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The evaluation of a risk degree for the process of a brown coal spontaneous ignition on dumps with using of modern numeric methods

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Abstract— **The article is a summary of information about evaluation of a risk degree for a brown coal spontaneous ignition which is realized on the base of a database analysis of information about the development of stative quantities and desorbated gases in the stored bodies of the brown coal. The data were gained from the long term complex measurements which were realized at chosen companies during the coal mining in the previous parts of the project. In the last part of the project, we examined results of temperature models from thermographs with results of gasses and coal samples from the mines. Then, the influence of atmospheric conditions (insolation, water downfall, changes of barometric pressure etc.), the influence of coal mass degradation, the influence of physical and chemical factors, and the influence of other defective factors on the process of the coal spontaneous ignition. The gasmetry was assess with gas in-situ samples and laboratory gas models of indicative gasses for the spontaneous ignition, which were taken from the method of the thermic oxidation with the aim of the correlation finding for an epicentre of temperature within the spontaneous ignition.**

Index Terms— **spontaneous ignition, brown coal, dumps, evaluation of predisposition to a spontaneous ignition.**

I. INTRODUCTION

The correction of a measuring model, the determination of climatic conditions influence, the determination of physical and chemical parameters degradation influence and another failure factor influences to spontaneous ignition processes were realised on the grounds of a long term operating coal dumps measurement analysis. The principles of the estimate of the temperature of a spontaneous ignition epicentre were realised on the grounds of desorbated gases operation sampling with application of verified spontaneous ignition indicative gases figures. The time description of the steam epicentre temperature field development is the result. The calculations are realised by analytical or numerical methods according to a optimal need with application of accessible programmes for partial differential equations, especially statistical methods.

The creation of the simplified steam epicentre model was realised with application of the combination of a temperature field statistical – mathematical description and physical – chemical analysis. The evaluation of a convective oxygen diffusion to the epicentre influence, atmospheric influence etc. is the target of this model.

The preparation of the steam reaction origin and development data is the main target of this research. These steam reaction can be described as the dynamic thermal source. The experimental physical – chemical parameters and new findings about the coal spontaneous ignition critical temperature are these data.

The new mathematical physical model of the dump temperature field was realised. The main factors are:

- mathematical - physical diagnostics for optimal temperature mapping of the dump (dumps, caving).
- evaluation of non-stationary partial differential equation of heat leading for the stock body with a Newton tangential condition on the surface of the dump and with heat sources presenting the development of the steam reaction.
- processing and interpretation of experimentally discovered physical and chemical quantities in theoretical calculations and models.
- proposals of some experiments and measurements „in situ“ according to the requirements of the theory.
- experimental findings in the fields of dynamics of the coal spontaneous ignition (incubation) and the critical temperature of the coal spontaneous ignition.

II. COAL SPONTANEOUS IGNITION MODEL IN THE DUMP (3D CFD MODEL)

The model has two domains:
- Heap - coal
- Wind – airflow of the heap by the wind

COAL DOMAIN

Coil heap evinces shape of cone: diameter 14,00 m
height 5,87 m
inclination of wall 40 °

Parameters of coal:

Moisture	wt [%]	1.7
Ash	wt [%]	3.0
Volantility	wt [%]	33,5
Solid carbon	wt [%]	63,5
Permeability	κ $[m^2]$	$8{,}23.10^{-10}$
Porosity	ε [%]	10
Grain	d [mm]	10÷20

Predisposition for self-ignition category I – high reactivity (q^{30}>7,5 $J.g^{-1}$)

Heat source:

Arrhenius equation: $r_{ox} = A.C_{O2}.e^{-E/RT}$

r_{ox} oxidation speed 1,144 $[s^{-1}]$

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A pre exponential factor 13500 [s^{-1}]
C_{O2} oxygen concentration - [1] mol share in gas mixture
E activation energy 50,5 [$kJ.mol^{-1}$]
R gas constant 8,3145 [$J.(mol.K)^{-1}$]`
T temperature 373 [K]

Chemical reaction:

Temperature $T<T_{th}$ coal + $O_2 \rightarrow 0{,}1CO_2 + 0{,}4H_2O$ + 1,4(oxy-coal)
Temperature $T>T_{th}$ coal + $O_2 \rightarrow 0{,}2CO_2 + 0{,}01CO + 0{,}8H_2O$ + 0,7(oxy-coal)
T_{th} is critical temperature (the start of oxygen process acceleration and start of temperature increasing).

Components of model:

- Dense net with component height < 0,1m to the depth 3 m.
- Maximum height of component inside the heap (maximum 3 m).

