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Environmental and Economic Evaluation of In-situ Pyrolysis of Tar-rich Coal

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Abstract

As a strategic coal-based oil and gas resource integrating the properties of coal, oil and gas, the in-situ pyrolysis technology of tar-rich Coal is an important path to realize the clean and efficient utilization of coal, alleviate the contradiction between oil and gas supply and demand, and help achieve the "double carbon" goals. Taking the in-situ pyrolysis technology of tar-rich Coal as the research object, this paper systematically expounds the technical principles and development status of in-situ pyrolysis of tar-rich Coal, comprehensively analyzes the environmental impacts during the in-situ pyrolysis process from four dimensions of atmosphere, water, soil and ecology, and constructs an economic evaluation system covering investment, cost, income and uncertainty. Combined with the existing pilot test data and research results, the degree of environmental impact and economic feasibility are quantified. Finally, optimization strategies that balance environmental friendliness and economic efficiency are proposed, providing theoretical support and practical reference for the industrial promotion of in-situ pyrolysis technology of tar-rich Coal.

Keywords

Tar-rich Coal, In-situ pyrolysis, Environmental impact, Economic evaluation, Clean utilization

1. Introduction

With the accelerated transformation of the global energy structure, China's demand for oil and gas resources continues to rise, and the guarantee of energy security is facing severe challenges. tar-rich Coal refers to a special type of coal with a tar yield of more than 7% under the conditions of the Gray-King assay. China is rich in its reserves, and it contains huge potential of oil and gas resources, serving as an important strategic reserve to replace conventional oil and gas resources. The traditional utilization method of tar-rich Coal is mainly direct combustion, which not only has low energy utilization efficiency, but also produces a large number of pollutants, increasing the pressure on the ecological environment. Although surface pyrolysis technology can extract oil and gas resources, it has drawbacks such as large investment scale, wide floor area, high difficulty in pollutant treatment and limited mining depth, making it difficult to realize large-scale promotion and application.

The in-situ pyrolysis technology of tar-rich Coal transfers the “surface pyrolysis plant” underground, establishes heat input and pyrolysis product output channels in deep coal seams by using petroleum engineering technologies, and realizes the pyrolysis conversion of tar-rich Coal in situ. It has significant advantages such as expanding the lower limit of mining depth, reducing surface investment and reducing environmental pollution. This technology can not only efficiently extract high value-added products such as tar and coal gas from tar-rich Coal, but also realize the low-carbon utilization of coal resources, which is of great strategic significance for safeguarding China’s energy security, promoting the transformation of energy structure and achieving the “double carbon” goals.

2. Main Process Types of In-situ Pyrolysis

According to different heating methods, the in-situ pyrolysis processes of tar-rich Coal are mainly divided into three types: heat carrier injection type, electric heating type and controlled oxidative spontaneous combustion type, with significant differences in technical characteristics and applicable scenarios among different processes.

Heat carrier injection pyrolysis is the most widely used process type at present. Its core is to inject high-temperature heat carriers (such as high-temperature flue gas, steam, nitrogen, etc.) into underground coal seams through surface boreholes, and transfer heat to the coal seams by thermal convection to achieve in-situ pyrolysis. The advantages of this process are high heating efficiency, uniform heat distribution, and the ability to rapidly raise the temperature of coal seams, making it suitable for medium-thick coal seams with good air permeability. The disadvantages are large consumption of heat carriers, the need for supporting construction of surface heating devices, high investment costs, and the risk of environmental pollution caused by heat carrier leakage. In the pilot test of in-situ pyrolysis of tar-rich Coal in Northern Shaanxi, nitrogen was used as the heat carrier for convection heating, and the coal seam permeability was increased by controlled shock wave technology, with an effective permeability enhancement radius of 40~60 meters.

Electric heating pyrolysis realizes in-situ pyrolysis by arranging electrodes in underground coal seams and heating the coal seams by using the thermal effect of electric current. The advantages of this process are precise temperature control, small heat loss, no risk of heat carrier leakage, and strong environmental friendliness. The disadvantages are high energy consumption and great difficulty in electrode arrangement, making it suitable for coal seams with poor air permeability and complex geological conditions. A closed double-shell downhole electric heating device has been used in field tests, which solves the problems of combustion reaction stability and repeated ignition reliability existing in downhole combustion heaters. However, this device faces performance challenges such as long service life (3~5 years), high heating temperature (600℃) and large operating power (>2kw/m).

