Then, $\Delta d = \Delta t \times v$. So, the newly formed area is equal each time and is denoted as a_1'. Then, $a_1' = \Delta d \times L$.

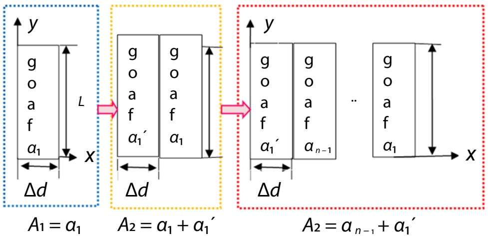

Figure 1. The dynamic process of goaf creation

The positive direction of the goaf is the x-axis is along the forward direction of the open cut, and the y-axis is the width of the mining face. Figure 1 presents the process of goaf creation under working face advancement over time.

According to the fixed co-ordinates and variable-size simulation algorithm, the mesh grid can remain unchanged without considering the influence of the suffocation zone on the spontaneous combustion zone in the goaf. If the advancing speed of the working face is v, the advancing distance of the working face within a certain time, $\Delta\tau$, can be treated as the relative displacement of each quantity followed by a backward translation distance of $\Delta\tau \times v$. Considering the sensitivity of the relationship between the advancing distance, x, and $\Delta\tau \times v$, the specific algorithm can be expressed [15]:

– If $x < v\Delta\tau$:

$$C(\Gamma)^{\tau+1}(x, y) = C(\Gamma)_0 \tag{8}$$

– If $x \geq v\Delta\tau$:

$$C(\Gamma)^{\tau+1}(x, y) = C(\Gamma)^{\tau}(x - v\Delta\tau) \tag{9}$$

Variable-size geometric goaf model

The selected calculation example was the 21201 coal face of a coal mine with a *U*-shaped ventilation system. The ventilation rate was 1200 m^3 per minute, and the coal seam gas content was 18 m^3/t. The advancing speed was 3 m per day, and the wind resistance was 0.013 Ns^2/m^8. The fully mechanized caving method of coal mining was utilized, and the mechanical mining height was 3.9 m. The mining ratio of the working face was approximately 1:1.8, and the shortest spontaneous combustion period of the coal seam was about 17.4 days. The inlet and outlet air lanes of the working face were at a height of 4 m, while the width was 4.5 m. The goaf area was 200 m long, and the mixed gas temperature was 18.6 °C. The average air density of the mine was 1.225 kg/m^3 with an air viscosity coefficient of 1.7894 × 105 kg/m·s at room temperature. The gas diffusion coefficient was 2.88 × 103 m^2/s. The looseness coefficient was set to 1.5, and the working face was 90 m wide. The width of the air inlet and outlet roadway was 3 m. The average inclination angle of the coal seam was 11°, and the actual wind speed at the working face was 1.62 m/s. The leakage wind speed was 0.24 m per minute. The falling height was about 10.5 m, and the coefficient of breakage within the goaf was 1.12-1.5. The permeability coefficient was 1.342-72.53 m^2/(Pa·s) at a porosity of 0.14-0.34. The coal and rock had a thermal conductivity of 1.72 W/(m°C) in the goaf. The thermal conductivity of gas was 0.0264 W/(m°C), and the specific heat capacity of the coal in the goaf was 5.12 × 105 J/(m^3°C). The specific heat capacity of the mixed gas in the goaf was 1206 J/(m^3°C). Finally, the initial temperature was 18 °C.

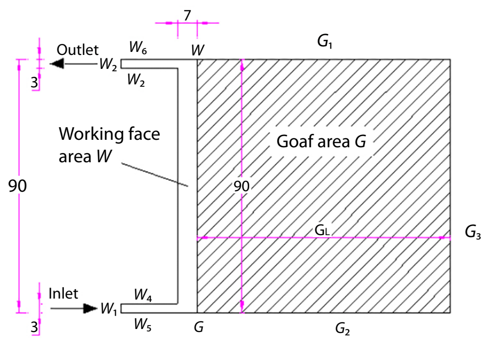

Figure 2. Geometry model of goaf with advancement of the working face

With a working face length of 90 m and a width of 7 m, the length of the goaf area presented a stage change. When the average of the working face advancing speed was taken as 3 m per day, W_1 was the air inlet of the inlet lane, and the width was 3 m. The W_2 was the return air opening of the outlet lane, and the width was 3 m. The goaf could be fixed for transient analysis at a certain point in time. With the continuous advancement of the working face, the W and G co-ordinates constantly changed. The G_3 was set as a fixed boundary, while W-G was a moving boundary. As shown in fig. 2, the length of the goaf, G_L, increased with time.

