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Influence of Air Supply Velocity on Temperature Field in the Self Heating Process of Coal

(Pengaruh Halaju Bekalan Udara pada Bidang Suhu dalam Proses Pemanasan Sendiri Arang Batu)

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ABSTRACT

The air supply velocity is an important factor affecting the spontaneous combustion of coal. The appropriate air velocity can not only provide the oxygen required for the oxidation reaction, but maintains the good heat storage environment. Therefore, it is necessary to study the influence of the actual air velocity in the pore space on the self-heating process of coal particles. This paper focuses on studying the real space piled up by spherical particles. CFD simulation software is used to establish the numerical model from pore scale. Good fitness of the simulation results with the existing results verifies the feasibility of the calculation method. Later, the calculation conditions are changed to calculate and analyze the velocity field and the temperature field for self-heating of some particles (the surface of the particles is at a certain temperature) and expound the effect of different air supply velocities on gathering and dissipating the heat.

Keywords: Coal self-heating; flow field; pore scale; self-heating point; temperature field

ABSTRAK

Halaju bekalan udara adalah faktor penting yang mempengaruhi pembakaran spontan arang batu. Halaju udara yang sesuai bukan sahaja dapat memberikan oksigen yang diperlukan untuk reaksi pengoksidaan, tetapi mengekalkan persekitaran penyimpanan haba yang baik. Oleh itu, adalah perlu untuk mengkaji pengaruh halaju udara sebenar di ruang liang pada proses pemanasan sendiri zarah arang batu. Makalah ini memberi tumpuan kepada mengkaji ruang sebenar yang ditimbun oleh zarah sfera. Perisian simulasi CFD digunakan untuk menubuhkan model berangka daripada skala liang. Kesesuaian yang baik daripada keputusan simulasi dengan keputusan sedia ada mengesahkan kelayakan kaedah pengiraan yang digunakan. Kemudian, keadaan pengiraan diubah untuk mengira dan menganalisis medan halaju dan medan suhu untuk pemanasan sendiri beberapa zarah (contohnya permukaan zarah berada pada suhu tertentu) dan menjelaskan kesan halangan bekalan udara yang berlainan pada pengumpulan dan menghilangkan haba.

Kata kunci: Bidang aliran; medan suhu; pemanasan sendiri arang batu; skala lubang; titik pemanasan sendiri

Introduction

The fire caused by the oxidation and spontaneous combustion of coal is one of the major disasters in the mine and the main cause of many accidents such as gas and dust explosion. The low temperature oxidation of coal is an extremely complex and dynamic physical and chemical process which automatically accelerates (Xu & Hua 2002) and is in fact a process of slow oxidation, heat release, warming and finally combustion.

In the field of spontaneous combustion of coal, most of the simulation studies have taken goaf or stacking coal particle as a porous medium at a macroscopic scale. Krishnaswamy et al. (1996) established a model for coal piles exposed to air, and examined in details the effects of coal porosity, particle size and other factors on the spontaneous combustion of coal. By analyzing the numerical simulation results and the experimental results obtained from spontaneous combustion test device, Deng et al. (2002) obtained the change law of reaction products with time, such as coal temperature, oxygen, CO and CO_2. In the model, Yuan and Smith (2009) added the chemical reaction source term in Arrhenius form to simulate the temperature field inside the large-scale coal pile. All of the above studies use the concept of pore porosity and permeability to describe the dynamic characteristics and analyze the energy changes by providing the local thermal equilibrium hypothesis in which the gas has the same temperature with coal particles. However, in order to study the heating process of coal particles in different air supply conditions, it is necessary to relate the flow and heat transfer at the micro level and deeply analyze the changes in flow field and temperature field inside the pore space of particles. Among the pore-scale studies on flow heat and mass transfer of porous medium, the study on catalytic equipment including packed bed, which is widely applied in the chemical field, is developed relatively maturely. Many scholars analyze the internal chemical reactions by using the fluid dynamics method (CFD).