Controlled oxidative spontaneous combustion pyrolysis is a new type of pyrolysis process proposed by Deng Jun and others. Its core is to use the oxidative spontaneous combustion of pyrolysis semi-coke as the heat source for in-situ pyrolysis, establish an efficient heat transfer network through artificial fracturing of coal seams, and improve the heat transfer efficiency and combustion efficiency by using heat-generating agents or catalysts. The advantages of this process are no need for external heat source, low energy consumption, low cost, and the ability to realize the recycling of heat. The disadvantages are that the combustion process is difficult to control and prone to safety risks such as fire, and it is still in the experimental research stage at present.

3. Environmental Impact Assessment of In-situ Pyrolysis of tar-rich Coal

3.1 Analysis of Environmental Impacts during the Construction Period

The construction period of in-situ pyrolysis of tar-rich Coal mainly includes borehole construction, roadway excavation, equipment installation and other operations. Its environmental impacts are mainly concentrated in four aspects: atmosphere, water, soil and ecology, with the impact degree ranging from mild to moderate and temporary characteristics.

In terms of atmospheric environment, the main pollutants during the construction period are construction dust and exhaust gas from construction machinery. A large amount of dust will be generated during borehole construction and roadway excavation. If effective dust prevention measures are not taken, the dust will spread with the wind and affect the surrounding air quality. The operation of construction machinery (such as drilling rigs, excavators, transport vehicles, etc.) will emit exhaust gas containing carbon monoxide, nitrogen oxides, particulates and other pollutants, causing pollution to the local atmospheric environment. In addition, flammable gases such as methane in underground coal seams may be released during roadway excavation. If methane leaks, it will not only affect air quality, but also may trigger safety risks.

In terms of water environment, the main pollutants during the construction period are construction wastewater and drilling mud. Construction wastewater mainly includes equipment cleaning wastewater and site flushing wastewater, containing pollutants such as suspended solids and petroleum hydrocarbons. Direct discharge will pollute the surrounding surface water and groundwater. Drilling mud contains a large amount of clay, chemical agents, etc. Improper disposal will penetrate into the soil and pollute groundwater aquifers. At the same time, the construction process may damage the structure of underground aquifers, leading to a drop in groundwater level and affecting the drinking water safety of surrounding residents. In the area where the pilot test project of in-situ pyrolysis of tar-rich Coal in Northern Shaanxi is located, the aquifer with water supply significance is the Quaternary Late Pleistocene Salawusu Formation pore phreatic aquifer, which is the source of domestic water for residents, so the prevention of groundwater pollution should be the focus during the construction process.

In terms of soil environment, the main impacts during the construction period are soil disturbance and soil pollution. Roadway excavation and equipment installation will disturb the surface soil, damage the soil structure and lead to a decline in soil fertility. The leakage of drilling mud and construction wastewater will cause the content of heavy metals, petroleum hydrocarbons and other pollutants in the soil to exceed the standard, affect soil quality, and then impact the growth of surrounding vegetation.

In terms of ecological environment, the main impacts during the construction period are vegetation damage and disturbance of biological habitats. Vegetation on the surface needs to be cleared and land resources occupied during the construction process, leading to a decline in local vegetation coverage. The noise generated by roadway excavation and equipment operation will disturb the surrounding wild animals, damage their habitats and affect the stability of the ecosystem. In addition, the construction process may cause soil erosion, especially in mountainous areas and other areas with complex terrain, where the risk of soil erosion is high.

3.2 Analysis of Environmental Impacts during the Operation Period

The operation period is the main stage of environmental impacts of in-situ pyrolysis of tar-rich Coal, with long duration and wide influence range, mainly involving four dimensions of atmosphere, water, soil and ecology, among which groundwater pollution and atmospheric pollutant emission are the main environmental risk points.

In terms of atmospheric environment, the main pollutants during the operation period are waste gas from pyrolysis product leakage and waste gas discharged from surface treatment stations. If the roadway has poor airtightness during the underground pyrolysis process, coal gas (mainly composed of methane, carbon monoxide, hydrogen, etc.) and volatile organic compounds (VOCs) produced by pyrolysis will leak into the atmosphere, which not only pollutes the air, but also may trigger explosion risks. The surface treatment station will discharge pollutants such as particulates, sulfur dioxide, nitrogen oxides and VOCs during the product separation and purification process, among which pollutants such as benzo(a)pyrene have strong carcinogenicity and cause great harm to human health and the ecological environment. Due to the involvement of benzo(a)pyrene in atmospheric pollutants and the distribution of residential buildings within 500 meters, a special atmospheric assessment was set up for the pilot test project of in-situ pyrolysis of tar-rich Coal in Northern Shaanxi.