WIND DOMAIN

Main parameters: Wind direction
Wind velocity
Wind temperature
Time course – meteorological station record (is available).
Wind in height z: $v_z = v_{10}.(z/10)^{0,22}$ $v_{10} = 4\ m.s^{-1}$

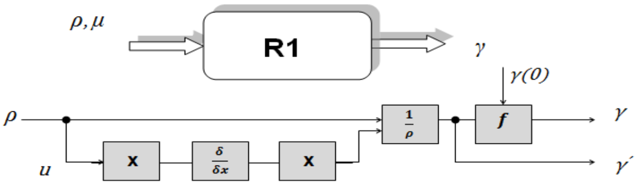
Model:
Coal heap situated in homogenous atmosphere.
Airflow of heap – turbulent.
Inside of heap – laminar diffusion with effect of buoyancy.
Model boundary – ca 10x dimension of heap.

DYNAMICAL RELATIONSHIP

Continuation equation – R1

$$\frac{\delta}{\delta t}\rho.\gamma+\frac{\delta}{\delta x_j}(\rho.u_j)=0$$

ρ ... density of mixture [$kg.m^{-3}$]; ρ=1300
u ... wind velocity vector component [$m.s^{-1}$]
γ ... porosity [$kg.m^{-3}$]; 0,15
t ... time [s]
x ... coordinates of location [m]
j ... number of component



Moment equation – R2

$$\frac{\delta(\rho.y.\mu_i)}{\delta t}+\frac{\delta(\rho.u_j.u_i)}{\delta x_j}=-\frac{\delta p}{\delta x_i}+\frac{\delta}{\delta x_j}\left(\mu.\frac{\delta u_i}{\delta x_j}\right)+\rho.f_i-\frac{\mu}{\alpha}u_i$$

ρ ... density of mixture [$kg.m^{-3}$]; ρ=1300
u ... wind velocity vector component [$m.s^{-1}$]
γ ... porosity [$kg.m^{-3}$]; 0,15
μ ... molecular viscosity [Pa.s]
α ... permeability of porous zone [m^2]; cca $8{,}23.10^{-10}$ direct relationship between oxidation velocity and coal grain area;
p ... static pressure [Pa]; from flow calculation
f ... gravitation force; gravitation acceleration
t ... time [s]
x ... coordinates of location [m]
i,j ... number of component

Transport equation – R3

$$\frac{\delta(\rho.y.Y_i)}{\delta t}+\frac{\delta(\rho.u_j.Y_i)}{\delta x_j}=-\frac{\delta}{\delta x_i}J_{j,i}+R_i+S_i$$

ρ ... density of mixture [$kg.m^{-3}$]; ρ=1300
u ... wind velocity vector component [$m.s^{-1}$]
γ ... porosity [$kg.m^{-3}$]; 0,15
t ... time [s]
x ... coordinates of location [m]
i,j ... number of component
Y_i ... weight part of component i in mixture [-]
$J_{j,i}$ ... diffusion flow between components j and i [$kg.m\text{-}^{2}.s^{-1}$]
R_i ... measure of component i production by chemical reaction [$kg.m^{-3}.s^{-1}$]
S_i ... measure of component i production by adding from disperse phase [$kg.m^{-3}.s^{-1}$]
Components ... CO_2, CO, O_2, CH_4

$J_{j,i}$ ... diffusion flow between components j and i

$$J_{j,i}=\rho.D_{i,m}\frac{\delta Y_i}{\delta x_j}$$

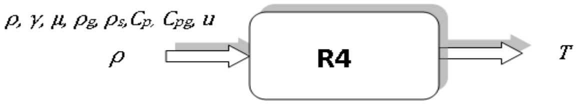
$D_{i,m}$ ... diffusion coefficient [$m\text{-}^{2}.s^{-1}$]; determined on the ground of experience

Energy equation – R4

$$\frac{\delta T}{\delta t}\left(\rho_g.y.c_{pg}+(1-\gamma)\rho_s.c_{ps}\right)+\frac{\delta}{\delta x_j}(\rho.u_j.c_{pg}.T)=\frac{\delta}{\delta x_j}\left(\lambda.\frac{\delta T}{\delta x_j}\right)+\frac{\delta}{\delta x_j}(J_{j,i}.c_p.T)+S_h$$

T ... temperature [K]
γ ... porosity [$kg.m^{-3}$]; 0,15
ρ ... density of mixture [$kg.m^{-3}$]; ρ=1300
u ... wind velocity vector component [$m.s^{-1}$]
ρ_s … density of solid component [$kg.m^{-3}$]
ρ_g … density of fluid component [$kg.m^{-3}$]
c_{ps}… specific heat of solid component [$J.kg^{-1}.K^{-1}$]; c_{ps}=1090
c_{pg}… specific heat of fluid component [$J.kg^{-1}.K^{-1}$]
c_p … specific heat of mixture [$J.kg^{-1}.K^{-1}$]

