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Analytical research on dynamic temperature field of overburden in goaf fire-area under piecewise-linear third boundary condition

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ABSTRACT

During the process of underground coal spontaneous combustion (UCSC) in mine goaf, the coal and country rocks (roof overburden) in the vicinity of coal fire are subjected to high temperature which may be in excess of 1000 °C. Coal fires impose significant geomechanical changes to the overburden, which are called as combustion-metamorphic or burnt rocks. The highest temperature distribution in overburden decides the degree and range of burnt rocks. In order to study the temperature field evolution law and obtain the highest temperature distribution in overburden during the whole process of coal fire development (heating, continuous high-temperature and cooling stages) in mine goaf, we established a one-dimensional unsteady heat conduction mathematical model of convective heat transfer between overburden and boundary airflow whose temperature varies piecewise linearly, and the non-dimensional temperature analytical solution of one-tier super thick overburden is gained by using Laplace transform and inversion formula. The results show that: during heating and continuous high-temperature stages, temperature in overburden increases continually, and the maximum temperature have been located at the overburden boundary; during cooling stage, temperatures at each point increase first and then decrease, and the peak values of temperature curves decrease gradually and move to the interior of overburden; during the whole process of heat conduction, there is an envelope curve of temperature curve-cluster in overburden, and the highest temperature values at each point are determined by envelope curve. The envelope curve provides a basis for the range calculation under different threshold temperature, and by determining the judgement standards of burnt range and temperature influence range, their ranges are obtained by the envelope curve respectively. The influence of thermal conductivity coefficient k, specific heat capacity c, convective heat transfer coefficient h, Biot number Bi, and Fourier number Fo on envelope curves and heat-increment distribution were also analyzed.

1. Introduction

Underground coal fire, caused by underground coal spontaneous combustion (UCSC) are considered as one of the major disasters worldwide, which have greatly threatened the mining industry and caused serious economic and environmental problems [1–4]. In China, more than 60% of coal reserves are buried at depth over 700 m, and about 100–200 million tons of coal per year are affected, which accounts for 2–3% of the world CO_2 production [1,5]. Similar problems are faced in India, USA, Australia, Indonesia and South Africa [1,6].

During the process of UCSC in mine goaf, the high temperature airflow in combustion space, whose highest temperature can raise up to 1000–1300 °C [7,8], bakes the coal roof directly, and makes an unsteady temperature field existing within overburden. When the rock temperature raises up to a certain value (generally >600 °C), pyrometamorphism or combustion-metamorphism generally occurs on rocks, which can be called as burnt rocks [7,9]. Because of variation of the degree of thermal alteration produced by burning coal beds, the overburden may contain altered rocks ranging from slightly baked to entirely fused [7], that is to say, the highest temperature that rocks have experienced are different, and it will greatly influence the physical and mechanical properties of such combustion-metamorphic rocks. For example, because of the difference of highest temperature (whether the highest temperature up to the blocking temperature T_b and Curie temperature T_c or not), the thermomagnetic curve (κ–T curve) in the heating

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Nomenclature

k	thermal conductivity coefficient of overburden, W/m °C
c	specific heat capacity of overburden, J/kg °C
R	characteristic thickness of overburden, m
$t(z,\tau)$	overburden temperature, °C
t_0	initial temperature, °C
t_c	temperature of stage II, °C
$t_D(z_D,\tau_D)$	non-dimensional of $t(z,\tau)$, $(t(z,\tau)-t_c)/t_c$
h	convective heat transfer coefficient, W/m^2 °C
Bi	Biot number, hR/k
b_i	ratio of coal fire development stages with τ_c, $i = 1, 2, 3$, $b_1 + b_2 + b_3 = 1$
$g(\tau)$	boundary temperature of gas flow, °C
z	spatial height coordinate, m
z_D	non-dimensional of z, z/R
A, B, C, D, E, F	coefficients of analytical solution
q	heat flux density, W/m^2
q_D	non-dimensional of q, (qR/kt_c)
Q	heat increment per unit area, J/m^2
Q_D	non-dimensional of Q, $Q/\rho cRt_c$

