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Temperature field distribution and parametric study in underground coal gasification stope

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ABSTRACT

In order to study the distribution characteristics and related parameters of the temperature field in underground coal gasification stope, Laplace transform and inverse Laplace transform were used to determine the analytical solution to temperature propagation in the stope under type one boundary conditions. Additionally, Mathematic software was used to conduct numerical simulation. Results indicate that in an unsteady stage, the temperature field gradually propagated in the coal seam, and that the propagation rate became steady after a gradual increase. The time required for the temperature field in the coal seam undergoing gasification to transform from the unsteady to the steady state was inversely proportional to the advance rate of the flame working face. During the stages of temperature increase and decrease, the temperature field in the roof, floor, and surrounding coal seam gradually moved towards the interior. During the temperature increase stage, the peak of the temperature field occurred on the surface of the surrounding rock and gradually increased; it also moved inward from the surface and gradually decreased during the temperature decrease stage. The temperature decrease stage had greater influence on the temperature field in the roof, floor, and surrounding seam than the temperature increase stage. The influence of the temperature increase stage was related to the advance rate of the flame working face; this influence is negligible when the advance rate of the flame working face exceeded a threshold value. Finally, based on the features of the envelope curves of temperature curve families, the ranges of the surrounding coal seam with no load-bearing capacity and coking cycle were obtained, as were after determination of their respective criteria and temperature threshold values.

1. Introduction

Underground coal gasification (UCG) is the process by which the gasification agent (air, steam and/or oxygen) is injected into an underground gasifier through pipes and then burnt in a controlled manner in combination with underground coal to generate combustible gas. It is a new coal mining technology which enables green, safe, and efficient mining, and it changes the uses of coal gas to help achieve clean and comprehensive use of gas resources [1–4]. The existence of a temperature field in the UCG stope is not only the key to a normal gasification process, but it may also cause underground heat disasters. Previous research has shown that the temperature of the flame working face can normally reach 800–1200(°C) during gasification [5–7]. The thermal energy in the working face can be transferred to surrounding rock through thermal conduction, convection, and radiation, resulting in changes in the temperature field within surrounding rock. The temperature field propagation (TFP) in coal seam undergoing gasification not only preheats the seam, but it also improves the quality of coal gas by facilitating the secondary reaction between

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the high-temperature seam in gas passage and the produced coal gas. This is conducive to a smooth gasification process. The TFP in roof, floor, and surrounding coal seam around the combustion cavity can increase heat loss and reduce the efficiency of gasification, and it may even reduce the quality of coal gas by lowering the gasifier's temperature. This has a negative impact on a gasification process. Moreover, the temperature changes of rock strata will alter their mechanical properties [8–11], which has adverse effects on the stability of surrounding rock and the safety of gasification. Therefore, a grasp of the distribution pattern of the temperature field in the UCG stope is not only of great significance to further research on the stability of surrounding rock, development of fractures, and gasifier's structural and size parameters, but can also provide an important guide to improvement of gasification technologies and development of combustion control techniques.

Researchers have used various methods, such as numerical simulations, laboratory testing, and field testing [12–26], to study patterns of heat transfer and fracture evolution in surrounding rock and the growth pattern of combustion cavity in the high-temperature UCG stope. The authors of references [23] and [24] conducted an experimental investigation of temperature field distribution characteristics during the gasification of lignite and anthracite with pure oxygen by evenly distributing thermocouples in the coal seam in which the gasifier was located, as well as in the overlying strata. Results indicated that at distances of 0.2 m from the gasification gallery, the temperatures recorded during the gasification of anthracite were greater than those recorded during the gasification of lignite. This was primarily due to the high water content of lignite and its low calorific value. However, these studies have had limitations in their research content and results. Many studies regarding temperature field have been aimed at assisting with research on other topics, resulting in limitations in their research content. Moreover, studies have focused only on the pattern of TFP in roof and floor, but have disregarded the TFP in coal seam undergoing gasification. These studies have failed to notice that a rise in temperature of roof or floor is normally associated with variation in coal seam's temperature in a real project. Evidently, there is lack of systematic research into the UCG stope. Furthermore, results of these studies are mostly qualitative rather than quantitative. Due to the limited research approaches, these studies have only qualitatively revealed the patterns of TFP, but have failed to discover quantitative changes in these patterns caused by quantitative variation in a certain initial condition. Mathematical analytical solutions to the temperature field are necessary for the quantitative study of the pattern of TFP in a gasification stope. However, few studies on this topic have been conducted due to the complexity of the UCG process and resource and geological conditions. Xin Lin [27,28] has used a Laplace transform to establish a basic heat conduction equation and equations for temperature field distribution in multi-layer overlying strata under the first and fourth boundary conditions. However, his research only looked at the distribution of temperature field in the roof, floor, and surrounding coal seam, ignoring that in coal seam undergoing gasification. Moreover, the influence of strata temperature increase was not taken into consideration when solving the heat conduction equation.