λ_s ... heat conductivity of solid component $[W.m^{-1}.K^{-1}]$; λ_s=0,3
λ_g ... heat conductivity of fluid component $[W.m^{-1}.K^{-1}]$
λ ... effective heat conductivity $[W.m^{-1}.K^{-1}]$
S_h … source member $[W.kg^{-1}.m^{-3}]$
t … time [s]
x ... coordinates of location [m]
i,j ... number of component

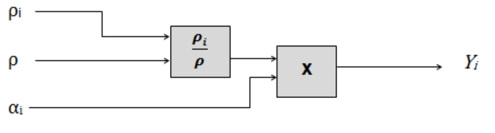


Diffusion flow equation – R5

$$J_i = \rho \cdot D_{i,ni} \cdot \frac{\sigma}{\sigma x} Y_I$$

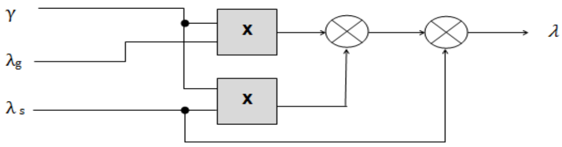
STATIC RELATIONSHIP

Weight part of component:



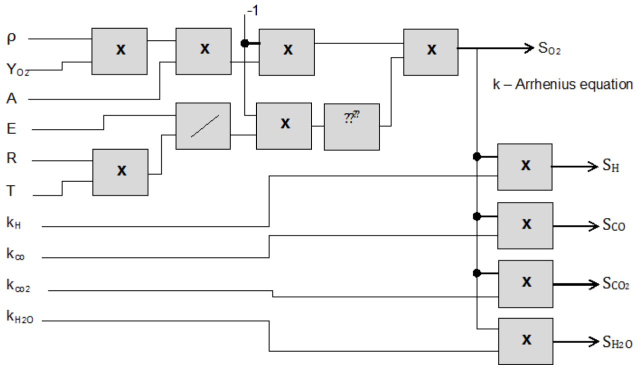
$$Y_i = \frac{\rho_i}{\rho} \cdot \alpha_i$$

Heat conductivity



$$\lambda = \gamma.\lambda_g + (1-\gamma).\lambda_s$$

Component origin measure:



Heat conductivity

$$\lambda = \gamma.\lambda_g + (1-\gamma).\lambda_s$$

Source member

Oxygen	$S_{O_2} = -\rho Y_{O_2} A.e^{\frac{-E}{RT}}$
Hydrogen	$S_h = const_h.S_{O_2}$
Oxide	$S_{CO} = const_{CO}.S_{O_2}$
Oxide	$S_{CO_2} = const_{CO_2}.S_{O_2}$
Water	$S_{H_2O} = const_{H_2O}.S_{O_2}$

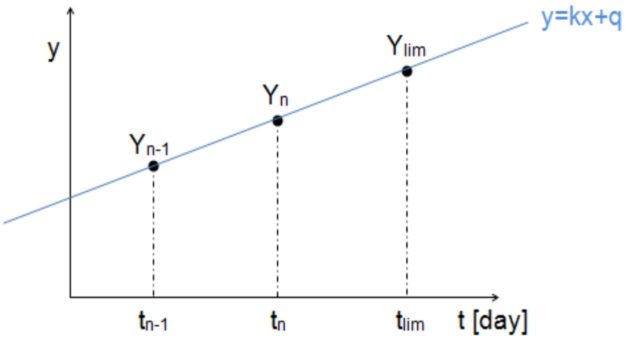
$const_h = Y_h/Y_{O2}$
$const_{CO} = Y_{CO}/Y_{O2}$
$const_{CO2} = Y_{CO2}/Y_{O2}$
$const_{H2O} = Y_{H2O}/Y_{O2}$
Y_{O2}… weight share of oxygen
Y_h … weight share of hydrogen
Y_{CO}… weight share of oxygen oxide carbon monoxid
Y_{CO2}… weight share of O_2 oxide carbon dioxid
Y_{H2O}… weight share of water

III. PREDICTION OF TIME INTERVAL TO COAL SPONTANEOUS IGNITION

The finding of the method of timely prediction of the origin of irreversible steam situation of brown coal in coal dump bodies, coal pillars and coal products dumping grounds is the main target of this project. This target is very important for providers (mining companies) and customers (power industry). The new methodology must be area-wide, quick and exact, primarily in the case of locating of irreversible steam situation possible places with the prospective of spontaneous ignition.

