# An approach to the modelling of spontaneous combustion in the goaf

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## Synopsis

**The phenomenon of spontaneous combustion is one of the major hazards encountered in underground coal mines both from the safety aspects and on economic grounds. Every occurrence, however small, if not tackled effectively in the early stages can develop into open fire, or explosion of gas or coal dust.**

**In terms of economy, even dealing with small incidents may be costly in terms of labour and materials, and in case of a sealing off of a district being necessitated, the loss of face equipment and sterilization of reserves is potentially great. Therefore, expense and effort in prevention and detection of such heating, together with a high state of readiness for dealing with likely event, is completely justified and may be considered as a sound investment. In order to achieve this investment, it may be worth to pinpoint the centre of the fire occurring due to autogenously heating which is supposed to be great assistance to inert it at a least cost and time. Therefore, it is the aim of this work to model the spontaneous combustion in the goaf.**

## Introduction

Coal undergoes self-oxidation at ambient temperature producing heat. If the heat in concern is not dissipated, the coal temperature will increase resulting in acceleration at the rate of oxidation. This oxidation process that will go on until the mass of coal will ignite is commonly known as spontaneous combustion.

Scientists and miners have been and still giving an utmost importance to define the nature of spontaneous heating as it may cause irreversible problems if not prevented or controlled on time. As the result of spontaneous combustion, we may suffer from:

- ➤ hazardous gases causing severe fatalities
- ➤ loss of equipment (worth more than £ 3.0 million (Singh *et al*., 1984),
- ➤ loss of an outstanding amount of coal reserves.

Therefore, it is of high importance to determine the centre of a fire in the goaf of a longwall face using a few measurements so that the fire extinguishing process can take place directly in the centre of heating with a possible consequence of less time, money and material consumption.

In making a general assumption of that the centre of spontaneous combustion is a source of carbon monoxide as well as heat, there are, therefore, two models that have to be considered. In a first simplified theoretical model, the mass flow of carbon monoxide is used for the determination of the centre of the fire. This model is called as gas model disregarding the difference in temperature. The second theoretical model considers the mass and the heat flow and called as heat model.

## Theory of the gas model

The mass flow in the goaf is purely based on three mechanisms namely convection, diffusion and dispersion. The difference taking place in pressure is the main parameter that forms the convection. The velocity is also influenced by the porosity of the goaf (comparable to the Darcy Velocity (Wactawik *et al*., 1997) although the density is not constant as in groundwater models).

Beside the mass transportation by the convection, the diffusion and the dispersion have to be taken into consideration. These mechanisms are forced by the difference in the concentration of gases and based on molecular power. By using the Law of Fick, these two transport mechanisms can be described. However, all three transport mechanisms can be given by the utilization of the Law of Continuity (Gerthsen, 1982; Huette, 1989; Sahimi, 1995):

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$$\overset{\text{(convection)}}{\frac{\partial(n.\rho)}{\partial t} = -\frac{\partial(n.\rho.V_x)}{\partial x} - \frac{\partial(n.\rho.V_y)}{\partial y} - \frac{\partial(n.\rho.V_z)}{\partial z}} +$$

$$\text{(dispersion and diffusion)}$$

$$\frac{\partial}{\partial x}\left[n\left\{(D_{xxy} + D_{mol})\frac{\partial\rho}{\partial x} + D_{xy}\frac{\partial\rho}{\partial y} + D_{xz}\frac{\partial\rho}{\partial z}\right\}\right] + \quad [1]$$

$$\frac{\partial}{\partial y}\left[n\left\{D_{yx}\frac{\partial\rho}{\partial x} + (D_{yy} + D_{mol})\frac{\partial\rho}{\partial y} + D_{yz}\frac{\partial\rho}{\partial z}\right\}\right] +$$

$$\frac{\partial}{\partial z}\left[n\left\{D_{zx}\frac{\partial\rho}{\partial x} + D_{zy}\frac{\partial\rho}{\partial y} + (D_{zz} + D_{mol})\frac{\partial\rho}{\partial x}\right\}\right] + g \text{ (source and consumption)}$$

Where:

$\rho$ : density (kg/m³)

$n$ : part of porosity ()

$(D_{xx} + D_{mol})$ : diffusion and dispersion coefficient (m²/s)

$V$ : velocity (m/s)

$t$ : time (s)

Additionally, the gas model should also take care of the carbon monoxide make, as it is universally accepted sign of spontaneous combustion. The carbon monoxide production has to be measured in the return airway and in the goaf. Therefore, the total volume flow rate of the carbon monoxide source has to be determined in a given period by integration of the total area of the goaf.