Results and discussion

The discussion and analysis are mainly from three perspectives: the relationship between the advancing speed of the working face and the spontaneous combustion period, the determination of the safe advancing speed of the working face, and the distribution of the spontaneous combustion oxidation zone in the goaf at different advancing distances and speeds.

The relationship between working face advancing speed and period of spontaneous combustion

It is generally considered that when the temperature reaches 80 °C, coal starts to spontaneously ignite. Theoretically, and regardless of objective factors such as moisture, unbalanced air leakage and other random factors, the advancing speed of the working face is approximately exponentially related to the spontaneous combustion period, which is presented in fig. 3. It is revealed that the faster the working face advances, the longer the period of spontaneous combustion. This relationship is shown:

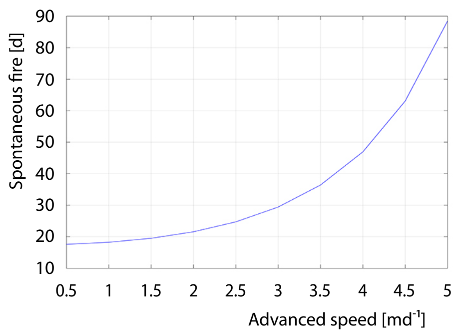

Figure 3. Spontaneous ignition period under different working face advancing speeds

$$V(T) = \frac{Q(C_1 - C_2)}{sLn} \tag{10}$$

In the working surface of the aforementioned calculation example, $\tau_0 = 17.4$ d, $a = 0.046$, and $d = 2.215$.

Heat release intensity

According to the specific mining process of the calculated example, the air supply volume of the working face was 1200 m^3 per minute. According to the statistical data, it can be determined that the shortest period of spontaneous combustion at the working face was 17.4 d. When the advancing distance was 90 m, the oxidation heating zone was the widest at the air inlet at a width of 48 m. According to the actual conditions of the fully mechanized caving face, the safety factor was 1.2, and there were 30 working days per month.

The width of the spontaneous combustion oxidation zone was 48 m. Thus, the safe time [15] for the non-self-ignition of coal in the goaf is expressed:

$$\tau_1 = \frac{L_\mathrm{m}}{v_i'} \tag{11}$$

Hence, the safe advancing speed of the working face is shown:

$$v_\mathrm{s} = \frac{L_\mathrm{m}}{\tau_1'} = \frac{48}{17.4} = 2.73 \tag{12}$$

It can be seen from eq. (12) that to avoid spontaneous combustion in the goaf and to ensure safety, the advancing speed of the working face must theoretically not be less than 2.73 m per day. This is because broken coal becomes a suffocation zone prior to spontaneous combustion in the oxidation heating zone. If the working face advancing speed is less than 2.73 m per day but the advancing time is less than 35 days, there is still a risk of spontaneous combustion within the goaf.

Distribution of the spontaneous combustion oxidation zone in the goaf at different advancing distances

According to the four criteria for spontaneous coal combustion and the difficulty of spontaneous coal combustion, the three-zone criteria for the goaf are presented in tab. 1 [16].

In this discussion, the oxygen concentration was selected as the index to divide the spontaneous combustion oxidation zone in the goaf. When the air leakage wind speed was 0.24 m per minute, the law of the spontaneous combustion oxidation zone was obtained for different advancing distances of the working face within the goaf. The advancing distances were 30, 60, 90, 120, and 180 m, respectively.

Table 1. Indicators for the division of three zones in the goaf

Area	Leakage wind speed [mmin^{-1}]	Oxygen concentration	Heating rate [°Cd^{-1}]
Heat sink zone I	>0.24	>18	<1
Oxidation zone II	0.1 ~ 0.24	10 ~ 18	≥ 1
Choking zone III	<0.1	<10	<1

It can be seen in fig. 4 that the spontaneous combustion oxidation zone distribution reveals a gradual decreasing trend when oxygen concentration is used as an indicator. When the advancing distance is 30 m, the air leakage velocity is higher in the goaf. In particular, the oxygen concentration gradient is faster at the inlet side, while the width of the oxidation zone at the inlet side is less than at the outlet side. As the advancing distance of the working face increases, the air leakage resistance of the goaf also increases; there is a gradual increase in the width of the oxidation zone of the inlet side, and the oxidation depth slowly spreads to the depth of the goaf. However, when the advancing distance is longer than 120 m, the remaining coal is no longer oxidized in the goaf. The width of the calculated oxidation zone is asymmetrical at the inlet and outlet sides when using oxygen concentration as an indicator. Finally, the outlet side is smaller than the inlet side.