Predicted time interval to spontaneous ignition since last measuring:

Linear trend:



$$t_{pred} = t_{lim} - t_n \qquad t_{lim} = \frac{y_{lim} - q}{k}$$

$$k = \frac{y_n - y_{n-1}}{t_n - t_{n-1}}; \quad q = y_n - k \cdot t_n$$

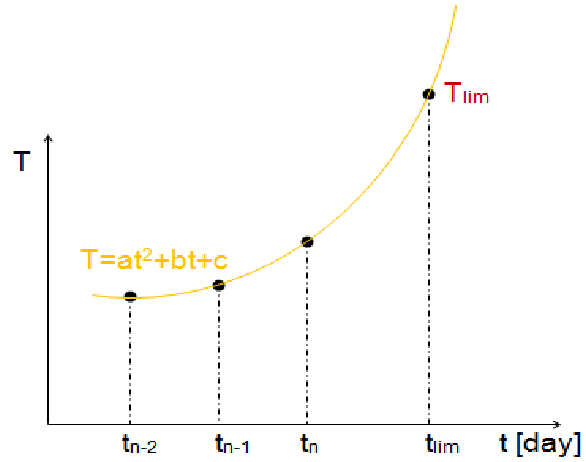
t …. time [day]
y … quantity T, CH_4, CO_2, CO, O_2

or with application of coefficients k, q to determine by linear regression from following formula:

$$q = \frac{1}{n}[(y_{n-1} + y_n) - k(t_{n-1} + t_n)]; \; n = 2$$

$$k = \frac{t_{n-1} \cdot y_{n-1} + t_n \cdot y_n}{2 \cdot (t_{n-1} + t_n) - (t_{n-1}^2 + t_n^2)}$$

Quadratic trend:



$$t_{pred} = t_{lim} - t_3$$

$$t_{lim} = \min\left(-\frac{b}{2a} \pm \frac{\sqrt{D}}{2a}\right)$$

$$D = b^2 - 4a(c - T_{lim})$$

$$T_{lim} \geq c - \frac{b^2}{4a}$$

We can determine constants a, b, c with application of quadratic regression for final 3 samplings, for times t_{n-2}, t_{n-1}, t_n and relevant quantities, it is T, CO_2, CO, O_2, CH_4. For instance temperatures T_{n-2}, T_{n-1}, T_n.

We can determine coefficients a, b, c from following formulas (if this regression is not available):

$$a = \frac{1}{n}\left(\sum_{i=1}^{n} y_i - b\sum_{1}^{n} x_i - c\sum_{1}^{n} x_i^2\right)$$

$$b = \frac{Z_3}{Z_1} - c \cdot \frac{Z_2}{Z_1}$$

$$c = \frac{Z_1.Z_6 - Z_3.Z_4}{Z_1.Z_5 - Z_2.Z_4}$$

$$z_1 = \sum_{1}^{n} x_i^2 - \frac{1}{n}\left(\sum_{1}^{n} x_i\right)^2$$

$$z_2 = \sum_{1}^{n} x_i^3 - \frac{1}{n}\sum_{1}^{n} x_i^2 \sum x_i$$

$$z_3 = \sum_{1}^{n} x_i y_i - \frac{1}{n}\sum_{1}^{n} x_i \sum y_i$$

$$Z_4 = Z_3$$

$$z_5 = \sum_{1}^{n} x_i^4 - \frac{1}{n}\left(\sum_{1}^{n} x_i^2\right)^2$$

$$z_6 = \sum_{1}^{n} y_i x_i^2 - \frac{1}{n}\sum_{1}^{n} y_i \sum_{1}^{n} x_i^2$$

For instance:
$X_1 = t_{n-2}$ $y_1 = T_{n-2}$ n= 3; i= 1,2,3,
$X_2 = t_{n-1}$ $y_2 = T_{n-1}$
$X_3 = t_n$ $y_3 = T_n$ y signified
(in sequence) T, CO_2, CO, O_2, CH_4.

IV. CONCLUSION

This methodology of "*the evaluation of the brown coal spontaneous ignition danger level in dump bodies*" was realised on the grounds of numerical formulation of criterion MHU by summing of individual indicators of point load. These indicators are described in this article. The indicators of group D (additional parameters) are evaluated by "minus" points. They represent the possibility how to reduce a negative evaluation of the concrete dump. The verification of this new methodology of coal dumps evaluation was realised in this (final) year of TA01020351 programme ALFA project solving. Specialists with great experience in this field of research comment this proposition. This article introduces the final version of evaluation after the opponent comments. It is a fundamental groundwork for a creation of a certified methodology **„The evaluation of risk degree for the process of a brown coal spontaneous ignition on dumps** (CRITERION MHU)" and **software „The application for a prediction of the coal spontaneous ignition** PREDISAM". The prediction of **brown coal spontaneous ignition** origin is the main result. These new knowledge allow to eliminate the danger of the mining fire in the open pit mine brown coal seam or in the coal dump bodies.

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