优秀博士学位论文摘要

煤层中封存二氧化碳的双重孔隙力学效应研究

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摘　要:利用煤层进行 CO_2 地质封存成为了学术研究的热点之一。煤具有典型的双孔结构特征,在煤层中注入 CO_2 既可有效地封存温室气体,还可驱替和提高煤层气产量,有广阔的应用前景。但是在煤层中封存 CO_2 的过程中涉及到煤的变形、气体的吸附、渗流与扩散等一系列力学问题,极大地制约了这项技术的实施。根据多孔介质弹性力学理论,综合利用理论分析和数值模拟手段系统研究了 CO_2 煤层封存中的煤体变形、气体吸附、气体渗流和气体扩散等多物理场耦合系统,主要得到以下结论:

(1) 根据裂隙和孔隙系统之间相互作用,建立了适合各自特点的渗透率变化模型。根据多孔介质弹性理论的有效应力原理建立了包含气体流动和吸附作用影响的煤的变形方程。根据气体在煤中的流动和吸附储存的特点分别建立了裂隙和孔隙中的气体流动控制方程。控制方程中包含了固体变形、流体渗流、流体吸附等多物理场耦合作用。

(2) 考虑到煤中残余水分对气体吸附的影响,利用 Ettinger 模型,建立了包含湿度效应的裂隙和孔隙系统的渗透率变化模型,并将湿度效应引入双重孔隙介质多物理场耦合模型。

(3) 利用 COMSOL Multiphysics 结合双重孔隙介质模型,对 CO_2 煤层封存进行了模拟,并对相关影响因素进行了分析。煤层的裂隙发育程度直接决定了 CO_2 注入的速度。煤层中裂隙越多,裂隙的初始渗透率越大,受到注气影响时变化越大。当水平方向上地应力的值不相等时,气体渗透具有方向性。气体在沿着最大应力方向上的渗透速度较快。当煤层中含有残余水分时,气体注入速度则更快,但是煤层对 CO_2 的总封存量越小。

(4) 利用图像处理法和数值生成法研究了煤层中裂隙分布问题。图像处理法包括:数字图像处理技术和断层 X 射线扫描成像技术。前者通过处理平面图像获得初始裂隙的二维空间分布,后者通过一组 CT 扫描图片构造出岩样裂隙分布的三维模型。数值生成方法利用 Weibull 分布模型构建了岩样中裂隙的分布,讨论了 Weibull 均匀性指数对裂隙分布的影响。

(5) 将双重孔隙介质的多物理场耦合模型应用于 CO_2 – ECBM 中,建立了在二元气体竞争吸附过程中,裂隙的裂隙率和渗透率变化模型、孔隙中的孔隙率和渗透率变化模型。根据多孔介质弹性理论的有效应力原理和多元气体竞争吸附引起煤的变形关系,推导了煤层耦合变形方程。根据裂隙和孔隙中流体的质量守恒方程,动力扩散方程,Fick 定律分别建立了包含二元气体竞争吸附效应的裂隙和孔隙中气体对流扩散耦合方程。

(6) 以沁水盆地煤层气增产试验为工程背景,将建立的 CO_2 – ECBM 模型应用于现场模拟,分别对不注气抽采煤层气、不同注气压力下抽采煤层气等情况进行了模拟研究。模拟结果表明,在煤层中注入 CO_2 能有效地提高煤层气的采出率。

关键词:CO_2 封存; 双重孔隙介质; 多物理场耦合; 裂隙分布; CO_2 – ECBM

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Dual poroelastic response of coal to CO_2 sequestration

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Abstract: Geological sequestration of CO_2 in coal seams shows great potential to reduce greenhouse gas emissions and has been studied worldwide in recent years. The typical dual-porosity property and organic component of coal together with the liquid state and steady property of CO_2, as well as methane production make coal seams a promising target. However, the CO_2 sequestration in coal seams involved a serial of mechanical problems such as coal deformation, the adsorption, seepage and diffusion of gas, which restricted the implement of this technology. Studied the multi-physics system which coupled the coal deformation, gas adsorption, seepage and diffusion equations on the basis of poroelastic medium, theory analysis and numerical simulation, and the following conclusions are obtained.

(1) Based on the interaction of two systems, the porosity models for both matrix and fracture were developed. The coal deformation model was developed on the basis of effective stress in poroelastic medium, in which the gas flow effect was included. A set of interacted three-equation system including the multiphysics effect of the solid deformation, gas flow and adsorption was developed in which the flow of gas in coal and the adsorption capacity of coal were studied.

(2) Given the effect of the residual water on the gas adsorption, permeability models including the moisture effects for fracture and matrix system were developed on the basis of Ettiger model, to which the wettability was introduced.

(3) The coupled models were implemented in the COMSOL Multiphysics, in which the CO_2 sequestration process was simulated and the relative factors were analyzed. The injection rate of CO_2 was directly decided by the fracture development. The more fractures in the coal seams, the larger the initial permeability of the fracture, and the faster of the gas transportation in them. In the meanwhile, the more cleats, the larger contact area of gas and coal will be. When the ground stresses are not equal in the horizontal directions, the gas permeability is directional. Gas permeates fastest in the direction of the largest geo-stress. The injection rate of gas is faster when residual water exists in the coal seams. The larger the moisture content, the smaller of the CO_2 sequestration.

(4) The initial fracture distribution was studied by image processing and numerical generation. The image processing consists of digital image processing technique and X-ray computerized tomography technique. By using the former method, two dimensional space distributions of the initial fracture can be obtained. While by using the latter, a set of CT scanning pictures can generate the 3D fracture distribution model of the core sample. The fracture distribution in the core sample is constructed and the effect of different homogeneity indices on the fracture distribution is studied in the numerical generation method on the basis of the Weibull distribution model.

(5) The dual-porosity model was applied to the CO_2-ECBM, and the porosity and permeability models for both fracture and matrix systems were generated during the competitive adsorption of binary gas. The coupled coal deformation equation is derived on the basis of effective stress theory and the deformation relation caused by the competitive adsorption of binary gas. In addition, the coupled gas convection and diffusion equations are attributed to the mass conservation law, hydraulic diffusion equation as well as the Fick's law.

(6) The CO_2-ECBM model was implemented into a field case in Qinshui CBM field. The simulation was conducted under different situations of gas producing without CO_2 injection and gas producing by various injection pressures. The simulation results demonstrate that the gas production is enhanced by CO_2 injection effectively.

Key words: CO_2 sequestration; dual porosity medium; multiphysics coupling; fracture distribution; CO_2 – ECBM