Jiang and Lu (2006) used water as a fluid to simulate the packed bed which is equipped with wall heating and obtained convective heat transfer coefficients at different flow rates and different particle diameters; Dixon et al. (2011) systematically studied the meshing method suitable for three-dimensional numerical simulation from the perspective of pore scale of particles. Wu et al. (2010) compared the advantages and disadvantages of the porous medium hypothesis method and the pore space simulation method, and expounded the necessity of pore-scale simulation. Ahamed and Loganathan (2017) most of the relevant studies on the packed bed choose to heat from the peripheral wall and add the chemical reaction energy source to the particles. In this paper, the self-heating of spherical coal particles replaces the manually external heating means and the stacking coal particles replace the catalyst particles in the packed bed. In addition, the pores formed by the actual accumulation of particles with limited number take the place of the macroscopic porosity concept. The calculation model is established to simulate the internal space. The effect of the air supply velocity on gathering or dissipating the energy inside the pores is analyzed to preliminarily discuss the influence of the wind speed on self-heating of coal.

For the flow characteristics inside the pores, the Re is used as the criterion to determine laminar flow state and the turbulent flow state. The flow state is divided into: Darcy flow: Re <1; Inertial flow: 1<Re<150; Unstable laminar flow: 150 <Re <300; and Turbulent flow: Re> 300 (Jolls & Hanratty 1966; Tobiś & Ziółkowski 1988). For the heat transfer characteristics, Wakao and Funazkri (1978) summarized the convective heat transfer criterion formula inside the packed bed: $Nu = 2 + 1.1Pr^{1/3}Re^{0.6}$ (15 <Re <8500). Achenbach (1995) extended the applicable range of the Re and added the effect of the porosity φ. He proposed a heat transfer criterion formula for the spherical particles packed bed: $Nu=\{(1.18Re^{0.58})^4+[0.23(Re/\varphi)^{0.75}]^4\}^{1/4}$ (1<Re<77000). In the above formulas, the particle diameter dp refers to the characteristic length. In this paper, considering the fact that the airflow speed is low in case of coal spontaneous combustion, the momentum equation of the stable laminar flow state is used and combined with the continuity equation and the energy equation to obtain the velocity field and temperature field Noraini et al. (2016). The specific calculation model is described in the literature (Patankar 1988).

$$\frac{\partial \rho_g}{\partial t} + div(\rho \vec{u}) = 0 . \tag{1}$$

$$\frac{\partial(\rho_g u)}{\partial t} + div(\rho_g u\vec{u}) = div(\mu gradu) - \frac{\partial p}{\partial x} - \left(\frac{150(1-\varphi)^2\mu}{d_p^2\varphi^3}u + \frac{3.5(1-\varphi)}{d_p\varphi^3}\frac{1}{2}\rho_g|\vec{u}|u\right). \tag{2}$$

$$\frac{\partial(\rho_g v)}{\partial t} + div(\rho_g v\vec{u}) = div(\mu gradv) - \frac{\partial p}{\partial x} - \left(\frac{150(1-\varphi)^2\mu}{d_p^2\varphi^3}v + \frac{3.5(1-\varphi)}{d_p\varphi^3}\frac{1}{2}\rho_g|\vec{u}|v\right). \tag{3}$$

$$\frac{\partial(\rho_g w)}{\partial t} + div(\rho_g w\vec{u}) = div(\mu gradw) - \frac{\partial p}{\partial x} - \left(\frac{150(1-\varphi)^2\mu}{d_p^2\varphi^3}w + \frac{3.5(1-\varphi)}{d_p\varphi^3}\frac{1}{2}\rho_g|\vec{u}|w\right). \tag{4}$$

$$(\varphi\rho_g c_{pg} + (1-\varphi)\rho_c c_{pc})\frac{\partial T}{\partial t} + \rho_g c_{pg}\left(u_x\frac{\partial T}{\partial x} + u_y\frac{\partial T}{\partial y} + u_z\frac{\partial T}{\partial z}\right) = (\lambda_g + (1-\varphi)\lambda_c)\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + Q \tag{5}$$

where ρ_g is the air density, kg/m^3; t is the time, s; u, v, w is the velocity, m/s; μ is the coefficient of air kinetic viscosity, Pa·s; φ is the porosity of particle pile; d_p is the particle diameter, m; c_{pg} is the air specific heat, J/kg.K; p is the air pressure, Pa; ρ_c is the solid particle density, kg/m^3; c_{pc} is the solid particle specific heat, J/kg.K; λ_g is the coefficient of thermal conductivity of air, W/m·K; and λ_c is the coefficient of thermal conductivity of solid particle, W/m·K.