Greek symbols

ρ	mass density of overburden, kg/m^3
τ	temporal coordinate, s
τ_c	total length of three stages of coal fire, s
τ_D	non-dimensional of τ, τ/τ_c
τ_j	cumulative time of coal fire, $\tau_c\sum_{i=1}^{j} b_i$, $j = 1, 2, 3$
τ_{Dj}	non-dimensional of τ_j, $\sum_{i=1}^{j} b_i$, $j = 1, 2, 3$
β	non-dimensional of t_0, $(t_c - t_0)/t_c$
Fo	Fourier number, $\tau_c k/\rho cR^2$

and cooling processes and the final magnetization are greatly different [10,11], which can be used to detect the degree and range of UCSC as a magnetic detection method [11,12]. In addition, the evolution laws of thermophysical and mechanical parameters of rocks, such as thermal conductivity coefficient [13,14], specific heat capacity [13,14], thermal expansion coefficient [13,15,16], elastic modulus [13,15–18], poisson ratio [13], compression strength [13,17,18] and tensile strength [13,19], are significantly correlated to the highest heating temperature. Therefore, studying the temperature field distribution and obtaining the highest temperature of overburden in the process of UCSC are very necessary to calculate the overburden burnt range and further to study the detection of coal fire by thermometry and magnetic method.

The heat transfer within overburden or coal seam during UCSC is a complex thermo-hydro-mechanical coupled process, which is as same as the process of underground coal gasification (UCG), and many scholars have done lots of studies by laboratory tests [20], field tests [21], theoretical and numerical analysis [2,20,22,23] and numerical simulation [2,22–24]. Although thermal [22,23], thermal–mechanical [25], hydro-thermal [2,8,20,26], and hydro-thermal–chemical [24,27] processes have been simulated, an interrelation between the underground coal-fire development process and the highest temperature distribution has not been addressed in previous studies.

In mine goaf fire-area of UCSC, heat transfer between high temperature airflow and overburden boundary is mainly processed as convective heat transfer. During the whole process, airflow temperature is not constant or singly changed but changed in stages as increasing, constant and decreasing. There are few studies considering the boundary airflow temperature varying with the coal fire development process (heating, continuous high-temperature and cooling stages), especially on the aspect of analytical solution. The difficulty level for getting analytical solution depends on the type and quantity of boundary conditions, in order to obtain the temperature analytical solutions as much as possible, most scholars simplified the initial and boundary conditions by setting the initial temperature as a constant value and assuming the boundary temperature or heat flux density is a constant value [28–30] or a single change with time (a single linear change [23], or a single non-linear change [31], or a single periodic variation [32]). So, their studies are not enough to solve the temperature distribution problems within overburden in the whole development process of coal fire, and most publications seldom involved in the study on the highest temperature distribution within overburden in the whole process which decides the ranges of burnt rocks, heat transfer and coal-wall-coking cycle [23].

The aims of this paper are twofold. Firstly, we will build heat transfer equations during the whole processes of coal fire development, and obtain the analytical solution. For the heat conduction problem of variable boundary conditions, the difficulty to get the analytical solution is: when the first stage is ended, an instantaneous temperature distribution will be formed inevitably, so the initial temperature in the second stage is not a homogeneous constant but a function of position coordinate. Only in exceptional circumstances, the analytical solution of the temperature equation in this process can be obtained [33]. To make it simplified, we assume that fire-area airflow temperature changes linearly in above-mentioned three stages, so the problem is transformed into convective heat transfer between overburden and airflow whose temperature is changed piecewise linearly. In this paper, the overburden heat conduction model in goaf fire-area of UCSC is established under the strict initial conditions and boundary conditions, by using the Laplace transform and inversion formula and by building the basic equations of heat conduction in different stages, the analytical solutions of temperature field for one-tier super thick overburden which meet the third kind of boundary conditions are obtained. Secondly, the highest temperature distribution within overburden during the whole process is obtained, which is used to calculate the burnt range and heat transfer range of overburden. Conclusions drawn from the theoretical analysis results will help to interpret temperature field evolution with more care.

2. Temperature field model of overburden in mine goaf fire-area

2.1. Building temperature field model

2.1.1. Model hypothesis

The overburden strata in mine goaf can be considered as a superposition of multi-layer infinitely great rock plates with different thickness. Due to large-scale coal mining, the overburden is exposed in mine goaf, and its size is large in strike and inclination. Within a certain limited time, temperature disturbance of boundary surface only can spread to a limited depth, beyond this depth, objects remain in their original state (the initial state). In this limited time, finite thickness bodies can be taken as semi-infinite bodies. Temperature change in z-axis which is perpendicular to the rock plates is considered only, temperature in x-axis and y-axis is assumed unchanged ($\partial t/\partial x = \partial t/\partial y = 0$), thus the matter is one-dimensional.

The forced convection heat transfer occurs between down-surface of overburden and high temperature airflow. In