Based on the results of previous studies, the present study simplified the temperature field propagation of underground coal gasification, provided mathematical descriptions of the temperature field propagation in the coal seam undergoing gasification as well as in the roof, floor and surrounding coal seam under the first boundary conditions, and used the Laplace transform and inverse Laplace transform to obtain the analytical solutions to the temperature field in the roof, floor, and surrounding coal seam in the temperature increase stage, temperature decrease stage, and the overall process, and determined the analytical solution to the temperature field in the coal seam undergoing gasification. Values were assigned to the relevant parameters presented in the equations to obtain the 2D and 3D distribution patterns of the temperature field in the stope. Additionally, the time required to complete the transition from the unsteady to the steady state was investigated, as well as the distribution of three zones in the coal seam undergoing gasification and the ranges of the surrounding coal seam undergoing gasification. The present study also investigated the ranges of the surrounding coal seam with no load-bearing capacity and the coking cycle, as well as ranges of the temperature field and its scopes of influence. The conclusions drawn in the present study can be used to directly determine the thermal damage range of surrounding rock, reasonable pillar widths and the scope of influence of the underground temperature field.

2. Simplification and mathematical description

2.1. Simplification

TFP in the surrounding rock of UCG stope can be divided by boundary conditions into two ways: (1) TFP in coal seam undergoing gasification; and (2) TFP in the roof, floor, and coal seam around the combustion activity, or “surrounding coal seam”. TFP in coal seam undergoing gasification is a moving boundary problem, as the position of the flame working face changes constantly, while TFP in the roof, floor, and surrounding coal seam is a stable boundary problem.

In view of lithological differences, the TFP in the roof and floor can be treated as a problem of heat conduction through a multilayer infinite flat plate, while the TFP in coal seam can be treated as a problem of heat conduction through a semi-infinite body. The temperature field distribution in UCG stope is overall a three-dimensional unsteady heat conduction problem, but finding the solution is highly complex. Some factors, such as the presence of voids, fractures, joints, and faults within the roof, floor, or coal seam, lithological variation within a stratum, and variations in the thermophysical parameters (specific heat capacity c, thermal conductivity λ, and density ρ) of the surrounding rock and coal caused by temperature change, can also add to the difficulty [29–32]. The following simplifications have been made in the present study: a. The rock strata in the roof and floor were treated as two single-layer, semi-infinite bodies; b. The three-dimensional problem was simplified into an one-dimensional problem by assuming that temperature variation only occurred in one direction: c. The roof, floor, and coal seam were assumed to be homogeneous, continuous media, and the influences of lithological variation and fractures in strata on TFP were not considered; d. The thermophysical parameters of surrounding rock were treated as fixed values-represented with the average parameter values for the corresponding temperature; e. It was assumed that a high-temperature working face was formed immediately after the combustion process was ignited and then advanced at a constant speed and temperature, which disregarded the stage after the ignition and before a stable flame working face was formed; f. During the UCG process, the flame working face was considered as an advancing vertical face perpendicular to the roof and floor; g. The combustion cavity left in the coal seam after gasification was assumed to be a rectangular space; and h. The influence of ash produced during gasification on the heat conduction through the floor was not taken into account. Fig. 1 shows the simplified heat conduction model for the temperature field during UCG.