VALIDATION OF MATHEMATICAL MODELS

In order to verify the reliability of the model which is applied to the simulation of the internal pores, the method is used to simulate the packed bed particles under the boundary condition where the wall temperature is identical. Then, the calculation results are compared with the above-mentioned criterion formula.

The background of the confirmatory calculation is as follows: Inside an outer boundary with circular contour, 11 small particles are distributed in each layer to form a cell structure. Ahamed et al. (2017) the calculated area is stacked by four rows of unit structures which rotate at an angle of 60° to form a pore space composed by 44 particles (Guardo et al. 2004), where the particle diameter is 0.05 m and the porosity is 0.4 ~ 0.5. In order to avoid the difficulty in meshing and convergence calculation due to point of contact among particles and between particles and the wall boundary, 1% of the particle diameter is overlapped at the point of contact. After the calculation area is divided by the Gambit software into cells (shown in Figure 1), the CFD calculation software Fluent is used for simulation.

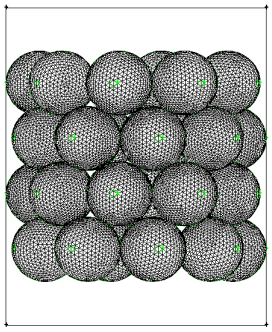

FIGURE 1. Meshing results of particle packing area

Temperature boundary condition is set in accordance with the literature (Guardo et al. 2004): the inlet air temperature is 293 K, wall temperature of the particle is 423 K and the outer boundary is the insulation boundary. The flow conditions at Re = 1, 5, 20, 85, 133, 177, 265 are calculated and the corresponding inlet velocity boundary condition is 0.0009 ~ 0.225 m/s. The following formula is used to acquire the Nu.

$$h = \frac{q}{T_s - T_g} . \tag{6}$$

$$Nu = \frac{hd_p}{\lambda} . \tag{7}$$

$$\mathrm{Re} = \frac{\rho u d_p}{\mu} . \tag{8}$$

where h is the surface heat transfer coefficient, W/m^2·°C; q is the quantity of unit surface heat transfer, W/m^2; T_s is the solid surface temperature, °C; T_g is the fluid average temperature, °C; d_p is the particle diameter, m; λ_g is the coefficient of thermal conductivity of air, W/m·°C; ρ is the air density (kg/m^3; μ is the coefficient of air kinetic viscosity, Pa·s; Re takes d_p as its characteristic length.

Equations (6) ~ (8) are used to deal with the calculation results. The simulation results are compared with those obtained by correlation equations from scholars including (Achenbach 1995; Wakao & Funazkri 1978). The results are shown in Figure 2.

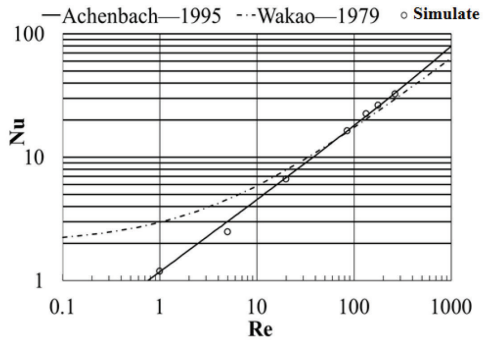

FIGURE 2. Comparison diagram between the simulation values and theoretical values

It can be seen from Figure 2 that two theoretical values are basically the same when the Re value is large (> 40) and are different mainly when the Re value is small. According to Sardar et al. (2017), the main reason for this difference is that Wakao and Funazkri (1978) did not take into account the pore and other correction factors in earlier experiments and studies. The simulation results in this paper can well fit with the correlation equation of theoretical value in case of a wide Re range, especially the low Re value. It is shown that the pore-scale model established herein can truly reflect the pore heat transfer characteristics between the particles, which provides a basis for further simulating the warming and self-heating of coal particles.