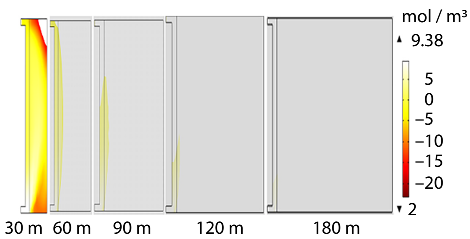

Figure 4. The spontaneous combustion oxidation zone within the goaf

Distribution of the spontaneous combustion oxidation zone in the goaf with different advancing speeds

It is evident from section *Distribution of the spontaneous combustion oxidation zone in the goaf at different advancing distances* in the goaf that the probability of spontaneous combustion in the goaf is minimal when the advancing distance of the working face is longer than 90 m. Therefore, the advancing distance of the goaf was set to 90 m at different simulated advancing speeds of 2, 3, 4, and 5 m per day, respectively. An oxygen concentration (CO_2) of

10-18% was selected as the dividing index. The distribution of the spontaneous combustion oxidation zone in the goaf was investigated, and the zone is presented in fig. 5.

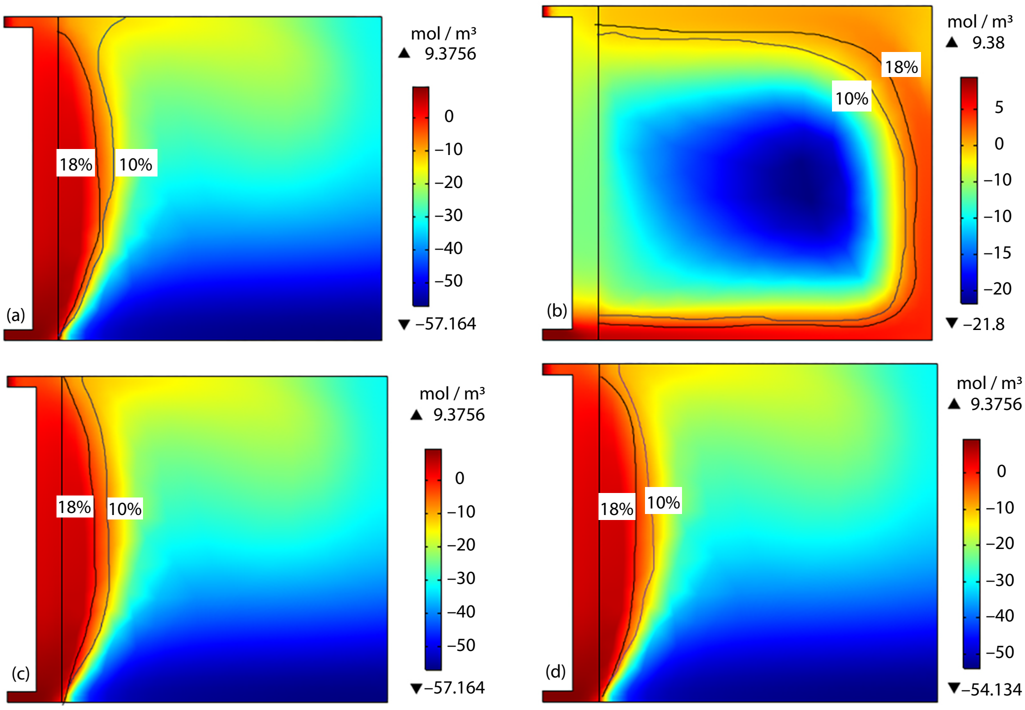

Figure 5. Regional changes in the oxidation zone at different advancing speeds; (a) *v* = 2 m/d, (b) *v* = 3 m/d, (c) *v* = 4 m/d, and (d) *v* = 5 m/d