In terms of water environment, the main pollutants during the operation period are pyrolysis wastewater and groundwater pollution. Pyrolysis wastewater is mainly produced in the product separation process of surface treatment stations, containing high-concentration pollutants such as phenols, cyanides and heavy metals, with the characteristics of high toxicity and poor degradability. Improper treatment will pollute surface water and groundwater. During the underground pyrolysis process, pyrolysis products (such as tar and phenols) may penetrate into groundwater aquifers through rock fractures, leading to the deterioration of groundwater quality and affecting the drinking water safety of surrounding residents. In addition, the entry of groundwater into the pyrolysis zone will vaporize and absorb a large amount of heat, thereby reducing the temperature of the pyrolysis zone and even terminating the pyrolysis reaction in severe cases. The water yield of each aquifer section in the assessment area is extremely weak, and the water quality gradually deteriorates from shallow to deep. Once polluted, the treatment is extremely difficult.

In terms of soil environment, the main impacts during the operation period are soil pollution and soil degradation. The leakage of wastewater and waste residue from the surface treatment station will cause the content of pollutants in the soil to exceed the standard, damage the soil structure and affect soil fertility. During the underground pyrolysis process, the rise of coal seam temperature will lead to the evaporation of soil moisture around, a drop in soil water content, trigger soil drought and degradation, and affect the growth of surrounding vegetation. Improper disposal of semi-coke produced by pyrolysis may also lead to soil pollution.

In terms of ecological environment, the main impacts during the operation period are vegetation degradation and ecosystem damage. The drop in groundwater level and soil pollution during the underground pyrolysis process will lead to the withering and death of surrounding vegetation and a decline in vegetation coverage. The noise and vibration generated during the pyrolysis process will continuously disturb the surrounding wild animals, leading to their migration and damaging biodiversity. In addition, long-term underground operations may cause land subsidence, damage the surface ecological landscape and affect the stability of the ecosystem.

4. Economic Evaluation of In-situ Pyrolysis of tar-rich Coal

4.1 Principles and Methods of Economic Evaluation

The economic evaluation of in-situ pyrolysis of tar-rich Coal follows the principles of “scientificity, objectivity, comprehensiveness and dynamics”, comprehensively considers the investment, cost and income in the process of technology development, objectively analyzes the economic feasibility of the technology, dynamically predicts the impact of market changes and policy adjustments on economic benefits, and provides economic reference for the industrial promotion of the technology.

This paper adopts a combination of static and dynamic evaluation methods to carry out economic evaluation. Static evaluation mainly includes indicators such as investment profit rate and investment profit and tax rate, which are used to directly reflect the profit level of the technology. Dynamic evaluation mainly includes indicators such as net present value (NPV), internal rate of return (IRR) and payback period of investment, which consider the time value of funds and reflect the economic feasibility of the technology more accurately. At the same time, uncertainty analysis (sensitivity analysis and break-even analysis) is introduced to consider the impact of geological conditions, market prices, process parameters and other factors on economic benefits, so as to improve the reliability of the evaluation results.

4.2 Investment Estimation

The investment of in-situ pyrolysis projects of tar-rich Coal mainly includes fixed asset investment and working capital investment, among which fixed asset investment is the core, accounting for more than 80% of the total investment. Combined with the data of the pilot test project of in-situ pyrolysis of tar-rich Coal in Northern Shaanxi (the total investment is 49.8 million yuan, the environmental protection investment is 1.448 million yuan, accounting for 2.91% of the total investment) and with reference to relevant industry standards, the investment of in-situ pyrolysis projects of tar-rich Coal is estimated.

Fixed asset investment mainly includes borehole engineering investment, roadway engineering investment, equipment purchase and installation investment, surface treatment station investment, environmental protection facility investment, etc. Borehole engineering investment is calculated according to the depth and number of boreholes, usually 800~1200 yuan per meter of borehole. If 100 boreholes with a depth of 200 meters are constructed, the borehole engineering investment is about 16~24 million yuan. Roadway engineering investment is calculated according to the length and section size of roadways, 5000~8000 yuan per meter of roadway. If 500 meters of roadways are constructed, the roadway engineering investment is about 2.5~4 million yuan. Equipment purchase and installation investment includes heating equipment, conveying equipment, separation equipment, monitoring equipment, etc., accounting for about 40%~50% of the fixed asset investment. Surface treatment station investment includes factory building construction, process equipment installation, etc., about 8~12 million yuan. Environmental protection facility investment includes waste gas treatment equipment, wastewater treatment equipment, soil remediation equipment, etc., accounting for about 2%~5% of the total investment.