The dependence between porosity and pressure difference should also be included in the gas model. Due to this reason, a consideration of the parasitic flow in the goaf can be dropped. The inclination of the goaf causing a difference in levels is determined by the difference in pressure.

Determination of an unknown parameter in a system of equations may only be possible when the number of parameters is equal to the number of solutions in the system. For solving the Law of Continuity, the change in density has to be known. In the gas model, the density is directly linear depending on the pressure.

A solution is possible with the help of the law of Movement (Equations [2] and [3] (Gerthsen, 1982)). The dynamic viscosity in these equations of isotherm model could be set constant. The system of equations is soluble utilizing the finite element method. As a result, a function of concentration distribution ($c = c(x,y,t)$) can be obtained. This function merely depends on time and location which means that the highest carbon monoxide concentration can not only often be expected near the centre of the fire, but also behind the goaf due to the transport mechanism. At the point where the gradient of the function is equal to zero, it gives the centre of fire location.

$$\rho\left[\frac{\partial V_x}{\partial t} + V_x\frac{\partial V_x}{\partial x} + V_y\frac{\partial V_x}{\partial y}\right] = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial x}$$

$$\left\{\eta\left[2\frac{\partial V_x}{\partial x} - \frac{2}{3}\left(\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y}\right)\right]\right\} + \frac{\partial}{\partial y}\left\{\eta\left[\frac{\partial V_x}{\partial y} + \frac{\partial V_y}{\partial y}\right]\right\} \quad [2]$$

$$\rho\left[\frac{\partial V_y}{\partial t} + V_x\frac{\partial V_y}{\partial x} + V_y\frac{\partial V_y}{\partial y}\right] = -\frac{\partial P}{\partial y} + \frac{\partial}{\partial x}$$

$$\left\{\eta\left[\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial x}\right]\right\} + \frac{\partial}{\partial y}\left\{\eta\left[2\frac{\partial V_y}{\partial y} - \frac{2}{3}\left(\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y}\right)\right]\right\} \quad [3]$$

Where:

$P$ : pressure (Pa)

$\eta$ : dynamic viscosity (kg/ms).

### Theory of the heat model

This model considers the mass and the heat transport. In this case, convection does not only depend on the pressure difference, but also on the temperature difference. Transportation by diffusion and dispersion is influenced by the increase of energy taking place inside the goaf. As the heat model is not isotherm, the way of change in airflow conditions is unknown according to the ideal gas equation. With an approximate knowledge of the physical parameters, the type of change in airflow conditions can only be assumed. As a difference from the gas model, the dynamic viscosity in the equation of movement depends on temperature ( $\eta = \eta\ (T)$).

In order to take the change in temperature into consideration, additionally the Equation of Energy has to be employed. In this equation, the source of heat (centre of fire) and energy consumption (heat transfer between gas and rock) is considered. To find out the capacity of the heat source and the heat transfer, the Fourier and the Biot parameters have to be known. To calculate the capacity, a measurement of temperature in the goaf and near the roadway is necessary. Integration of these three parameters over the square of the goaf by using the Fourier and Newton's Law of cooling leads to the determination of the capacity of the source and the consumption (Equation [4] (Gerthsen, 1982)).

$$\rho C_p\left[\frac{\partial T}{\partial t} + V_x\frac{\partial T}{\partial x} + V_y\frac{\partial T}{\partial y}\right] = \frac{\partial P}{\partial t} +$$

$$V_x\frac{\partial P}{\partial x} + V_y\frac{\partial P}{\partial y} + \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) + \quad [4]$$

$$\eta\left\{\begin{matrix} 2\left[\left(\frac{\partial V_x}{\partial x}\right)^2 + \left(\frac{\partial V_y}{\partial y}\right)^2\right] - \frac{2}{3} \\ \left(\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y}\right)^2 + \left(\frac{\partial V_x}{\partial y} + \frac{\partial V_y}{\partial x}\right)^2 \end{matrix}\right\} + g \text{ (source and consumption)}$$

Where:

$C_p$ : specific heat capacity (kJ/kg.K)

$T$ : temperature (K)

$\lambda$ : heat capacity (kW/m.K).

To localize the centre of the fire, two possibilities exist. The first solution is made possible by utilizing the gradient of function of the carbon monoxide distribution, similar to the gas model.