SIMULATION OF FLOW FIELD AND TEMPERATURE FIELD AT SELF-HEATING OF COAL PARTICLES

Due to complexity of the particle stacking structure in the coal pile, the particle size is not uniform. In order to simplify the calculation, this paper treats those particles as spheres with equidistant diameter. The above stacking method is used. Assuming that the oxygen supply is sufficient, self-heating of some coal particles have occurred and the heating effect of coal particle due to oxidation reaction is simplified as the process where the surface temperature of particles rises continuously. Thus, when calculating, a certain value of the surface temperature is selected as a boundary condition for contact surface. In order to reflect ability of the particles to heat by themselves, a particle is taken respectively from the middle of the second layer and of the third layer and the wall temperature is set to 70°C. For the other particles, their temperature is set to the normal surrounding rock temperature of 30°C. The specific location of the heating particle is shown in Figure 3.

Noraini et al. (2016) change the boundary conditions for wind speed at the inlet, calculate several working conditions which comply with actual air leakage rate under the shaft: v = 0.0005, 0.001, 0.004, 0.008, 0.012, 0.018 m/s. The mathematical model established is used for the calculation. When the residual error satisfies the requirement, the calculation process is considered to have converged. Figure 4 shows the temperature cloud picture of the same section (× = 0 plane) at different wind speeds. The heating particles are shown in the figure as two round surfaces in the middle of the second row and the third row.

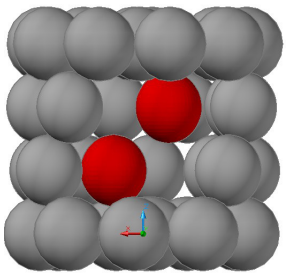

FIGURE 3. Location map of the heating particle

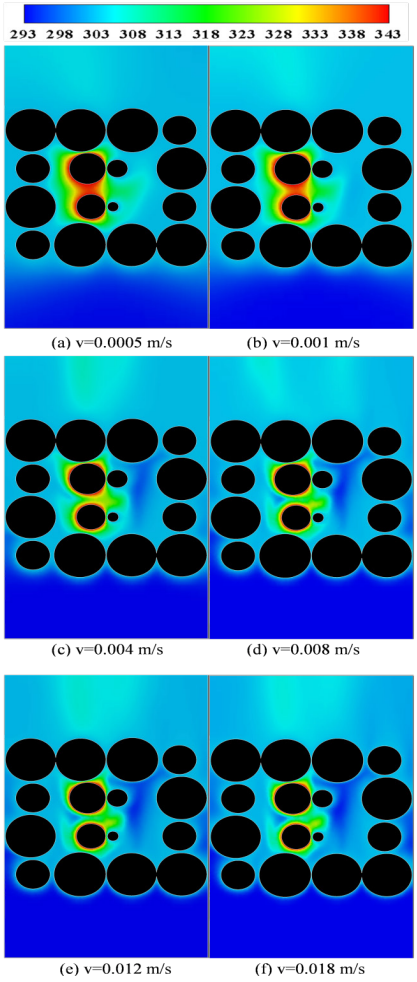

FIGURE 4. Temperature cloud picture (× = 0 plane) at different wind speeds

It can be seen from Figure 4 that when the wind speed is slow, the convective heat transfer effect is very weak and the effect of air flow on distribution of the temperature field is not obvious. The dominant heat transfer mechanism is the heat conduction and a high temperature area is formed around the heating particle. With the increase of wind speed, the increased air flow takes more heat and the convective heat transfer is gradually strengthened. As shown in Figure 4(b) to 4(e), the range of influence of the high temperature particles is significantly narrowed. At the same time, within some areas around the heating particles, the temperature changes slowly and is even accompanied by a certain warming phenomenon (see right sides of the two hot spheroids in Figure 4(b) and (e)), although the wind speed increases. The temperature does not decrease with the increasing wind speed. In order to further study this rule, several points which are located in representative positions are selected around the particles. See Figure 5 for location maps of the four feature points.