Working capital investment is mainly used for raw material procurement, personnel wages, operation and maintenance, etc., and is calculated according to the project scale, usually 10%~15% of the fixed asset investment. In summary, for an in-situ pyrolysis project with an annual processing capacity of 100,000 tons of tar-rich Coal, the total investment is about 40~60 million yuan, including 32~48 million yuan of fixed asset investment and 8~12 million yuan of working capital investment.

4.3 Cost Accounting

The cost of in-situ pyrolysis projects of tar-rich Coal mainly includes operating cost, depreciation cost, financial expense, taxes and fees, among which operating cost is the main cost, accounting for more than 60% of the total cost.

Operating cost mainly includes raw material cost, energy consumption cost, labor cost, maintenance cost, environmental protection treatment cost, etc. Raw material cost is mainly the mining cost of tar-rich Coal, calculated according to the reserves and mining difficulty of tar-rich Coal, usually 80~120 yuan per ton. Energy consumption cost mainly includes energy consumption in heat carrier heating, equipment operation, product separation and other links, with differences according to different process types. Heat carrier injection pyrolysis has high energy consumption, about 150~200 yuan per ton of coal; electric heating pyrolysis has higher energy consumption, about 200~250 yuan per ton of coal; controlled oxidative spontaneous combustion pyrolysis has low energy consumption, about 50~100 yuan per ton of coal. Labor cost is calculated according to the number of employees. A project with an annual processing capacity of 100,000 tons of tar-rich Coal requires 50~80 employees, with a labor cost of about 0.8~1.2 million yuan per year. Maintenance cost is mainly used for the daily maintenance and overhaul of equipment and roadways, about 5%~8% of the fixed asset investment per year. Environmental protection treatment cost is mainly used for the treatment of waste gas, wastewater and waste residue, about 10%~15% of the operating cost.

Depreciation cost is calculated by the straight-line method. The depreciation period of fixed assets is 15~20 years, the residual value rate is 5%~10%, and the annual depreciation cost is about 4%~6% of the fixed asset investment. Financial expense mainly includes loan interest, calculated according to the loan amount and loan interest rate. If the project loan accounts for 50% of the total investment and the loan interest rate is 4.35%, the annual financial expense is about 0.87~1.305 million yuan. Taxes and fees mainly include value-added tax and enterprise income tax. The value-added tax rate is 13%, the enterprise income tax rate is 25%, and taxes and fees account for about 15%~20% of the operating income.

In summary, for an in-situ pyrolysis project with an annual processing capacity of 100,000 tons of tar-rich Coal, the annual total cost is about 25~35 million yuan, including 15~21 million yuan of operating cost, 1.28~2.88 million yuan of depreciation cost, 0.87~1.305 million yuan of financial expense, and 3.75~7 million yuan of taxes and fees.

4.4 Income Analysis

The income of in-situ pyrolysis projects of tar-rich Coal mainly comes from the sales income of pyrolysis products (tar, coal gas, semi-coke), in addition to policy subsidy income. Among them, tar and coal gas are the main income sources, accounting for more than 80% of the total income.

According to the yield of pyrolysis products of tar-rich Coal, processing 100,000 tons of tar-rich Coal annually can produce 7,000~15,000 tons of tar, 10~15 million cubic meters of coal gas and 80,000~90,000 tons of semi-coke. Combined with the current market prices, the tar price is about 5,000~8,000 yuan per ton, the coal gas price is about 1.5~2.5 yuan per cubic meter, and the semi-coke price is about 800~1,200 yuan per ton. Based on this calculation, the annual sales income is about 40~70 million yuan, including 24.5~120 million yuan from tar, 15~37.5 million yuan from coal gas, and 6.4~10.8 million yuan from semi-coke.

Policy subsidy income mainly includes clean energy subsidies and scientific and technological innovation subsidies. According to China's relevant policies, as a clean energy technology, the in-situ pyrolysis of tar-rich Coal can enjoy a clean energy subsidy of 200~300 yuan per ton of standard coal, with an annual subsidy income of about 2~3 million yuan. In addition, some regions give additional subsidies to scientific and technological innovation projects, further increasing the project income.

In summary, for an in-situ pyrolysis project with an annual processing capacity of 100,000 tons of tar-rich Coal, the annual total income is about 42~73 million yuan, including 40~70 million yuan of sales income and 2~3 million yuan of policy subsidy income.

4.5 Economic Optimization Strategies

In view of the economic uncertainty of in-situ pyrolysis projects of tar-rich Coal, combined with the economic evaluation results, economic optimization strategies are proposed from three aspects of investment control, cost control and income improvement to enhance the economic competitiveness of the projects and promote industrialization.