In the second model, a field of temperature is determined. The centre of fire is then found out when the gradient of this function is equal to zero ($T = T(x,y,t)$).

If the centre of fire determined by these two possibilities differs from each other, the gas flow conditions have to be varied until the centres of fire are the same. Therefore, the heat model is an enlargement of the gas model. It considers the change in density as it may vary due to the change in temperature.

### Results

In the formulation of concealed fires in the goaf for mathematical model, many difficulties such as the definition of physicochemical parameters of heterogeneous combustible material together with the filtration properties of the medium may be encountered. The characterizing remarks of heat and gas transport related with the process of coal oxidation vary in a wide spectrum in the literature. The mathematical model of heat and gas transport here given is purely based on some assumptions made for simplification reasons.

The application of the combined gas and heat model for the localization of the centre of spontaneous combustion has safety and economic benefits. With this achievement, the fire can be extinguished more quickly and successfully by injecting e.g. nitrogen directly into the centre of spontaneous combustion resulting in the minimization of material and labour cost and decreasing the risk of firedamp and coal dust explosions.

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# New Head of the Department for Metallurgical Engineering at Tuks*

Professor Chris Pistorius has been appointed the new Head of the Department of Materials Science and Metallurgical Engineering at the University of Pretoria. He succeeds Prof. Roelf Sandenbergh who has been appointed Dean of the Faculty of Engineering, Built Environment and Information Technology at UP.

Prof. Pistorius obtained his B.Eng. and M.Eng. degrees in 1987 and 1988 respectively, from the University of Pretoria and proceeded to complete his Ph.D. in 1991 at the University of Cambridge. He joined the department in October 1991 as associate professor and has been professor since January 1997.

Currently, Professor Pistorius is supervising or co-supervising the activities of seven part-time and four full-time postgraduate students. Twenty graduate students have thus far successfully completed their studies under his supervision or co-supervision.

Prof. Pistorius is registered as a professional engineer with ECSA, and active as consultant through the firm RE@UP (owned by UP). He is rated as a 'B'-grade (internationally recognized) researcher by the National Research Foundation (NRF) of South Africa. His current research interests in pyrometallurgy include chlorination of titania slags, mould flux behaviour, fundamentals of titania slags, reduction kinetics, and process modelling as the basis of control, and in corrosion protection by paint, and electrochemistry.

Prof. Pistorius is a member of various professional societies such as the South African Institute of Mining and Metallurgy, Academy of Science of South Africa, and the Corrosion Institute of Southern Africa (of which he is the vice-president). He is the author or co-author of 34 papers in refereed journals, and presenter at numerous conferences.

The Department of Materials Science and Metallurgical Engineering is the only one of its kind in South Africa, offering integrated undergraduate and graduate programmes which span the full spectrum of metallurgy, including minerals processing, hydrometallurgy, pyrometallurgy, physical metallurgy, and corrosion. Prof. Pistorius says the vision for the department is to gather and maintain a team of skilled acadamic staff, who can develop our graduates, and can lead industrially relevant research projects that span this metallurgical spectrum. ◆

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# Joint approach in North America*

A partnership between AMIRA International and CAMIRO's Metallurgical Processing Division is set to improve the benefits and service to the North American members of both organizations.

As a result of the partnership, Bogdan Damjanovic will become AMIRA International's first North American based Research Coordinator, while retaining his position as Research Director at CAMIRO's Metallurgical Processing Division.

Based in Toronto, Bogdan's role is to develop and manage new research projects to meet the needs of North American members.

'A local Research Coordinator will give us a clearer picture of our North American members' research needs and help us to better direct research projects to give members significant 'bottom line' benefits,' said Dick Davies, CEO of AMIRA International.

'Bogdan also has a valuable network of contacts in the industry that will help us identify and engage the best researchers for these projects.'

The Canadian Mining Industry Research Organization (CAMIRO) promotes and manages collaborative research in three divisions, Exploration, Mining and Metallurgical Processing.

AMIRA International develops and manages collaborative research and development for members involved in exploration, mining and mineral processing in Australasia, Asia, Europe, Africa, South America and North America.

'The partnership will advance collaborative research throughout North America by pooling the networks and experience of both organizations,' said Mr Davies.

'Both AMIRA International and CAMIRO use collaboration in research projects to reap greater benefits for our members than they can achieve individually.

'At a time when major mining companies are merging and going global, this partnership enables us to better serve our members' international and local collaborative research needs.

'In simple terms, we will reap greater benefits for our members in North America through bringing collaboration into research management.'

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