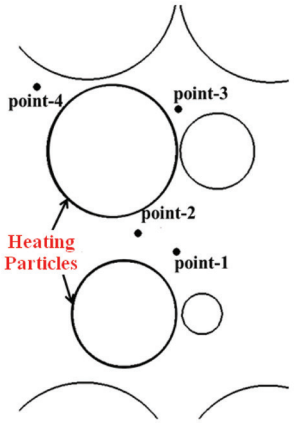

FIGURE 5. Distribution diagram of feature pints

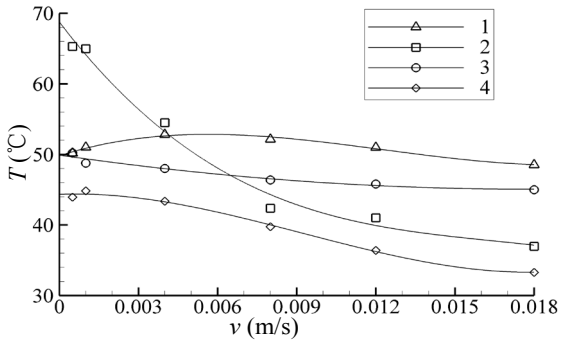

FIGURE 6. Wind speed-varying change curve of feature point temperature

Figure 6 shows the change curve of the corresponding feature point temperature which varies with the air supply velocity. With the increase of wind speed, the temperature of point 2 and 4 shows a significant monotonically decreasing trend. The temperature of point 1 is increased and then decreased slowly when the wind speed falls within 0.002-0.008 m/s. Although the temperature of point 3 is declined, the change is not large, but more stable. Figure 7 shows the enlarged partial view of velocity vector in the areas where the feature points are located (where the arrow color represents the speed and the arrow direction represents the velocity direction). Comparing the velocity vector and the temperature change, we can see that at point 2 and 4, the wind speed increases with the unchanged velocity direction which is consistent with the main direction. According to Noraini et al. (2016), such air flow can easily take away the energy emitted around the particles, therefore the temperature goes down significantly. However, at the point of 1, there is a difference in pore space due to the arrangement of the particles, resulting in occurrence of a significant cross flow and reflow in case of the larger

flow rate. This flow makes it difficult to take away the heat energy in this area and the gradually gathering heat energy leads to an escalating trend of the temperature, instead. Similarly, although the mainstream wind speed changes greatly, the flow rate of point 3 does not change greatly and the reflow occurs, because point 3 is located in the rear of the heating particles. Thus, compared with point 2 and 4, point 3 witnesses a slow temperature change and is little affected by the mainstream wind speed.

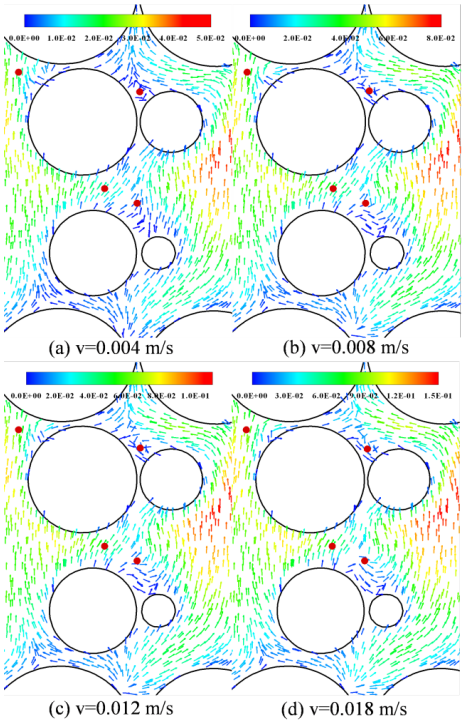

FIGURE 7. Enlarged Partial Views of velocity vector (see figure 5 for point marker)

By simulating and analyzing self-heating of some coal particles, it is found that in case of the pore scale, the flow heat transfer inside the clearance space of the spherical particles is closely linked and the velocity field greatly influences the temperature field. The flow field simulated with stacking spherical particles has complex characteristics. As for the flow field of stacking non-spherical particles, the heat energy is more difficultly dissipated. Although the airflow rate is large, the complex flow field distribution leads to existence of the high temperature region, further accelerating the heat release due to oxidation of the coal particles, gradually forming the local hot spot and finally leading to the occurrence of coal spontaneous combustion.

Conclusion and Recommendations

In this paper, the computational fluid dynamics software is used to establish the solution models for velocity field and temperature field inside the pore space of a finite number of stacking coal particles. In order to facilitate the calculation, this paper assumes that the coal particles are the spheres which stack according to certain rules. The surface temperature of the spherical coal particles is used to describe the self-heating and warming and study the change the temperature field at different wind speeds. Compared with the porous medium analysis method, the method herein discusses the self-heating of coal from a more microscopic point of view and obtains a more direct and accurate information related to temperature field and flow field. The conclusions are as follows:

Inside pore space of the stacking spherical coal particles, the temperature field changes complexly. As for some areas around the heating particles, the temperature does not monotonically decrease with the increasing wind speed, but rises and changes slowly.