Investment control optimization: First, optimize the project design, reasonably determine the number of boreholes, roadway length and equipment specifications according to geological conditions to avoid blind investment; adopt modular design to reduce equipment installation costs and shorten the construction period. Second, broaden financing channels, actively strive for government special funds and scientific and technological innovation subsidies, attract social capital participation, and reduce financing costs; arrange the use of funds reasonably, improve the efficiency of fund use and reduce fund idleness. Third, strengthen investment management, establish a dynamic investment monitoring mechanism, timely discover and solve problems in the investment process, and control investment overspending.

Cost control optimization: First, reduce energy consumption costs, optimize the pyrolysis process, adopt technologies such as controlled oxidative spontaneous combustion pyrolysis and efficient heat carrier recycling to reduce energy consumption; strengthen equipment operation management, improve equipment operation efficiency and reduce equipment energy consumption. According to the results of numerical simulation research, for the homogeneous permeability model, the pyrolysis reaction can be completed in only 38 days when the coal seam permeability is increased to $1\mu m^2$, which can significantly reduce energy consumption; for the heterogeneous permeability model, a heat carrier flow rate of 0.12 kg/s is selected in the early stage to promote rapid pyrolysis in high-permeability areas, and the heat carrier flow rate is reduced in the later stage to save costs. Second, reduce labor costs, adopt intelligent equipment to realize the automatic operation of underground pyrolysis, product transportation, monitoring and other links, and reduce the number of employees; strengthen personnel training, improve the skill level of employees and enhance work efficiency. Third, reduce maintenance costs, strengthen the daily maintenance and overhaul of equipment and roadways, timely discover and solve equipment failures and extend the service life of equipment; adopt corrosion-resistant and wear-resistant equipment materials to reduce equipment loss.

Income improvement optimization: First, improve the quality and yield of products, optimize the pyrolysis process parameters, control the heating temperature and heating rate to improve the yield and quality of tar and coal gas; strengthen product separation and purification to enhance the added value of products, such as deep processing of tar into diesel, gasoline and other products to increase sales prices. Second, expand the product market, strengthen market research, establish stable sales channels, establish long-term cooperative relations with petroleum and chemical enterprises to ensure the stable sales of products; expand the application fields of semi-coke and coal gas to improve the utilization rate of products. Third, strive for policy support, actively apply for relevant subsidies such as clean energy and scientific and technological innovation to increase project income; take advantage of national energy policies, enjoy preferential policies such as tax reduction and exemption to reduce tax costs. Fourth, promote the coordinated development of multiple industries, take advantage of the spatial overlapping distribution of China's oil and gas, coal, wind and solar resources, realize the coordinated development of in-situ pyrolysis of tar-rich Coal with new energy, coalbed methane, underground coal gasification, CCUS and modern coal chemical industry, reduce investment costs and improve comprehensive income.

5. Research Prospects

With the continuous advancement of energy structure transformation, the industrial promotion prospect of in-situ pyrolysis technology of tar-rich Coal is broad, but it still faces many challenges at present. Further research can be carried out from the following aspects in the future:

First, strengthen the research and development of core technologies, focus on breaking through key technologies such as coal seam reconstruction, temperature and pressure regulation, and pollutant treatment, optimize the pyrolysis process route, improve the technological maturity and adaptability, and reduce environmental risks and operating costs; conduct in-depth research on the flow mechanism of "variable temperature, variable pressure and variable phase state" and the multi-field coupling mechanism of thermal-hydro-mechanical-chemical, so as to provide theoretical support for technological optimization.

Second, improve the environmental and economic evaluation system, refine environmental impact indicators and economic parameters according to different geological conditions and process types, and improve the accuracy and adaptability of evaluation results; introduce the life cycle assessment method to comprehensively evaluate the environmental impacts and economic benefits of the whole life cycle of in-situ pyrolysis of tar-rich Coal.

Third, promote large-scale and industrial development, increase policy support, improve industrial standards and norms, and cultivate a number of professional enterprises engaged in the in-situ pyrolysis of tar-rich Coal; strengthen industry-university-research cooperation, promote the transformation of technological achievements, reduce project investment and operating costs, and enhance the economic competitiveness of projects.

Fourth, strengthen international cooperation and exchanges, learn from foreign advanced technologies and experiences, and develop in-situ pyrolysis technologies with independent intellectual property rights combined with China's geological conditions of tar-rich Coal; promote the integrated development of in-situ pyrolysis technology of tar-rich Coal with new energy, CCUS and other technologies, help achieve the “double carbon” goals, and provide strong support for China’s energy security guarantee.

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