The following can be drawn from fig. 5:

– When the advancing speed increased from 2-5 m per day, the oxidation area in the goaf gradually increased. The distribution position of the O_2 concentration-line at CO_2 = 18% was approximately unchanged. The distribution position of the O_2 concentration-line at CO_2 = 10% slowly shifted to the center of the goaf. There was a weak relationship between the air-flow field near the end of the working face and advancing speed in the goaf, although the air-flow field in the center of the goaf was closely correlated with the advancing speed.
– When the advancing distance was 90 m, the advancing time was 45, 30, 23, and 18 days at different advancing speeds of 2, 3, 4, and 5 m per day. It is evident that a faster advancing speed requires a shorter duration. This reduces the effective compaction of the collapsed coal and rock mass in the goaf, allowing oxygen to penetrate the coal and rock more smoothly and allow more oxidation of the coal. Additionally, the width of the oxide band was increased. The oxidation zone was at its smallest at an advancing speed of 3 m per day, which indicates that this advancing speed is the most reasonable. In section *Heat release intensity*, the safe advancing speed was calculated at 2.7 m per day, which is relatively close to this result and indicates the reliability of the simulation results. Conversely, a slower advancing speed took more time, thereby increasing the effective compaction of the collapsed coal and rock mass in the goaf. The point at which the oxygen reached the coal and rock mass was relatively shallow; therefore, the reaction involved less coal. Finally, the width of the oxide band was also smaller.

Conclusion

- The working face advanced at a certain speed with time, while the spontaneous high temperature area moved with the working face inside the goaf. By increasing the advancing speed of the working face, the remaining coal in the goaf took longer to ignite naturally, this might avoid the possibility of a spontaneous fire. However, when limiting the advancing speed, other technical fire-fighting measures must be installed.
- When the goaf area met the air leakage and oxygen supply conditions, the spontaneous combustion area of the remaining coal revealed an exponential relationship with the advancement of the fully mechanized mining face. By controlling the air leakage of the fully mechanized mining facing the goaf, the spontaneous combustion period could be extended. This could reduce the risk of the spontaneous combustion of coal within the goaf.
- With an increase in the advancing distance of the working surface, the width of the oxidation zone calculated using oxygen concentration as an indicator was asymmetrical at both the inlet and outlet sides. Additionally, the outlet side was smaller than the inlet side. The distribution of the spontaneous combustion oxidation zone presented a gradually decreasing trend.

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Nomenclature

a, d – the regression coefficient, [–]
C – concentration of gas in the goaf, [molm^{-3}]
c_e – equivalent volume specific heat capacity of coal and rock in the goaf, [Jm^{-3}°C^{-1}]
$C(\Gamma)$ – distribution of physical quantities in the goaf (CH_4,O_2,CO,T), [–]
c_g – specific heat capacity of air, [Jm^{-3}°C^{-1})
c_i – concentration of mixed gas i in the goaf, [molm^{-3}]
c_m – volume specific heat capacity of coal and rock in the goaf, [Jm^{-3}°C^{-1}]
D_i – diffusion coefficient of mixed gas i in the goaf, [m^{2}s$^-$1]
H – coal rock fall height, [m]
k – permeability coefficient, [m^{2}Pa^{-1}s^{-1}]
n – void ratio, [–]
p – mixed gas pressure in the goaf, [Pa]
Q – goaf heat source, [–]
v – gas velocity in coal body, [ms^{-1}]
v_i – advancing speed of the working face, [ms^{-1}]
W_i – gas sources participating in the reaction in the goaf, [–]

Greek symbols

β – non-Darcy flow factor, [m^{-1}]
λ_e – equivalent thermal conductivity of coal and rock in the goaf, [W m$^-$1°C^{-1}
λ_g – thermal conductivity of mixed gas, [W m^{-1}°C^{-1}]
λ_m – thermal conductivity of coal and rock in the goaf, [W m^{-1}°C^{-1}]
μ – dynamic viscosity of flowing gas, [Pas]
ρ_e – equivalent density of mixed gas in the goaf, [gcm^{-3}]
ρ_g – air density, [gcm^{-3}]
ρ_m – coal and rock density in the goaf, [gcm^{-3}]
$\Delta\tau$ – time step, [s]
τ, τ+1 – before and after moments, [s]
τ_0 – the shortest spontaneous fire period, [d]

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