The flow field varies very largely from the arrangement of particles. The lateral flow and reflow occur in local areas. This is not helpful for air flow to dissipate the heat energy emitted by the coal particles, which causes accumulation of the local heat.

This paper assumes that the oxygen is sufficient for calculation. In the next step, the surface oxidation reaction process of spherical coal particles will be considered in details. In addition, self-heating of coal is combined with the actual oxygen concentration and a more comprehensive energy source is added to explore the change law of the flow field and the temperature field inside the pore space.

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REFERENCES

Achenbach, E. 1995. Heat and flow characteristics of packed beds. *Experimental Thermal and Fluid Science* 10: 17-27.

Ahamed, A.J. & Loganathan, K., 2017. Water quality concern in the Amaravathi River Basin of Karur district: A view at heavy metal concentration and their interrelationships using geostatistical and multivariate analysis. *Geology, Ecology, and Landscapes* 1(1): 19-36.

Deng, J., Xu, J-C, & Wang, H-Q. 2002. Numerical simulation study on the spontaneous combustion process of the column coal sample. *Journal of Liaoning Technical University (Natural Science Edition)* 21: 129-132.

Dixon, A.G., Taskin, M.E., Nijemeisland, M. & Stitt, E.H. 2011. Systematic mesh development for 3D CFD simulation of fixed beds: Single sphere study. *Computers and Chemical Engineering* 35(7): 1171-1185.

Guardo, A., Coussirat, M., Larrayoz, M.A., Recasens, F. & Egusquiva, E. 2004. CFD flow and heat transfer in nonregular packings for fixed bed equipment design. *Industrial & Engineering Chemistry Research* 43(22): 7049-7056.

Jiang, P.X. & Lu, X.C. 2006. Numerical simulation of fluid flow and convection heat transfer in sintered porous plate channels. *International Journal of Heat and Mass Transfer* 49(9-10): 1685-1695.

Jolls, K.R. & Hanratty, T.J. 1966. Transition to turbulence for flow through a dumped bed of spheres. *Chemical Engineering Science* 21: 1185-90.

Krishnaswamy, S., Bhat, S. & Gunn, R.D. 1996. Low-temperature oxidation of coal. *Fuel* 75: 333-362.

Noraini, T., Ruzi, A.R., Ismail, B.S., Ummu Hani, B., Sahimi, S. & Azeyanty, J.A. 2016. Petiole vascular bundles and its taxonomic value in the tribe Dipterocarpeae (Dipterocarpaceae) *Sains Malaysiana* 45(2): 247-253.

Patankar, S.V. 1988. *Numerical Heat Transfer and Fluid Flow* (New York: Taylor & Francis. pp. 13-16.

Sardar, M.S., Zafar, S. & Farahani, M.R. 2017. Computing sanskruti index of the polycyclic aromatic hydrocarbons. *Geology, Ecology, and Landscapes* 1(1): 37-40.

Tobiś, J. & Ziółkowski, D. 1988. Modelling of heat transfer at the wall of a packed-bed apparatus. *Chemical Engineering Science* 43: 3031-3036.

Wakao, N. & Funazkri, T. 1978. Effect of fluid dispersion coefficients on particle-to-fluid mass transfer coefficients in packed beds: Correlation of Sherwood numbers. *Chemical Engineering Science* 33: 1375-1384.

Wu, C.Y., Ferng, Y.M., Chieng, C.C. & Liu, C.C. 2010. Investigating the advantages and disadvantages of realistic approach and porous approach for closely packed pebbles in CFD simulation. *Nuclear Engineering and Design* 240: 1151-1159.

Xu, J. & Wang, H. 2002. The neural network prediction method for the limit parameters of coal self-ignition. *Journal of China Coal Society* 27: 366-370.

Yuan, L. & Smith, A.C. 2009. CFD modeling of spontaneous heating in a large-scale coal chamber. *Journal of Loss Prevention in the Process Industries* 22: 426-433.

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